sierra research

Report No. SR2008-08-01

Impacts of MMT® Use in Unleaded Gasoline on Engines, Emission Control Systems, and Emissions

prepared for:

Canadian Vehicle Manufacturers' Association and Association of International Automobile Manufacturers of Canada

August 29, 2008

prepared by:

Sierra Research, Inc.
1801 J Street
Sacramento, California 95811
(916) 444-6666

Report No. SR2008-08-01

IMPACTS OF MMT® USE IN UNLEADED GASOLINE ON ENGINES, EMISSION CONTROL SYSTEMS, AND EMISSIONS

prepared for:

Canadian Vehicle Manufacturers' Association and
Association of International Automobile Manufacturers of Canada

August 29, 2008

Principal author:

James M. Lyons

Sierra Research, Inc.
1801 J Street
Sacramento, CA 95811
(916) 444-6666

IMPACTS OF MMT® USE IN UNLEADED GASOLINE ON ENGINES, EMISSION CONTROL SYSTEMS, AND EMISSIONS

Table of Contents

List of Figures

List of Tables

GLOSSARY

AAMA	American Automobile Manufacturers Association
AIAM	Association of International Automobile Manufacturers
AIT	Agreement on International Trade
AKI	anti-knock index
Alliance	Alliance of Automobile Manufacturers
ALVW	Adjusted Loaded Vehicle Weight
ASTM	formerly American Society for Testing and Materials
AT PZEV	Advanced Technology Partial Zero Emission Vehicle
Ba	barium
BC	British Columbia
CARB	California Air Resources Board
CC	close-coupled
CGSB	Canadian General Standards Board
CO	carbon monoxide
cpsi	cells per square inch
CRC	Coordinating Research Council
CVMA	Canadian Vehicle Manufacturers' Association
CVS-75	Chassis dynamometer based emission test procedure (See generally 40 CFR Part 85, Subparts B and C, and section 86.130 for specific testing sequence)
DF	deterioration factor
DTC	diagnostic trouble or fault code
E200	the percentage of a gasoline sample that has evaporated by the time it has been heated to 200º C
EGR	exhaust gas recirculation
ELPI	electrical low pressure impactor
EPA	(U.S.) Environmental Protection Agency
EU	European Union
EURO	refers to automobile emission standards established by the European Union
FTP	(U.S.) Federal Test Procedure
g/km	grams per kilometer
g/mi	grams per mile
GM	General Motors
GVWR	Gross Vehicle Weight Rating
HC	hydrocarbon
HCHO	formaldehyde

HDCC	high cell density close-coupled
HEGO	Heated Exhaust Gas Oxygen
HLDT	heavy light-duty truck
km	kilometer
LDV	light-duty vehicle
LEV	Low Emission Vehicle
LLDT	light light-duty truck
MDPV	medium-duty passenger vehicle
MECA	Manufacturers of Emission Controls Association
mg/l	milligram per litre
mg Mn/l	milligram of manganese per litre
MIL	malfunction indicator light
MMT®	methylcyclopentadienyl manganese tricarbonyl ($CH_3C_5H_4Mn(CO)_3$)
Mn	manganese
Mn_3O_4	manganese tetroxide
MON	Motor Octane Number
MOU	Memorandum of Understanding
MOUDI	micro-orifice uniform deposit impactor
MSAT	Mobile Source Air Toxics
MTBE	methyl tertiary butyl ether
MY	model year
NAFTA	North American Free Trade Agreement
NLEV	National Low Emission Vehicle
NMHC	nonmethane hydrocarbon
NMOG	nonmethane organic gas
NO	nitric oxide
NO_2	nitrogen dioxide
NOx	oxides of nitrogen
OBD	on-board diagnostic
OMS	(U.S. EPA) Office of Mobile Sources
Pb	lead
Pd	palladium
PIXE	particle-induced X-ray emission
PM	particulate matter
$PM_{2.5}$	particulate matter less than 2.5 microns in diameter
ppm	parts per million
Pt	platinum
PZEV	Partial Zero Emission Vehicle
REP05	representative driving cycle number 5
RFG	reformulated gasoline
Rh	rhodium
RON	Research Octane Number
Rvp	Reid vapor pressure
SFTP	Supplemental Federal Test Procedure
SMA	Standard Mileage Accumulation
SMPS	scanning mobility particle sizer

SULEV	Super-Ultra-Low Emission Vehicle
T2B5	Tier 2 Bin 5
T50	the temperature at which 50% of a gasoline sample has been distilled
T90	the temperature at which 90% of a gasoline sample has been distilled
TEL	tetra-ethyl lead
THC	total hydrocarbon
TLEV	Transitional Low-Emission Vehicle
TOR	Terms of Reference
TPR	Third-Party Review
UF	under-floor
ULEV	Ultra-Low Emission Vehicle
US	United States
VOC	volatile organic compound
ZEV	Zero-Emission Vehicle

1. EXECUTIVE SUMMARY

In response to concerns regarding the environmental impacts of smog-forming pollutants emitted by gasoline-powered vehicles first identified over 40 years ago, the federal, provincial, and state governments in Canada and the United States have developed extensive regulatory programs intended to reduce emissions of these pollutants. The significantly more stringent Tier 2 emission standards, which began in 2004, require new vehicles in Canada and the U.S. to emit less than 2% of the amount of hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) pollutants emitted by the new vehicles of the 1960s, which were not subject to emissions regulations. In addition, vehicles must comply with these standards in customer service for periods of 160,000 kilometres or more and must be equipped with on-board diagnostic (OBD) systems that alert operators to the presence of defects or malfunctions that increase emissions beyond certain regulated thresholds throughout the life of the vehicle.

The technological advancements that allow for compliance with the Tier 2 standards include the incorporation of high-density close-coupled (HDCC) catalysts, which differ from earlier catalysts in that there are more catalyst cells per unit area. This increase in cell density significantly increases the active surface area of the catalyst while reducing the mass of the catalyst and therefore the time required to achieve operating temperature. In addition, catalyst formulations have been modified so that they can routinely withstand temperatures in excess of 800º C for extended periods of time. These advancements have provided vehicle manufacturers with catalysts that can be situated closer to the engine. This allows the catalyst to reach optimum operating temperature quickly after the engine is cold-started in order to achieve very low pollutant emissions during all modes of operation. In addition to locating catalysts very close to the engine, manufacturers have developed computerized engine control systems that enable catalysts to reach operating temperatures more quickly by temporarily increasing exhaust temperatures after an engine is cold-started, again to reduce emissions. In addition to improvements in catalyst technology, manufacturers have redesigned engines in order to lower pollutant levels in the exhaust gas coming from the engine, which then passes through the catalyst. HDCC systems like those described above are expected to be the dominant, if not the exclusive, technical approach for compliance with Tier 2 emission standards both now as well as in the future.

In order to achieve compliance with current Tier 2 emission standards, the properties and composition of the fuel upon which a vehicle operates must be treated as an integral component of the vehicle emission control system during the design, testing, and routine operation of that system. During the late 1990s, new vehicles with advanced emission control systems of the types required to comply with the Tier 2 standards began to be introduced into the North American vehicle market. These new vehicles sold in the U.S.

and Canada were designed and built to achieve identical emissions performance. However, their in-use operation was different in that the majority of gasoline sold in Canada contained the organo-metallic, octane-enhancing additive methylcyclopentadienyl manganese tricarbonyl, or MMT®. MMT® was present in Canadian gasoline until its use was voluntarily halted by Canadian refiners between 2003 and 2005. MMT®, like its now-banned predecessor tetra-ethyl lead, is manufactured exclusively by the Ethyl Corporation (now Afton Chemical). Although MMT® use is banned in California and in the reformulated gasoline sold in many urban areas of the U.S., in Canada the addition of MMT® to unleaded gasoline, generally at levels up to 18 milligrams of manganese per liter (mg Mn/l), has been practiced continuously from the mid-1970s through the 2003 to 2005 phase-out period. Since 2005, MMT® has not been used in Canada.

The use of MMT® in unleaded gasoline has long been controversial because, unlike other available octane boosters that burn completely, such as ethanol, the manganese atoms in MMT® form solid manganese oxide particles during the combustion process. These reddish-brown manganese oxide particles form deposits in the combustion chamber and accumulate on the front of catalytic converters and the surfaces of the exhaust system. They are also emitted to the atmosphere from the tailpipes of vehicles. The impact of manganese oxide deposits on the engine, emission control system, and emissions of vehicles using MMT®-containing fuels has long been a source of concern. These concerns about the impacts of MMT® have led to numerous studies by Ethyl Corporation and Afton Chemical, automobile manufacturers, and auto industry trade associations, as well as governmental agencies. The purpose of this report is to review the available studies and to present new information regarding the impact of MMT® on vehicles with advanced emission control systems, such as those that were sold and continue to be sold in Canada in order to comply with the Tier 2 emission requirements.

The studies conducted by Afton (Ethyl Corporation) have purported to demonstrate either that the use of MMT® in gasoline was benign, or that it improved catalyst performance to some degree, and/or reduced certain emissions. However, recent studies by Afton as well as some Ethyl studies dating back to the 1970s have demonstrated that MMT® can lead to catalyst plugging.

Studies performed by the auto industry have consistently found that the use of MMT® in gasoline led to vehicle problems that included increases in engine-out HC emissions, sparkplug misfire, exhaust valve leakage, varying degrees of catalyst plugging, tailpipe emissions increases, and/or exceedances of applicable emission standards. The auto industry studies also indicate that vehicles designed with the most sophisticated emission control systems—in particular, those with HDCC catalysts—are most susceptible to being adversely affected by the use of MMT®-containing gasolines.

Given the fundamentally different conclusions reached by the auto industry and Afton, the Canadian Government considered conducting an independent or “third party” review of the effects of MMT®. This review became moot as the result of the voluntary phase-out of MMT® use by Canadian refiners from 2003 to 2005. However, data collected in anticipation of the review, and while MMT® was still in use in Canada, clearly demonstrate the adverse impacts of MMT® on advanced technology vehicles. These data demonstrate that the use of MMT® in Canadian gasoline adversely impacted **at least** 25 models of 1999 to 2003 model-year vehicles produced by **nine** manufacturers, which accounted for approximately 85% of Canadian light-duty vehicle sales in 2006. The means by which MMT® adversely impacted these models include severe catalyst plugging. Similar plugging was not identified on these models in virtually identical vehicle operating conditions in the United States, where MMT® is not in widespread use. Also, after MMT® use was voluntarily halted by gasoline refiners, data demonstrate that catalyst plugging cases in Canada quickly diminished.

The data demonstrating the adverse impacts of MMT® on exhaust emissions and advanced emission control technologies and systems on in-use Canadian vehicles were collected from the following sources:

1. In-use Canadian vehicles brought to dealerships by motorists for warranty service;

2. In-use Canadian vehicles recruited or obtained for data collection;

3. In-use parts from Canadian vehicles obtained by vehicle manufacturers;

4. Laboratory test programs performed in light of problems observed with in-use Canadian vehicles to confirm in-use findings and to investigate causative factors; and

5. Vehicle emissions testing.

Because vehicles with advanced emissions control technologies were only beginning to be introduced into the vehicle fleet at the time MMT® use was suspended in Canada, the ultimate impacts of MMT® use on vehicle and emission system control performance cannot be definitively determined for two reasons. First, some models introduced during the period when MMT® was still in use in Canada may not have been sufficiently exposed to MMT® before the voluntary phase-out for adverse impacts to have developed. Secondly, because vehicles with advanced technologies were just beginning to be introduced as MMT® was being removed, many advanced systems designs that are now in-use were never exposed to MMT®. Despite being only the "tip of the iceberg," what is known at this point about the consequences of the use of MMT®-containing fuels in vehicles that comply with the Tier 2 regulations is summarized below.

1. Plugging of catalysts due to manganese oxides on in-use vehicles can occur and has been documented at this point to be a substantial problem on a number of different models of in-use Canadian vehicles produced by a number of different manufacturers.

2. Vehicles with catalysts plugged by manganese oxides can have driveability problems due to excessive exhaust system backpressure. These problems can be corrected only by catalyst replacement.

3. Vehicles with catalysts plugged to a substantial degree by manganese oxides will generally experience MIL illumination and have fault codes stored indicating catalyst failure. The MIL can be extinguished and fault codes prevented from being stored only if the catalyst is replaced.

4. The plugging of catalysts by manganese oxides is most frequently observed on vehicles with advanced emissions controls systems that incorporate HDCC catalysts. Such vehicle designs are expected to become widespread as all new vehicles sold in the U.S. and Canada are required to comply with the requirements of the Tier 2/LEV II regulations.

5. Some advanced technology vehicles for which catalyst plugging due to MMT® has been demonstrated have also been shown to have, to varying degrees, increased tailpipe emissions of volatile organic compounds (VOC), CO, and NOx.

6. The rates of Canadian catalyst warranty replacement where MMT®-related plugging has been documented were significantly higher than the U.S. warranty rate for vehicles equipped with the same emissions control systems. The rate of increase in Canadian warranty rates slowed in direct response to the reduction in the use of MMT® in Canadian gasoline

7. There is no demonstrated method, other than eliminating MMT® from the fuel, to ensure that an emission control system that allows a vehicle to comply with the requirements of the Tier 2/LEV II regulations will not experience catalyst plugging caused by manganese oxides as well as one or more of the observed problems of degraded driveability, MIL illumination, and increased emissions.

In addition to being used to demonstrate the adverse impacts of MMT® on vehicles, the data collected by the auto industry on advanced technology vehicles from the in-use laboratory of Canada have been combined with existing data and incorporated into the MOBILE6C emission factor model to evaluate the impact of MMT® use on emissions from the Canadian vehicle fleet. This study reached the following conclusions:

1. Using conservative assumptions that likely understate the impact of MMT® use on emissions of in-use vehicles, it was estimated that reintroduction of MMT® in 2008 in Canada at historic levels would result in increases in VOC, CO, and NOx emissions of 77%, 51%, and 12%, respectively, by 2020; and

2. Despite the cessation of MMT® use in Canada in 2004, the legacy of MMT® use will be increases in VOC and CO emissions, as well as modest reductions in NOx emissions.

In summary, the recent Canadian in-use experience not only supports earlier auto industry study findings that demonstrated that MMT® impairs the operation of emission control systems and increases emissions, but also provides significant evidence that the use of this additive is not compatible with the advanced HDCC catalyst systems that are needed to achieve compliance with stringent Tier 2 emission regulations.

###

2. INTRODUCTION

In response to concerns regarding the environmental impacts of smog-forming pollutants emitted by gasoline-powered vehicles first identified over 40 years ago, the federal, provincial, and state governments in Canada and the United States have developed extensive regulatory programs intended to reduce emissions of these pollutants. As a result of these regulations and massive research and development programs undertaken by auto manufacturers, as well as component suppliers, governmental agencies, and research organizations, new gasoline-powered vehicles designed for compliance with current Tier 2 emission standards emit less than 2% of the amount of pollutants emitted by the new vehicles of the late 1950s and early 1960s, which were not subject to emissions regulations.

In addition to mandating compliance with performance-based emission standards for new vehicles, Canadian and U.S. emissions regulations now mandate that vehicles continue to comply with these standards in customer service for periods of 160,000 km or more and require that vehicles be equipped with on-board diagnostic systems that alert operators to the presence of defects or malfunctions that increase emissions beyond certain thresholds.

The key to compliance with the Tier 2 emission standards has been the development of advanced emission control systems based on high-density close-coupled (HDCC) catalysts, which differ from older catalyst designs in that the density of the cells of the monolith has been increased from the typical 400 per square inch to 600 or more per square inch and the catalysts can routinely withstand temperatures in excess of 800º C for extended periods of time. In addition to HDCC catalyst technology, manufacturers have developed computerized engine control systems and redesigned engines to reduce engine-out pollutant levels in the exhaust, which forms the feedgas for the catalytic converter.

A number of changes to gasoline composition made over the past 30 years in response to government regulations facilitate compliance with the Tier 2 emission standards. These include the mandated sale of unleaded gasoline, which began in 1975, and the complete elimination of leaded gasoline in Canada and the U.S. in the early 1990s. Lead additives had been used to increase gasoline octane ratings but were targeted for elimination after it was determined that their use rendered emission control catalysts ineffective.

The elimination of lead from gasoline created a need for gasoline refiners to find other methods of improving the octane rating of gasoline, and a number of approaches were identified. These include increasing the concentrations of branched alkane and/or aromatic compounds present in gasoline through modifications to refineries or refinery operation; using oxygenated gasoline additives such as ethanol and methyl-tertiary butyl ether; and using another metal-based additive, methylcyclopentadienyl manganese tricarbonyl (MMT®).

The use of MMT® differs from the other means available to refiners to increase gasoline octane ratings because the manganese present in MMT® forms solid manganese oxide particles during the combustion process. These particles, which are reddish-brown in color, form deposits in the engine cylinders and exhaust system and are also emitted to the atmosphere from vehicle tailpipes.

Since the introduction of MMT® in the mid-1970s by the Ethyl Corporation, there have been concerns regarding its impacts on engines, emission control systems, and emissions. These concerns led to a number of studies of the impacts of MMT® being conducted over the past 30 years, which found that MMT® use could lead to various problems, including the plugging of catalytic converters. As a result of these and other findings, a ban on the use of MMT® in unleaded gasoline in California began in the late 1970s, and a ban on the use of MMT® in unleaded gasoline throughout the U.S. was in effect from the late 1970s through 1995 and it continues to apply to reformulated gasoline. Today, MMT® appears to be used on a very limited basis in conventional gasoline in the U.S. In Canada, however, MMT® is allowed to be used in unleaded gasoline and it was widely used for around two decades until individual refiners voluntarily began to stop adding MMT® to gasoline between 2003 and 2005. MMT® use in Canada has essentially ceased since late 2005.

Looking to the future, it is clear that the use of MMT®-containing gasoline is incompatible with the engines and emission control systems required to comply with the Tier 2 regulations. This report is intended to be a comprehensive summary of the information and data that establish that fact. The remainder of the report is organized into nine chapters (3 through 11) addressing various aspects of the MMT® issue.

Chapter 3 summarizes the history of the control of exhaust emissions from gasoline-powered vehicles and the emission standards put in place by governmental agencies in Canada and the U.S. that led to the development of today's advanced emission control systems designed to comply with the Tier 2 regulations. Given the widespread recognition that fuels represent a critical component of vehicular emission control systems, Chapter 4 presents the history of gasoline performance standards and government regulations setting specifications for gasoline composition, while Chapter 5 presents a detailed history of the use of MMT® in unleaded gasoline in the United States and Canada.

Following Chapters 3 through 5, which provide historical information related to the establishment of vehicle emission standards and regulations on fuel composition as a means of improving air quality, Chapter 6 provides a technical overview of how pollutants are formed in gasoline-fueled engines. It also discusses the design and operation of exhaust emission control systems from their introduction in the mid-1970s to the present in order to facilitate an understanding of why the use of MMT® poses significant problems, particularly for vehicles with advanced emission control systems.

The next four chapters of the report—Chapters 7 through 10—provide a comprehensive review of the technical literature that is relevant to the impact of MMT® on engines, emission control systems, and emissions. Given the long period over which the impact of MMT® has been studied and the evolution of automobile engines and emission control systems, these data have been segregated by the vintage of the vehicles used in the assessment of MMT® impacts: Chapter 7 addresses early studies of MMT® impacts that focused on mid-1970s to early 1980s vehicles; and Chapter 8 addresses studies involving mid-1980s to early 1990s vehicles. The landmark study of MMT® impacts sponsored by the Alliance of Automobile Manufacturers (Alliance), the Association of International Automobile Manufacturers (AIAM), and the Canadian Vehicle Manufacturers Association (CVMA) is the subject of Chapter 9. Chapter 10 summarizes MMT®-related studies published since the release of the Alliance-AIAM-CVMA study.

Chapter 11 presents the only available real-world data regarding the impacts of MMT® on the engines, emission control systems, and emissions of advanced technology vehicles. These real-world data were collected by vehicle manufacturers in Canada, where the unique conditions of MMT® use and in-use operation of advanced technology vehicles existed during the period beginning in the late 1990s and continuing until MMT® was voluntarily removed from Canadian gasoline. These data, and supporting information and analyses compiled by vehicle manufacturers, clearly demonstrate that the use of MMT®-containing gasoline in advanced technology vehicles leads to serious adverse impacts on engines, emission control systems, and emissions.

###

3. HISTORY OF EXHAUST EMISSION STANDARDS AND REGULATIONS FOR LIGHT-DUTY GASOLINE-FUELED VEHICLES IN NORTH AMERICA

This chapter traces the development of emission standards in Canada and the United States from initial regulatory interventions in the 1960s to the Tier 2 standards that are now applicable.

3.1 Vehicle Emissions

The pollutants of primary concern that are emitted in the exhaust of gasoline-fueled engines are outlined below.

- Hydrocarbons (HC) − Exhaust hydrocarbons[*] are mainly compounds found in gasoline that are not burned or are partially burned in the engine. However, some specific species are formed during the combustion process. Hydrocarbon subcategories referenced in regulations include non-methane hydrocarbons (NMHC) and non-methane organic gases (NMOG).

- Carbon monoxide (CO) − Carbon monoxide in engine exhaust results from the incomplete combustion of gasoline in the engine.

- Oxides of nitrogen (NOx) − Oxides of nitrogen in engine exhaust are formed from the nitrogen and oxygen present in air drawn into the engine as a result of high temperature and pressure conditions that exist in the engine during combustion.

- Particulate matter (PM) − Particulate matter in gasoline-engine exhaust can arise from a number of sources, including incomplete vaporization of gasoline droplets, incomplete combustion, sulfur, and other inorganic compounds present in gasoline and lube oil, and metals such as lead and manganese that are introduced as fuel additives.

Vehicular emissions of HC and NOx were first linked to tropospheric ozone formation in conjunction with studies of Los Angeles “smog” in the 1950s, and efforts to control emissions of those pollutants began shortly thereafter.[1] Ozone is a strong irritant to the

[*] In addition, most so-called “toxic air contaminants”—such as benzene, formaldehyde, and 1,3 butadiene—are hydrocarbons.

lungs and eyes. At high concentrations it causes shortness of breath and aggravates asthma, emphysema, and other conditions. Prolonged exposure to high ozone concentrations can cause permanent reductions in lung function.

Vehicular CO emissions are of concern because CO is readily absorbed by human lungs and it displaces oxygen in the bloodstream. At high enough concentrations, it causes unconsciousness or even death due to a lack of oxygen in the bloodstream. At lower concentrations, the most significant adverse effect is that the heart needs to pump harder to supply an adequate amount of oxygen to the body. CO emissions also make a minor contribution to ozone formation.

Exposure to high ambient concentrations of PM can lead to, among other things, increased incidence of respiratory disease, lung damage, and cancer. Gasoline-fueled vehicles generally emit much less PM than Diesel-fueled vehicles and therefore there has been less concern regarding PM emissions from gasoline-fueled vehicles historically. However, more recent studies, such as those that led to the enactment of the U.S. National Ambient Air Quality Standard for $PM_{2.5}$,[*2] have shown that exposure to high ambient concentrations of PM leads to greater health effects than was previously thought, and PM emissions from gasoline-fueled vehicles are coming under greater scrutiny.

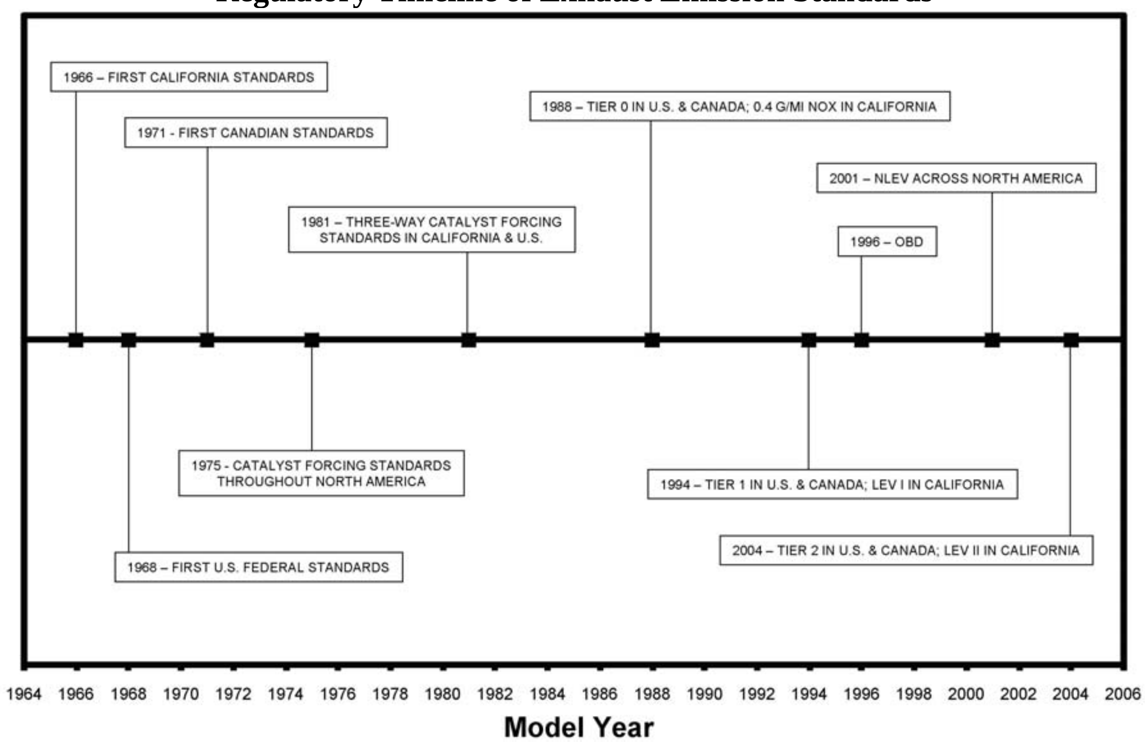
In recognition of the adverse health impacts associated with exhaust emissions from gasoline-fueled vehicles, government regulations limiting those emissions have been enacted. The first exhaust emission standards for new gasoline-fueled vehicles in North America were enacted by the California Air Resources Board (CARB) and applied to 1966 model-year vehicles. Over the four subsequent decades, CARB, the U.S. Environmental Protection Agency (EPA), the Canadian federal government through Transport Canada and Environment Canada, and, to a lesser extent, the provincial government in British Columbia (BC) have adopted increasingly stringent exhaust emission control regulations and standards for gasoline-fueled passenger cars and light- and medium-duty trucks.

The history of North American light-duty vehicle exhaust emission standards is summarized in this chapter.[†] Although California and U.S. federal standards have generally driven the development of vehicle emission reduction technology in North America, this chapter focuses on the development of Canadian standards given their particular relevance to the Canadian experience with MMT® usage examined in Chapter 11. However, because the history of the Canadian standards cannot be separated from the development of the U.S. federal and California standards, those are also addressed here. Also, although not addressed in this report, it should be noted that efforts to reduce vehicular exhaust emission levels through the adoption of a series of increasingly stringent new vehicle standards, which in turn forces the development of more advanced emission control systems, have occurred throughout the world, particularly in Europe and Japan.

[*] $PM_{2.5}$ refers to particulate matter less than 2.5 microns in diameter.
[†] Exhaust emission standards have similarly been developed for heavy-duty vehicles; however, given that most of these vehicles are Diesel-fueled, gasoline-fueled heavy-duty vehicles are not discussed in this report.

A timeline based on vehicle model year* showing some of the major milestones in the development of exhaust emission standards in North America is presented in Figure 3-1. Of particular note are the 1975 model-year standards that generally required the introduction of catalytic converters on new vehicles throughout North America, the 1981 model-year U.S. federal and California standards that required the introduction of three-way catalysts (see Chapter 4 for a description of three-way catalysts), the general alignment of Canadian and U.S. federal Tier 0 standards beginning with the 1988 model year, California's first round of "Low Emission Vehicle" (LEV) standards that came into place with the 1994 model-year, on-board diagnostic (OBD) system requirements that took effect in 1996 throughout North America, enforcement of LEV standards across North America in 2001, and the Tier 2 and the second set of LEV regulations (LEV II) that came into place with the 2004 model year.

Figure 3-1
Regulatory Timeline of Exhaust Emission Standards



It is important to note that as more sophisticated exhaust emission control systems have been developed, changes in gasoline composition, including the elimination of lead, limitations on phosphorus and sulfur content, and regulation of detergents and engine deposit formation, etc., have been required in order to facilitate the use of those technologies or ensure their durability. In establishing the current Tier 2 and LEV II

* Because the period during which vehicles of a given model are produced is not continuous and may include portions of more than one calendar year, the concept of model year was developed. At present, the "model year" of a vehicle is generally defined as the year associated with the January 1 that occurs during the production period of the model. See Sections 85.2302 to 85.2305 of Title 40, Code of Federal Regulations and U.S. EPA OMS Advisory Circular A/C No. 6b for additional details.

exhaust standards, it has been recognized by government regulators that stringent vehicular emissions control requires the vehicle engine and emission control components and the gasoline upon which the engine operates to be treated as a "system." It is not uncommon for gasoline properties to be mandated and restrictions placed on the use of fuel additives to enable emission controls. It is also well understood that both components of this system must be in place in consumer service[*] in order for the vehicles to comply with the stringent full useful life exhaust emission standards for the Tier 2 and LEV II programs.

3.2 Overview of Regulatory Approach

The exhaust emission standards that have applied to new vehicles have generally been performance based and expressed in terms of the mass of a pollutant allowed to be emitted by a vehicle as it travels a given distance.[†] In practice, North American standards have generally been cast in units of grams of pollutant allowed to be emitted per mile. Because the way in which the vehicle is operated affects the mass of pollutants emitted per unit distance, emission standards are linked to specific test procedures. Since 1975, most emission standards have been linked to the U.S. Federal Test Procedure (FTP) set forth in Part 86 of Title 40 of the United States Code of Federal Regulations. This procedure employs a chassis dynamometer and driving cycle that specifies vehicle speed on a second-by-second basis. It is conducted at a nominal ambient temperature of 24º C (75º F). More recently, additional test procedures and emissions standards have been adopted that are linked to other more severe driving conditions or lower ambient temperatures.[‡]

In addition to being linked to specific test procedures, exhaust emission standards are linked to the emissions of vehicles in consumer service at certain points in their lives. These points are usually defined in terms of the amount of mileage that the vehicle has accumulated. In general, exhaust emission standards apply to vehicles of a given model year over a period of vehicle operation that can range from about 80,000 km (50,000 miles) to about 240,000 km (150,000 miles), and different standards may apply at different mileage points.

As an illustration, consider the Tier 2, Bin 5 in-use emission standards[§] that apply to some 2004 and later model-year vehicles sold in Canada and the United States. These standards were chosen for use in this illustration because they are expected to be the ones to which most vehicles are certified under the Tier 2 regulations. The standards, which

---

[*] The terms "in customer service" and "in-use" are used to differentiate normal vehicle use from vehicle use during the emissions certification process described in this chapter.
[†] Because California and U.S. federal standards and the points at which they apply are generally set in terms of miles, the kilometer values discussed in this chapter have been rounded and are approximate rather than exact.
[‡] These are primarily the Supplemental Federal Test Procedure (SFTP) and cold-temperature standards also set forth in Part 86 of Title 40.
[§] As described in detail later in this chapter and in the appendices to this report, the Tier 2 Bin 5 is one of the eight permanent levels or "bins" of standards provided in the Tier 2 regulations. The Bins are numbered from 8 to 1, with Bin 8 being the least stringent and Bin 1 being the most stringent. There are also three temporary bins that are phased out by 2009.

set upper limits on allowable emissions, are shown in Table 3-1. As shown, separate standards exist for exhaust emissions of NMOG, CO, NOx, PM, and formaldehyde (HCHO). In addition, as shown, the allowable levels of in-use emissions depend on how much mileage the vehicle has accumulated. Emission levels permitted at 120,000 miles are somewhat higher than those allowed at 50,000 miles in order to provide some allowance for limited deterioration of the performance of the emission control system.

Table 3-1
Tier 2, Bin 5 In-Use Emission Standards
(g/mi)

	Pollutant				
Mileage	NMOG	CO	NOx	PM	HCHO
50,000	0.075	3.4	0.05	0.01	0.015
120,000	0.090	4.2	0.07	0.01	0.018

The regulatory requirements associated with compliance with the new vehicle exhaust emission standards are highly complex and can vary from the Canadian to the U.S. federal to the California standards. Given this, an exhaustive review of all aspects of the applicable regulations and standards is beyond the scope of this report. However, the general process of how compliance is demonstrated is summarized here in highly simplified terms. Note that this general process may not apply precisely to any one of the three jurisdictions.

Prior to being allowed to sell any new vehicle, a manufacturer must have the appropriate regulatory agency "certify" that the vehicle complies with all applicable requirements. In the certification process, a manufacturer's products are categorized by "engine family" or test group rather than model.* Engine families are defined based on, among other things, the type and displacement of the engine, the type of fuel metering system and other engine characteristics, and the characteristics of the emission control system.

During the certification process, manufacturers submit emissions test data from prototype vehicles that are as similar as possible to the vehicles that will be produced. The prototype vehicles are tested at low mileage and then subjected to accelerated mileage accumulation or some other procedure to "age" the emission control system to the point that would be expected on production vehicles at the final in-use mileage point where the standards apply. The low-mileage emission test point is usually at about 6,500 km (4,000 miles), a distance chosen to ensure that the performance of the emission control system has stabilized. Emissions are then projected to the end of the useful life of the vehicle either by using a deterioration factor (DF) developed for the vehicle or by testing a low mileage vehicle with critical emission control components installed that have been aged to be representative of the expected condition at the end of the full useful life period. If

* Certification is not done based on models, because several different engines that differ significantly in terms of their emissions and emission control systems may be offered in the same model and, conversely, one engine may be used in several models.

the projected emissions levels are all below the applicable emission standards, the vehicle is certified and allowed to be sold.

Certification is not by any means the end of the process, however. Manufacturers are required to provide emission control system warranties for their vehicles and must replace emission-related components that fail during specified periods of operation. In addition, manufacturers must report high incidences of emission control component failures to governmental agencies and in some cases take corrective actions, including recalling vehicles. On most 1996 and later model-year vehicles, on-board diagnostic (OBD) systems are required by new-vehicle regulations. The purpose of these systems is to inform the operator of the vehicle that the vehicle's emissions exceed the allowable emission standard by some threshold amount and to store information in the vehicle's computer that allows the reason for this to be easily identified and repaired.

Regulatory agencies and manufacturers may elect or be required to perform emission testing on vehicles that have been in normal consumer service as part of the process of demonstrating compliance with the new vehicle emission standards. This testing is performed using the same test procedures and test fuels used during the initial certification process. If the emission test data show that these in-use vehicles do not comply with the applicable emission standards, regulatory agencies may institute an enforcement action that could require manufacturers to recall and repair the vehicles.

3.3 Summary of Canadian Exhaust Emission Standards

The first Canadian exhaust emission standards applied to 1971 model-year vehicles and, as noted above, have generally become increasingly stringent over time. A detailed chronological presentation of Canadian exhaust emission standards applicable to new light-duty gasoline vehicles is presented in Appendix A.

Table 3-2 presents a chronological summary of Canadian federal exhaust emission standards (standards briefly adopted by the Province of British Columbia are discussed separately below) applicable to new passenger cars from the 1971 model year through the current Tier 2 regulations. Some of the Canadian standards were implemented by means of a Memorandum of Understanding (MOU) process between government and industry rather than by the imposition of governmental standards. Also shown are the approximate emission levels of uncontrolled (pre-1971 model year) vehicles and an estimate of the percentage of the emissions of each substance eliminated relative to uncontrolled levels as the result of compliance with each standard. As documented in Appendix A, the lifetime period over which vehicles must comply with Canadian emission standards has increased over time from about 80,000 km to as much as 200,000 km.

Table 3-2
Canadian Passenger Car Exhaust Emission Standards[a]
& Percent of Emissions Controlled
(g/mi at 50,000 miles unless otherwise indicated)

	HC, NMHC, or NMOG		CO		NOx	
Model Year	Standard	% Control	Standard	% Control	Standard	% Control
Pre-1971 (uncontrolled)	9.0	N/A	90.0	N/A	4.0	N/A
1971 (first year of control)	2.2	76	23	74	N/A	N/A
1975-1987	2	78	25	72	3.1	22.5
1988-1993, and 1996-1997 (Tier 0)[e]	0.41	95.4	3.4	96.2	1.0	75
1994-1995, and 1998-2000 (Tier 1)[e]	0.41	95.4	3.4	96.2	0.4	90
2001-2003 (NLEV)[b]	0.040-0.125	98.6-99.6	1.7-3.4	98.1-96.2	0.2-0.4	90-95
2004 and Later (Tier 2)[c]	0.010-0.100	98.9-99.9	2.1-3.4	96.2-97.7	0.02-0.14[d]	96.5-99.5

[a] Standards were either imposed by regulation or implemented pursuant to Memoranda of Understanding (MOU) with the auto industry (see Appendix A for further details).

[b] Range shown covers California standards for U.S. federal National Low Emission Vehicle (NLEV) program for passenger cars and light trucks excluding zero emission vehicles; less stringent standards applied for heavier light trucks.

[c] Tier 2 standards applicable after completion of phase-in period. Range of Tier 2 standards shown covers passenger cars, four categories of light-duty trucks, and medium-duty passenger vehicles and is based on 50,000-mile intermediate useful life standards for Bins 5 through 8, and the full useful life (120,000 mile) standards for Bins 2 through 4 (which do not have 50,000-mile standards).

[d] Tier 2 regulations include fleet-average NOx standard of 0.07 g/mi at 120,000 miles.

[e] As explained in Appendix A, Canada implemented U.S. Tier 1 standards in the 1994-95 model-years, and for the 1996-1997 model-years briefly reverted to U.S. Tier 0 standards before fully implementing Tier 1 standards for the 1998-2000 model-years.

Canadian standards for 1971 to 1974 model-year vehicles were the same as those that applied federally in the United States. Subsequently, Canadian standards for 1975 to 1987 model-year vehicles differed from those that applied either federally in the U.S. or in California, being less stringent after the mid-1970s model years. Beginning with the 1988 model year and continuing to the present, Canada has generally harmonized its federal standards with the U.S. federal standards, including, as each has been implemented, the U.S. EPA Tier 0, Tier 1, National Low Emission Vehicle (NLEV), and Tier 2 standards and OBD requirements described in more detail below, as well as in Appendices B and C. However, it should be noted, as shown in Table 3-2, that Tier 1 standards were implemented in Canada beginning with the 1994 model-year based on a Memorandum of Understanding (MOU) executed in 1992 by Transport Canada and automakers selling vehicles in Canada. Because agreement could not be reached regarding how the impact of MMT® use in Canadian gasoline would affect the requirements that in-use vehicles comply with the emission standards, the MOU was not in effect for the 1996 and 1997 model-year and Canada reverted back to the Tier 0 standards. The Tier 1 standards were again fully implemented in Canada for the 1998 to 2000 model-years.

In 1995, BC adopted regulations imposing the U.S. EPA Tier 1 standards for 1998–2000. For 2001 and later, BC adopted a unique combination of the California LEV I exhaust emission standards, fleet-average NMOG standards based on the U.S. NLEV program, and voluntary "sales targets" for cleaner vehicles in lieu of CARB's Zero Emission Vehicle (ZEV) mandate. The BC government repealed these regulations in 2002 when it became apparent that the Canadian federal government would be imposing the stringent U.S. EPA Tier 2 standards.

As shown by Table 3-2, exhaust emission standards are approaching near-zero levels in Canada. Under the Tier 2 regulations, HC emissions from passenger cars are now controlled by more than 99% to almost 100%, with NOx control levels at 96% to more than 99% and CO control levels being 96% or greater.

As with U.S. EPA and CARB, Canada also imposes OBD requirements and separate exhaust emission standards for in-use vehicles, with supplemental standards for aggressive driving, driving with air conditioner systems operating, cold temperature operation, and steady-state highway driving.

As is discussed in more detail in later chapters of this report, vehicles capable of complying with the Tier 2 requirements will require not only the development of highly sophisticated emissions control technology but also substantial modifications to fuel properties to ensure the proper function of this technology over the entire mileage covered by emissions standards. Compliance with the Tier 2 regulations requires that the engine, emission control systems, and fuel be treated as a system, as was recognized by the Canadian government at the time the standards were adopted.[3]

3.4 Overview of Tier 2 Requirements

As noted above, new Canadian vehicles must comply with the U.S. EPA's Tier 2 emission standards, which are being phased-in over the 2004 to 2009 model-years. The range of standards shown in Table 3-2 for the Tier 2 regulations results from the fact that manufacturers may certify engine families to different emission standard levels (also referred to as "bins"). Once the Tier 2 regulations are phased-in, manufacturers may certify their products to any one of the CVS-75[*] based standards (note that Supplemental Federal Test Procedure [SFTP] and cold-temperature standards also apply as described in Appendices A and B) associated with the eight permanent bins shown in Table 3-3.

[*] Chassis dynamometer-based emissions test procedure

Table 3-3 Tier 2 CVS-75 Exhaust Emission Standards (g/mi)										
	50,000-mile Durability Basis					120,000-mile Durability Basis				
Bin	NMOG	CO	NOx	PM	HCHO	NMOG	CO	NOx	PM	HCHO
8	0.100	3.4	0.14	---	0.015	0.125	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	---	0.015	0.090	4.2	0.15	0.02	0.018
6	0.075	3.4	0.08	---	0.015	0.090	4.2	0.10	0.01	0.018
5	0.075	3.4	0.05	---	0.015	0.090	4.2	0.07	0.01	0.018
4	---	---	---	---	---	0.070	2.1	0.04	0.01	0.011
3	---	---	---	---	---	0.055	2.1	0.03	0.01	0.011
2	---	---	---	---	---	0.010	2.1	0.02	0.01	0.004
1	---	---	---	---	---	0.000	0.0	0.00	0.00	0.000

As shown in Table 3-3, the U.S. fleet-average NOx standard for Tier 2 vehicles and Canada's fully phased-in fleet average NOx standard for Tier 2 vehicles is 0.07 g/mile and is the same as the bin 5 NOx exhaust emission standard. Given this, one potential compliance strategy would be for a manufacturer to certify all its vehicles to the bin 5 standards. However, the cost of bringing different vehicles into compliance with exhaust emission standards can vary widely depending on a number of factors. Therefore, the bin structure of the Tier 2 regulations was established so that manufacturers could maintain a diverse product line and optimize that product line for cost-effective compliance with the fleet-average NOx standard by certifying different vehicles to the different bins as necessary.

Ultimately, compliance with the Tier 2 regulations will be demonstrated through emissions testing of in-use vehicles. In recognition of the challenges that compliance with the lower bins of the Tier 2 regulations presents to vehicle manufacturers, the U.S. EPA has incorporated interim standards, shown in Table 3-4, that apply through the 2008

Table 3-4 Interim In-Use CVS-75 Tier 2 Standards[a] (g/mi)					
Certification Bin No.	Durability Period (mi)	NOx In-Use	NOx Certification[b]	NMOG In-use	NMOG Certification[b]
5	50,000 mi	0.07	0.05	---	0.075
5	120,000	0.10	0.07	---	0.090
4	120,000	0.06	0.04	---	0.070
3	120,000	0.05	0.03	0.09	0.055
2	120,000	0.03	0.02	0.02	0.010

[a] These standards apply to light-duty vehicles (LDVs) and light light-duty trucks (LLDTs) through the 2008 model year and to heavy light-duty trucks (HLDTs) and medium-duty passenger vehicles (MDPVs) through the 2010 model year.
[b] Shown for reference only

model-year for most in-use vehicles that allow for somewhat greater emission control system deterioration than will be tolerated for later model years. Although Canadian enforcement of the Tier 2 regulations will differ to some degree from U.S. enforcement, reference 3 indicates that the Canadian program will include emissions testing of typical in-use vehicles.

3.5 Summary of California Exhaust Emission Standards

As noted above, the first North American exhaust emission standards for new vehicles were adopted by California and since that time California has generally been at the forefront of the adoption of increasingly stringent standards in North America. A detailed chronological presentation of California's exhaust emission standards and OBD requirements applicable to new light- and medium-duty gasoline vehicles is presented in Appendix B.

Table 3-5 presents a chronological summary of the California emission standards and regulations applicable to new passenger cars from the 1966 model year through the current LEV II regulations. Also shown are the approximate emission levels of uncontrolled (pre-1966 model year) vehicles and an estimate of the percentage of the emissions of each substance eliminated as the result of compliance with each standard relative to uncontrolled vehicle emissions. As documented in Appendix B, the lifetime period over which vehicles must comply with CARB emission standards extends to as much as 150,000 miles.

As shown in Table 3-5, under the LEV II regulations, HC emissions from passenger cars are now controlled more than 99% relative to emissions from the uncontrolled vehicles, with CO and NOx control rising to near or above the 99% level by 2010. Somewhat less stringent standards are applied to light trucks in various weight categories up through the LEV I regulations. Under CARB's LEV II regulation, however, the same standards will apply (when the program is fully phased in) to cars and light trucks up to 8,500 lbs gross vehicle weight rating (GVWR).

Beginning with the LEV I regulations adopted in 1990, CARB moved away from requiring all vehicles of a given type (e.g., passenger cars) and model year to be certified to essentially the same standards and replaced that regulatory paradigm with one based on manufacturer compliance with a "fleet-average" emission standard. In the case of the LEV I regulations, CARB established the following four separate levels of emission standards, in order of increasing stringency:

- Transitional Low-Emission Vehicle (TLEV);
- Low-Emission Vehicle (LEV);
- Ultra-Low Emission Vehicle (ULEV); and
- Zero-Emission Vehicle (ZEV).

Table 3-5
California Passenger Car Exhaust Emission Standards
& Percent of Emissions Controlled
(g/mile at 50,000 mi unless otherwise indicated)

Model Year	HC, NMHC, or NMOG		CO		NOx	
	Standard	% Control	Standard	% Control	Standard	% Control
Pre-1966	9.0	N/A	90.0	N/A	4.0	N/A
1966 (first year of control)	275 ppm	N/A	1.5%	N/A	N/A	N/A
1974 (pre-catalyst)	3.2	64.4	39	56.7	2.0	50
1975 (first catalysts)	0.9	90.0	9.0	90.0	2.0	50
1981 (3-way catalysts)	0.41	95.4	7.0	92.2	0.7	82.5
1988	0.41	95.4	7.0	92.2	0.4	90.0
1994 (last year before LEV I phase-in)	0.25	97.2	3.4	96.2	0.4	90.0
2003 (end of LEV I phase-in)	0.062[a]	99.3	1.7-3.4	96.2-98.1	0.2	95.0
2004 (beginning of LEV II phase-in)	0.053[a]	99.4	1.0-3.4[b]	96.2-98.9	0.02-0.05[b]	98.8-99.5
2010 & Later (culmination of LEV II)	0.035[a]	99.6	1.0-3.4[b]	96.2-98.9	0.02-0.05[b]	98.8-99.5

[a] Fleet-average NMOG.
[b] Effective standard varies based on manufacturer-selected mix of standard levels.

These standards were applied to engine families in the same way as earlier standards, but now each manufacturer was allowed to certify engine families to a mix of these standards, provided that mix met a specified fleet-average NMOG standard. A manufacturer's fleet-average NMOG level was essentially computed by multiplying the NMOG standard applicable to each level by the number of vehicles of the applicable model year sold in engine families certified to those levels, adding those values together, and dividing the sum by the total number of vehicles sold in that model year. This value was then compared to the applicable standard. The concept of the fleet-average NMOG standard has continued under the CARB LEV II program. This regulatory concept, which was incorporated in the Tier 2 regulations for NOx by the U.S. EPA, provides manufacturers with the flexibility to ensure that they can provide a wide range of vehicles, some of which might otherwise not be available, by allowing the certification of some vehicles at levels above the fleet-average, provided these emissions are offset by other vehicles certified to emission levels below the fleet-average standard.

In adopting the LEV program standards, CARB explicitly recognized that the vehicle and the gasoline upon which it operates must be treated as a system. Further, adoption of the

LEV standards was predicated on the fact that reformulation of gasoline would be required in order to facilitate the development of a compliant vehicle-fuel system.[4] Another innovative feature of the CARB LEV I regulations was the use of "interim in-use" exhaust emission standards. These were special standards, less stringent than the actual emission standards, that applied only to in-use vehicles during the first few years that manufacturers were expected to have to build significant numbers of vehicles that complied with a new LEV standard level. These standards recognized the difficulty manufacturers could have in designing the new and highly advanced emission control systems required to comply with the LEV program and were intended to provide additional time to verify the in-use durability of these systems. However, manufacturers were still required to certify to the more stringent LEV certification standards. Interim in-use standards also apply under the LEV II regulations.

As part of the LEV I regulations, CARB imposed a ZEV regulation mandating 10% ZEVs in 1998 and later. This regulation is still in place but substantially modified, and is based on fuel cell rather than battery power. For large-volume manufacturers, a specified fraction of the vehicles they produce must have zero exhaust and evaporative emissions. These fractions range from 10% of their California car and light truck production in 2005 up to 16% in 2018 and later, with intermediate-volume manufacturers on a slower schedule. Because of the commercial failure of battery-powered electric vehicles, CARB has been forced to develop an elaborate mechanism of providing ZEV credits for what are essentially conventional or hybrid vehicles. The steps taken have included the development of new standard levels for Super-Ultra-Low Emission Vehicles (SULEVs) and Partial Zero Emission Vehicles (PZEVs). The complex array of allowances and credits allows non-ZEVs, such as PZEVs and advanced-technology PZEVs (AT PZEVs, e.g., hybrids), to count toward meeting the ZEV percentage requirements. Although the U.S. Clean Air Act preempts states other than California from setting their own vehicle emission standards, it does allow other states to adopt the California standards. As a result, a number of other states have adopted the California LEV II and ZEV requirements or are considering adoption.

CARB has also adopted supplemental standards addressing vehicle emissions during aggressive driving and driving with the vehicle air conditioner in operation, and standards for cold temperature operation and steady-state highway driving. The applicability of these standards has broadened over the years, as shown in Appendix B.

As noted above, in addition to establishing exhaust emission standards, CARB established OBD regulations and requirements. The OBD system is a computer-based monitoring system built into a vehicle's electronics for the purpose of detecting and reporting operational malfunctions in the emission control system. This is accomplished through the illumination of a malfunction indicator light (MIL) on the vehicle instrument panel and through the storage of a diagnostic trouble or fault code (DTC) in the vehicle's computer. Stored DTCs are read by attaching specially designed tools to the vehicle, thus providing technicians with specific information regarding the nature of the emissions-related problem.

CARB has been in a clear leadership position with regard to OBD. CARB adopted its initial "OBD I" regulations in 1985, then imposed more extensive "OBD II" requirements in 1989, 1991, 1994, 1996, and 2002. The U.S. EPA has generally followed CARB in this area, adopting its first OBD regulations in 1993 and accepting compliance with California requirements in satisfaction of all federal requirements. Under both the CARB and U.S. EPA programs, OBD II requirements have been in place on all light-duty vehicles beginning with the 1996 model year, but with California imposing more stringent requirements over time.

Although the requirements are complex, the general regulatory criterion for OBD systems is that the MIL must be illuminated any time exhaust emissions exceed 1.5 times an applicable emission standard. Given the form of the regulatory criterion, this means that OBD systems applied to vehicles certified to lower emission standards must be capable of detecting even smaller absolute changes in emissions than the systems found on vehicles certified to less stringent standards. The somewhat less stringent emission standards available at higher mileages also provide some margin for deterioration in the ability of the OBD system to detect a specified emission increase. As emission standards approach zero in the Tier 2 and LEV II programs, OBD systems clearly have to become much more complex to detect the small changes in emissions required, and the potential for OBD system problems due to impacts from unforeseen factors, such as MMT® use in gasoline, will clearly increase.

3.6 Summary of U.S. EPA Exhaust Emission Standards

U.S. federal exhaust emission standards, which began with 1968 model-year vehicles, have shown a similar progression in stringency as observed in California. Appendix C contains a detailed chronological presentation of U.S. federal exhaust emission standards and OBD requirements applicable to new light- and medium-duty gasoline vehicles.

A chronological summary of the U.S. federal exhaust emission standards and regulations applicable to new passenger cars from the 1968 model year through the current Tier 2 regulations is presented in Table 3-6. Also shown are the approximate emission levels of uncontrolled (pre-1968 model year) vehicles and an estimate of the percentage of the emissions of each substance eliminated as the result of compliance with each standard relative to uncontrolled vehicle emissions.

The NLEV standards applied to 12 Northeastern states for the years 1999–2000, then nationally for 2001–2003. The NLEV standards were based on California's LEV I standards, and were essentially a bridge between the Tier 1 and Tier 2 regulations.

The U.S. federal Tier 2 regulations are analogous but not identical to the CARB LEV II regulations. The Tier 2 regulations rely on a number of different standard levels (there are eight permanent standard levels, or "bins") and a fleet-average standard, but in this case that average applies to NOx rather than NMOG emissions. The Tier 2 fleet-average NOx standard of 0.07 g/mi at 120,000 miles can be met in a number of ways, including production of only vehicles certified to the Bin 5 standard level. As with the LEV II program, a key element of Tier 2 regulations is that (when fully phased in) they apply the same exhaust standards to all passenger and light-truck categories, including medium-duty passenger vehicles up to 10,000 lbs GVWR.

Table 3-6
U.S. Federal Passenger Car Exhaust Emission Standards
& Percent of Emissions Controlled
(g/mile at 50,000 mi unless otherwise indicated)

	HC, NMHC, or NMOG		CO		NOx	
Model Year	Standard	% Control	Standard	% Control	Standard	% Control
Pre-1968 (uncontrolled)	9.0	N/A	90.0	N/A	4.0 (2.5)	N/A
1968 (first year of control)	410 ppm	N/A	2.3%	N/A	N/A	N/A
1974 (pre-catalyst)	3.4	62	39	57	3.0	25
1975 (first catalysts)	1.5	83	15	83	3.10	22.5
1981 (3-way catalysts)	0.41	95.4	3.4	96.2	1.0	75
1988-1993 (Tier 0)	0.41	95.4	3.4	96.2	1.0	75
1994-1998 (Tier 1)	0.41	95.4	3.4	96.2	0.4	90
1998-2003 (NLEV)[a]	0.040-0.125	98.6-99.6	1.7-3.4	98.1-96.2	0.2-0.4	90-95
2004 and Later (Tier 2)[b]	0.010-0.100	98.9-99.9	2.1-3.4	96.2-97.7	0.02-0.14[c]	96.5-99.5

[a] Range shown covers standards for passenger cars and light trucks; less stringent standards are applied for heavier light trucks.
[b] Tier 2 standards are applicable after completion of phase-in period. Range of Tier 2 standards shown covers passenger cars, four categories of light-duty trucks, and medium-duty passenger vehicles and is based on 50,000-mile intermediate useful life standards for Bins 5 through 8, and the full useful life (120,000 mile) standards for Bins 2 through 4 (which do not have 50,000 mile standards).
[c] Tier 2 regulations include fleet-average NOx standard of 0.07 g/mi at 120,000 miles.

As with CARB, U.S. EPA also imposes OBD requirements and separate exhaust emission standards for in-use vehicles, with supplemental standards for aggressive driving, driving with air conditioner systems operating, cold operation, and steady-state highway driving.

###

4. BRIEF HISTORY OF THE DEVELOPMENT OF RECOMMENDED STANDARDS FOR AND GOVERNMENT REGULATION OF GASOLINE PROPERTIES AND ADDITIVES IN NORTH AMERICA

This chapter reviews the history of the development of performance- and emissions-related requirements for commercial gasolines in North America. These include government regulations on gasoline composition (e.g., banning the use of lead and manganese-based organo-metallic additives), setting maximum limits on the amount of sulfur and phosphorus that may be present, and requiring the use of detergent additives to minimize the formation of engine deposits.

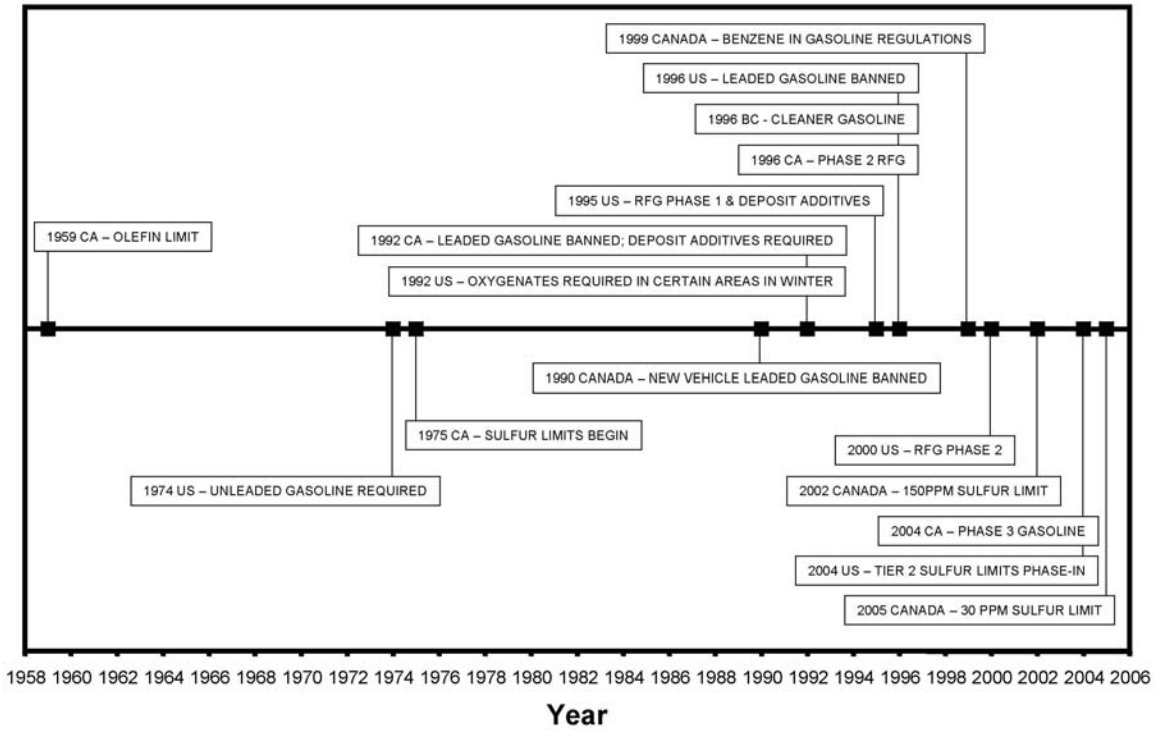
4.1 Overview

The development and use of gasoline engines in motor vehicles is inextricably linked to the properties and composition of the fuels that are commercially available for their operation. From a purely practical point of view, the value and utility of gasoline vehicles depend on the widespread availability of fuels that will yield good engine performance and durability. From an emissions perspective, the proper design of new lower emission engines and advanced emission control systems requires detailed knowledge of the composition and properties of the commercial fuels upon which the vehicles will operate, and changes in those fuels potentially may be necessary to meet their requirements.

As a result of the fundamental link between fuels and vehicles, industry standards have generally been developed to define the properties and composition of commercial gasolines to ensure that the gasolines that refiners produce are consistent with those that vehicle manufacturers design their engines to use. Overall, the purpose of these fuel "performance" standards is to provide for the proper operation of engines on commercial fuels in customer service. In addition, governments have developed regulations relating to the composition and properties of commercial gasoline that are intended to directly reduce pollutant emissions and/or facilitate the incorporation of advanced emissions control technologies into vehicle designs by ensuring the proper function and durability of those technologies.

A timeline showing some of the major milestones in North American efforts to regulate gasoline composition and properties in order to reduce exhaust emissions is presented in Figure 4-1.

Figure 4-1
Timeline of Fuel Regulations



Gasoline is generally distinguished from other liquid fuels such as Diesel or kerosene by its volatility and boiling range, as well as by its chemical composition and resistance to premature detonation or "knock" when burned in a spark ignition engine. Low-temperature gasoline volatility, which is important to engine starting, is usually characterized using the "Reid vapor pressure" (Rvp) or a related metric. The distillation curve of gasoline is directly measured and the volatility of the gasoline across the entire boiling range is characterized using the temperatures at which different volume percentages of a gasoline sample have been distilled or the amount of gasoline that has been distilled by the time a given temperature has been reached.* The chemical composition of gasoline is often described in terms of the amounts of aromatics, olefins, and saturates present, and can also be described in terms of the amount of specific chemicals, e.g., benzene or isooctane, present in the fuel. The amount of sulfur present in gasoline has also become an important factor with respect to gasoline composition. Gasoline resistance to knock is usually characterized by Motor and Research Octane Numbers (MON and RON, respectively) and the Anti-Knock Index (AKI), which is computed as (MON+RON)/2.

* For example, the so-called "midrange" properties of gasoline are characterized using either the T50 point, which is the temperature at which 50% of a gasoline sample has been distilled; or the E200 level, which is the percentage of a gasoline sample that has evaporated by the time it has been heated to 200º C.

There is a wide range of additives that have been and continue to be used with gasoline and affect both its properties and chemical composition. These additives include the following:

1. Organometallic compounds used to increase AKI values, which include tetra-ethyl lead and MMT®;

2. Oxygenates such as ethanol and methyl tertiary butyl ether (MTBE), which provide higher AKI values, alter volatility properties, facilitate reductions in emissions of certain pollutants, and extend gasoline supplies;[*]

3. Detergents intended to reduce the formation of intake, fuel injector, and combustion chamber deposits; and

4. Anti-oxidant and corrosion-inhibiting additives.

Over the years, the composition and properties of commercial gasoline have changed considerably as the result of developments in engine and emission control system design, changes in crude oil properties and refinery design and operation, the availability of additives, and government regulations. Some of these long-term changes have been documented in the literature for U.S. gasolines.[5,6,7]

4.2 History of North American Gasoline Performance Standards

As gasoline-fueled vehicles and the widespread availability of commercial gasolines developed in the 1900s, industry standard-setting organizations developed specifications for the properties of commercial gasolines. In the U.S., the standard-setting entity was originally known as the American Society for Testing and Materials, which is now ASTM International. In Canada, the standard-setting entity is the Canadian General Standards Board (CGSB).

The first ASTM specifications for gasoline were published in 1937 and addressed gasoline volatility, minimum octane ratings for regular and premium fuels, as well as standards for corrosion and gum formation tests. These specifications have been revised over time to include other performance-driven requirements intended to protect against vapor lock, as well as to establish the maximum lead and sulfur content of gasoline, among others. In addition, as gasoline properties have been subject to government regulations, ASTM and CGSB standards have been modified to generally reflect those regulations. The current ASTM standard for gasoline is designated as D4814-07. The CGSB standard is similar but not identical to the ASTM standard. The current CGSB standard for unleaded gasoline is designated as CAN/CGSB-3.5-2004 and variants of this standard exist for unleaded gasolines blended with a variety of oxygenates. At present, both standards prohibit the intentional addition of any lead-containing compound

[*] Oxygenates like MTBE and ethanol are not produced from compounds found in gasoline; therefore, their addition to gasoline extends the supply of gasoline on a volumetric basis. For example, use of ethanol in gasoline at 10% by volume will extend the amount of fuel available by up to 10%.

to unleaded gasoline and establish a maximum lead concentration of 5 mg of lead (Pb) per litre. The ASTM standard makes no mention of manganese, while the CGSB standard includes a maximum concentration for manganese of 18 mg Mn/l.

In addition to ASTM and CGSB standards, a number of associations representing vehicle and engine manufacturers have developed and updated recommended comprehensive standards for gasoline[8] that address fuel composition and characteristics from the point of view of both performance and emissions. The "Worldwide Fuel Charter" reflects the global focus on setting gasoline specifications to minimize emissions and to facilitate the use of advanced emission control systems. It establishes four different categories of gasoline specifications that are designed to address the general level of sophistication of vehicle emission control systems in a given country or region. These categories and the associated level of vehicle emissions control are listed below.

- Category 1: For vehicles designed with no or first-level emission controls equivalent to U.S. Tier 0 and EURO 1 emission standards.

- Category 2: For vehicles designed to meet stringent emission control standards equivalent to U.S. Tier 1 and EURO 2 and 3 levels.

- Category 3: For vehicles with sophisticated emission control systems designed to comply with standards equivalent to those of U.S. NLEV, California LEV I, EURO 3, and JP2005.

- Category 4: For vehicles with advanced emission control systems designed to comply with standards equivalent to those of U.S. federal Tier 2 regulations, California LEV II, EURO 4, and EURO 5.

The specifications for all four categories require that metal-based additives (including MMT®) not be intentionally added to gasoline unless the gasoline is to be used exclusively in non-catalyst-equipped vehicles to prevent valve seat wear and in this case potassium-based additives are recommended.

4.3 History of North American Government Regulation of Gasoline Composition and Properties

Canada – The CGSB establishes standards for gasoline in Canada. While the CGSB standards, like the ASTM standards, are not government regulations, they are mandated either in total or in part by the provinces of British Columbia, Ontario, Manitoba, and Quebec, while the Yukon territory references an older version of the standards. Other provinces may have their own regulations.

The Government of Canada adopted regulations in 1990 that banned the use of leaded gasoline in most vehicle applications and established limits on the allowable levels of lead and phosphorus in unleaded gasoline. As with similar regulations adopted in the

U.S., the purpose of establishing limits on lead and phosphorus in unleaded gasoline included the prevention of poisoning and deactivation of catalytic converters.

In 1995, British Columbia adopted the province's "Cleaner Gasoline" regulation.[9] This regulation established limits on gasoline volatility, and on aromatic, benzene, olefin and sulfur content. It also gave refiners an option to demonstrate compliance with the regulations using the U.S. EPA's Complex Model. Like other regulations requiring gasoline reformulation, this regulation was intended both to reduce emissions from existing vehicles as well as to ensure that the emission reductions expected from new vehicles under the province's low-emission vehicle regulations would be fully realized. These regulations became effective in 1996 and remain in effect.

In November 1997, the Government of Canada passed regulations limiting emissions of benzene by imposing a cap on benzene content through the establishment of a "benzene emissions number" computed using the Complex Model developed by the U.S. EPA as well as limitations on the benzene content of gasoline.[10] The purpose of this regulation was to reduce public exposure to benzene, which is a well-known toxic air pollutant.[11] These regulations became effective in July 1999 and remain in effect.

As discussed in detail in Chapter 5 of this report, the Government of Canada acted to restrict the use of MMT® by enacting the Manganese-based Fuel Additives Act in April 1997. This legislation led to the Government of Alberta filing a complaint against the Government of Canada under the Canadian Agreement on Internal Trade (AIT), and Ethyl Corporation filed legal challenges on constitutional grounds as well as under the investment provisions in Chapter 11 of the North American Free Trade Agreement (NAFTA). After the AIT ruling found the Act to be inconsistent with the AIT, the Canadian Government rescinded the Act in July 1998 and entered into a settlement with Ethyl Corporation regarding the other proceedings.

In June 1999, the Government of Canada passed regulations that restricted the sulfur content of unleaded gasoline sold in Canada[12] in two steps, with the first being effective July 1, 2002, and the second becoming effective in January 2005. In establishing the regulations, the Government noted that, without the availability of low sulfur gasoline in Canada, the performance of advanced emission control systems would be impaired and the low-emission vehicles required to be sold in Canada would "emit higher levels of pollutants than their designed intent or capability." It was also noted that a failure to reduce the sulfur content of gasoline would not allow advanced emission control technologies to achieve their full emission reduction potential. Poisoning of catalytic converters by sulfur is the primary reason why failure to reduce sulfur content would lead to lower than expected reductions in emissions from advanced emission control technologies.

<u>United States</u> − According to Gibbs,[6] the first North American government regulations on gasoline composition and properties were U.S. federal specifications for gasoline distillation properties that were promulgated in 1919 and revised in 1929 to ensure vehicle performance. As noted above, the first ASTM standards for gasoline were adopted in 1937, also to ensure vehicle performance, and have evolved since then. While the ASTM standards are not government regulations, they have formed and continue to

form the basis of many state laws and regulations governing gasoline properties and composition.

The first regulation of gasoline composition and properties aimed at improving air quality was instituted in 1959 in Los Angeles County, California. This regulation, based on a metric known as the "bromine number," effectively imposed limits on the olefin content of gasoline. The objective was to reduce emissions of olefins in both exhaust and evaporative emissions. Olefins were specifically targeted because the carbon-to-carbon double bonds that form the basis of their chemical designation cause them to be more reactive than other types of hydrocarbons in the generation of ozone.

In 1971, CARB adopted the first regulations limiting gasoline volatility as a means of controlling evaporative emissions. Since that time, volatility limits have also been established by other U.S. states and the U.S. federal government. In general, these volatility regulations have become more stringent over time.

In 1973, U.S. federal regulations were promulgated[13] that required the commercial availability of unleaded gasoline beginning in 1974 and set maximum levels of lead and phosphorus for unleaded gasoline. This regulation was adopted primarily to facilitate the introduction of catalytic converters on gasoline-fueled vehicles that were required to comply with new vehicle emission standards that applied to the 1975 model-year vehicles.[*] Compliance with those new vehicle emission standards would not have been possible without the availability of unleaded gasoline, because the catalysts would have quickly become poisoned and rendered useless by the lead and phosphorus present in leaded fuels. This regulation marked the first time that regulations on gasoline composition were specifically enacted to facilitate vehicle compliance with exhaust emission standards. Leaded gasolines were banned entirely in California in 1992[14] and throughout the U.S. in 1996.[15]

In 1975, California adopted regulations[16] to limit the sulfur content of unleaded gasoline to 500 parts per million (ppm) beginning in 1976, with that limit declining to 400 ppm in 1978 and 300 ppm in 1980. This regulation was adopted in response to concerns that the use of high-sulfur gasolines in catalytic converter-equipped 1975 and later model-year vehicles could lead to high levels of sulfate emissions.

In 1977, the U.S. Clean Air Act was amended to include new restrictions on the use of fuel additives in unleaded gasoline.[17] These restrictions prohibited the use of fuel additives that were not "substantially similar" to any fuel or fuel additive used in the certification of new 1975 model-year vehicles. The U.S. EPA subsequently defined the term "substantially similar" to mean that fuels or fuel additives could contain only atoms of carbon, hydrogen, oxygen, nitrogen, and/or sulfur. It is under these provisions that the use of ethanol, MTBE, and other oxygenates as additives to unleaded gasoline has been allowed in the U.S.

In addition, as discussed in more detail in Chapter 5, the 1977 Clean Air Act amendments limited the level of manganese allowable in unleaded gasoline to 16 milligrams per litre

[*] See Table 3-6.

(mg/l) beginning November 30, 1977. The use of manganese additives was banned altogether as of September 15, 1978, unless a waiver was received from the U.S. EPA based on a finding that their use would not cause or contribute to the failure of "an emission control device or system to achieve compliance by the vehicle" with applicable emission control standards.

Following extensive legal proceedings initiated by the Ethyl Corporation, the U.S. EPA finally granted such a waiver for the use of MMT® at 8 mg/l in conventional gasoline under a U.S. federal court order in 1995. However, while acceding to the court order, the U.S. EPA stressed concerns regarding the public health effects from exposure to manganese oxides from vehicles operating on MMT®, and there was considerable controversy associated with the largely unrealized potential for MMT® use in conventional gasoline in the U.S.[18] Also, as in 1977 and again as described in detail in Chapter 5 of this report, the State of California adopted regulations banning the use of manganese compounds in unleaded gasoline. These regulations remain in effect.

In 1990, the Clean Air Act was again amended, with the amendments including three major fuels-related provisions. The first of these[19] mandated the use of detergent additives to control engine deposit formation in all U.S. gasoline beginning in 1995. The second[20] was a requirement that oxygenated gasoline additives be used during winter months beginning in November 1992 in certain areas that were in violation of the U.S. National Ambient Air Quality Standard for CO. As a result, oxygenated gasolines have been and continue to be used in a number of areas of the U.S. during the winter.

The third major fuels-related provision[21] of the 1990 Clean Air Act Amendments directed the U.S. EPA to promulgate regulations requiring the sale of reformulated gasoline beginning in 1995 in certain areas of the country that were in violation of the U.S. National Ambient Air Quality Standard for ozone. The amendments specified the oxygenate and benzene content of reformulated gasoline, as well as so-called "performance requirements" for reductions in emissions of VOC and toxic air pollutants. Emission performance requirements were selected to provide refiners with greater flexibility in producing gasoline than they would have had if specific limits were set on gasoline properties, while ensuring that the emission reductions specified by the legislation were achieved. The amendments also required that reformulated gasoline be free of heavy metals, including manganese and lead, unless the U.S. EPA determined that those metals would not increase emissions of toxic air pollutants. The regulations developed by the U.S. EPA[22] included two phases, with the second phase having more stringent emission performance standards. The first phase began in 1995 and compliance could be demonstrated using both the U.S. EPA Simple and Complex models. The second phase began in 2000 and compliance had to be demonstrated using the U.S. EPA complex model.

Also in 1990, California adopted its Phase 1 reformulated gasoline regulations, which imposed new restrictions on gasoline volatility and imposed detergent additive requirements.[14] This was followed in 1991 by the more expansive Phase 2 reformulated gasoline regulations[23] that imposed limits on the aromatic, benzene, olefin, and sulfur content of gasoline. The regulations also limited Rvp during summer months and set limits on the T50 and T90* distillation temperatures. Finally, the regulations also established a minimum oxygenate level. The California Phase 2 reformulated gasoline requirements are considered to be more stringent than either the federal Phase 1 or Phase 2 reformulated gasoline requirements. While they set specific limits on fuel properties, the California regulations provide refiners with the option of using the California Predictive Model to provide greater flexibility in the production of gasoline while ensuring that required emission reductions are achieved.

While one goal of the California Phase 2 gasoline regulations was to reduce emissions from the existing fleet of vehicles in California, the other major goal was the development of a cleaner gasoline that would facilitate vehicle manufacturer efforts to design gasoline-fueled vehicles capable of complying with the emission standards contained in the LEV regulations that California had adopted in 1990.[24] In adopting this set of regulations, CARB affirmed that the vehicle and the fuel upon which it operates must be treated as a "system" with respect to the control of emissions. This was accomplished in two ways: (1) by allowing manufacturers to certify new vehicles designed to meet LEV program standards using an emission test fuel representative of Phase 2 reformulated gasoline;[25] and (2) by having in-use vehicles operate on a fuel that was the same as the test fuel used during their certification. In this way, in-use vehicles would actually operate on the fuel used in the design of their emission control systems.† It should be stressed that, because MMT® use is banned in unleaded gasoline in California, MMT® use is not a consideration in designing emission control systems for LEV program vehicles.

In December 1999, California adopted Phase 3 gasoline regulations[26] intended primarily to ensure that the elimination of the use of MTBE in reformulated gasoline would not lead to increases in emissions due to changes in gasoline oxygen levels or in other gasoline properties.‡

As noted above, states other than California have adopted fuel regulations that differ from those applicable to either federal conventional or reformulated gasolines or California reformulated gasolines. The requirements of these other state regulations (sometimes referred to as "boutique fuel" requirements) have been summarized by the U.S. EPA[27] and the development of new boutique fuels in the U.S. is now generally precluded by U.S. EPA regulations.[28]

In 2000, the U.S. EPA promulgated the Tier 2 Motor Vehicle Emission Standards and Gasoline Sulfur Control Requirements.[29] These regulations concurrently established stringent new emission standards for vehicles and required substantial reductions in the sulfur levels of gasoline sold throughout the U.S. beginning no later than 2004. In

---

* T90 refers to the temperature at which 90% of a gasoline sample has been distilled.

† Previously, concerns had arisen regarding the fact that the Indolene fuel used in vehicle certification was "cleaner" than most commercial gasolines and that in-use vehicles therefore had higher emissions than those reported during the vehicle certification process.

‡ MTBE content affects the distillation properties of gasoline, including Rvp, as well as the sulfur, aromatic, olefin, and benzene levels due to dilution (all other things being equal, addition of 10% MTBE by volume reduces a property such as benzene concentration by 10%). Ethanol, the only oxygenate replacement for MTBE allowed in California, tends to increase Rvp and leads to higher evaporative emissions due to permeation of fuel tanks and hoses.

developing the regulations, the U.S. EPA stated that the reduction in fuel sulfur levels was required to "enable" the "much-improved" emission control technology required for compliance with the new Tier 2 emission standards.[30] The reduction in fuel sulfur was needed to eliminate sulfur poisoning that would reduce the effectiveness of the advanced catalytic converters required to comply with the Tier 2 standards.

It should be noted that the regulatory actions involving fuel specifications described above were, in large part, supported by data from an extensive cooperative emission testing program conducted from 1989 through 1997. This program, known as the Auto/Oil Air Quality Improvement Research Program,[31] was designed using statistical methods and systematically investigated the exhaust and evaporative emissions impacts of changes in gasoline properties and the use of oxygenate additives on a wide variety of vehicles with emission control systems of differing levels of sophistication. Test vehicles ranged from early 1980s models through to vehicles with prototype advanced emission control systems that were being designed for future vehicles during the mid-1990s. However, MMT® was not added to any gasoline used in the Auto/Oil Program.

###

5. HISTORY OF MMT® USE IN UNLEADED GASOLINE IN CANADA AND THE U.S.

This chapter presents the history of fuel specifications and regulations relating to the use of MMT® in unleaded gasolines in the United States and Canada and documents levels of MMT® actually observed in commercial unleaded gasolines marketed in both countries.

5.1 Commercial Introduction of MMT®

MMT® is the acronym for methylcyclopentadienyl manganese tricarbonyl ($CH_3C_5H_4Mn(CO)_3$), a manganese-based organo-metallic compound long marketed by the Ethyl Corporation (now Afton Chemical[32]) as an octane-enhancing gasoline additive. As noted by Gibbs[33] and Owen and Coley,[34] among others, MMT® was commercialized by Ethyl Corporation in the late 1950s. It was originally used in combination with tetraethyl lead (TEL - $Pb(C_2H_5)_4$) (another product produced by Ethyl Corporation) to improve the octane rating of "leaded" gasolines, particularly as the use of TEL was phased-out in "leaded" gasolines marketed in the United States and Canada.*

With the availability of unleaded gasoline in 1974 being a necessity for the introduction of catalytic converters on vehicles, gasoline producers looked for other ways to improve the octane ratings of gasoline. Ethyl Corporation promoted the use of MMT® at levels up to 33 mg Mn/l as a means of reducing the cost of meeting gasoline octane requirements.[35,36] According to Ethyl Corporation,[37] MMT® was first used in unleaded gasoline in the U.S. in 1974 and by April 1976 it was being used by 32 oil companies representing about 20% of U.S. crude capacity. The widespread use of MMT® as an octane booster in unleaded gasoline in the U.S. appeared to be imminent in 1976[38] and the U.S. EPA directed automobile manufacturers to use unleaded gasoline containing MMT® at 30 to 36 mg Mn/l during the new vehicle certification process beginning with 1979 model-year vehicles.[39] That requirement never took effect,[40] however, as MMT® never entered widespread use in unleaded gasoline in the U.S. because of federal legislation passed in 1977 that restricted its use.

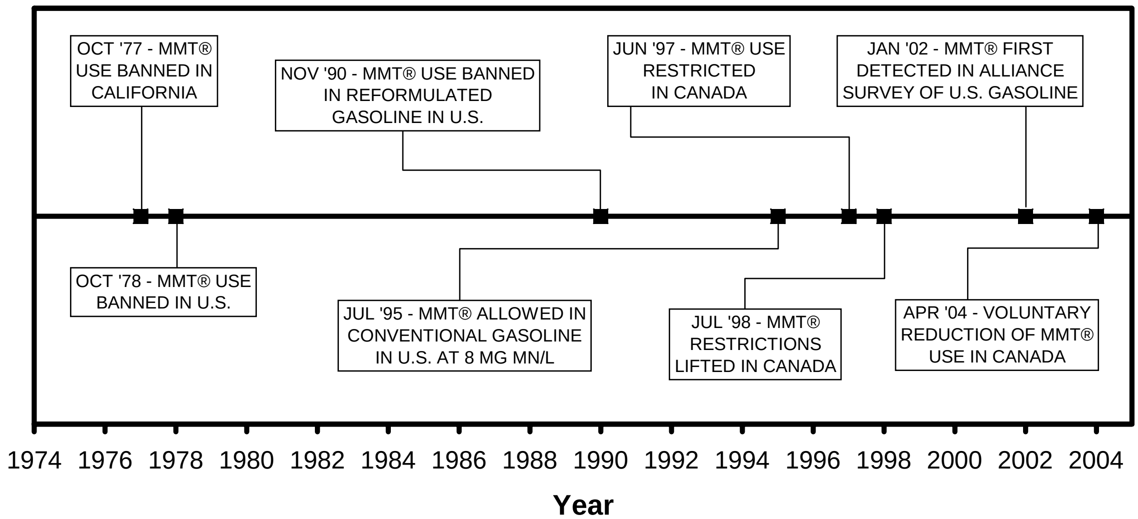
In contrast to the situation in U.S., MMT® has been used on a widespread basis in unleaded gasoline marketed in Canada, generally at levels up to 18 mg Mn/l, since the

* The sale of leaded gasoline for new on-road vehicles was banned in Canada in December 1990 (see Regulations Respecting Concentrations of Lead and Phosphorus in Gasoline, C-15.31 – SOR/90-247), by the State of California as of January 1, 1992 (see §2253.4 Title 13, California Code of Regulations). and throughout the United States as of January 1, 1996 (see §80.22 Title 40, Code of Federal Regulations).

late 1970s. However, there has never been a requirement to use MMT®-containing gasoline in the certification of new motor vehicles in Canada.

A timeline showing the major events that are discussed in this chapter is presented in Figure 5-1.

Figure 5-1
History of Restrictions on and Use of MMT® in Unleaded Gasoline in the U.S. and Canada



5.2 History of Regulations Regarding MMT® Use in Unleaded Gasoline in the United States and Canada

California − The first regulation specifically dealing with the use of MMT® in unleaded gasoline in the United States was adopted by CARB on July 7, 1977, and became effective shortly thereafter.[41] This regulation, codified at §2254 Title 13, California Code of Regulations, bans the addition of manganese compounds, including MMT®, to any unleaded gasoline sold in the state. In adopting §2254 in 1977, CARB indicated that it would:

> *. . . reconsider the limitation on the use of manganese additives, including MMT, in unleaded gasoline if sufficient data become available which demonstrate that manganese additives can be used without adversely affecting motor vehicle emissions or constituting a public health hazard.*

CARB staff reviewed the regulation in 1998 and recommended that the ban remain in place.[42] As of this date, §2254 has not been modified to allow the sale of MMT®-containing unleaded gasoline in California.

United States – Although beginning with the 1967 Clean Air Act, statutes and regulations have required that gasoline additives be registered with the U.S. EPA, the first action by the federal government that directly affected the use of MMT® in unleaded gasoline was part of the Clean Air Act Amendments of 1977. These amendments, which addressed fuel additives in general as well as manganese in particular, established a limit on manganese use at 16 mg Mn/l that took effect on November 30, 1977,[43] and banned the use of manganese as of September 15, 1978.[44] However, the 1977 Amendments also included provisions that would allow the U.S. EPA to grant waivers allowing the use of manganese and other fuel additives in gasoline provided that applicants for such waivers demonstrated that the use of the additive did not cause or contribute to the failure of any emission control device or cause vehicles to exceed the emissions standards to which they were certified.[45]

The U.S. EPA has interpreted the waiver provisions of the 1977 Amendments as requiring that applicants must bear the burden of demonstrating that their fuel additive complies with the "cause or contribute" test for all regulated pollutants. However, the U.S. EPA has interpreted the test to be directed to violations of vehicle emission standards, rather than the more rigorous test of not resulting in increased emissions.

In implementing the waiver process, the U.S. EPA has developed testing protocols and statistical methods for data analysis for fuel additives of various types for which waivers have been sought, including MMT®.[46] These protocols generally require designed and controlled vehicle emission test programs, rather than general use of the additive in in-use vehicles.

Ethyl Corporation applied for a waiver for the use of MMT® in gasoline in 1978.[47] This request sought to allow the use of MMT® at concentrations of 16 and 8 mg Mn/l. It was denied by the U.S. EPA in September 1978 because the agency found that Ethyl "failed to establish that MMT® will not cause or contribute to the failure of any emission control device or system to achieve compliance by the vehicle with emission standards with respect to which it has been certified."[48]

Ethyl Corporation submitted another waiver application[49] in 1981 for MMT® at concentrations equivalent to 4 mg Mn/l. It was again rejected by the U.S. EPA based on the finding that Ethyl had failed to demonstrate that MMT® use at the 4 mg Mn/l level would not cause or contribute to a failure of any vehicle or engine to comply with emission standards to which it was certified.[50]

A third waiver application[51] was submitted by Ethyl for MMT® at the 8 mg Mn/l level in 1990. It was later withdrawn by Ethyl,[52] and a fresh application for the use of MMT® at the 8 mg Mn/l level was submitted in 1991.[53] This application was also denied by the U.S. EPA, once again based on the finding that Ethyl had not met its burden of establishing that MMT® would not cause or contribute to the failure of vehicles to comply with the emission standards to which they were certified.[54] Ethyl sought legal review of this denial. Based on certain procedural concerns, the court remanded a decision on the use of MMT® at the 8 mg Mn/l level back to the U.S. EPA.[55] The U.S. EPA again denied Ethyl's waiver application. This time denial was based not on a finding that the use of MMT® would cause or contribute to a failure to meet an emission control standard, but on unresolved concerns regarding the potential impact of manganese emissions on public health.[46] Ethyl again sought legal review of this decision, this time successfully.[56] As a result of the court's decision, the U.S. EPA authorized the use of MMT® at levels up to 8 mg Mn/l in "conventional" unleaded gasoline marketed in the U.S. effective July 11, 1995.[57]

As a result of the addition of §211(k) to the Clean Air Act as part of the Amendments of 1990, gasoline sold in the U.S. is designated as either "reformulated" or "conventional." Reformulated gasoline (RFG) is intended to reduce emissions of precursors to ambient ozone formation during the summer ozone season and reduce emissions of toxic air pollutants on a year-round basis. Reformulated gasoline is required by the Clean Air Act in those areas of the U.S. that experience the highest ozone levels and by U.S. EPA regulations in other areas that have voluntarily "opted-in" to the RFG program.[58] Both the Clean Air Act[59] and U.S. EPA's implementing regulations[60] ban the presence of heavy metals, including manganese, in reformulated gasoline unless it can be shown that the metal will not increase toxic air pollutant emissions. It is important to note that this basis for the ban on MMT® is different from that found in the 1977 Clean Air Act Amendments. To date, no such showing has been made regarding any heavy metal, and the use of MMT® in reformulated gasoline in the U.S. remains banned.

Canada – MMT® use in unleaded gasoline in Canada began in 1978, about the same time that use began in the United States. MMT® has never been required to be registered as a gasoline additive in Canada and there are no existing regulations governing its use. The CGSB sets voluntary national standards[61] that permit the use of MMT® at levels up to 18 mg Mn/l, more than twice the maximum level currently allowed in conventional gasolines in the United States. Note that not all Canadian provinces enforce the CGSB standards and there is effectively no maximum limit on Mn concentration in these jurisdictions.

The establishment of the 18 mg Mn/l maximum limit by the CGSB[*] occurred in 1978,[62] shortly after the establishment of the MMT® ban in the U.S. The CGSB committee responsible for the recommendation regarding MMT® use noted that the U.S. ban on MMT® did not need to be followed, because less stringent Canadian vehicle emission standards would not require three-way catalyst control. It was also noted that the issue of a Canadian ban on MMT® needed to be considered in the context of the impacts of MMT® on three-way catalyst technology. Notably, this committee recommending MMT® use lacked any representation from the automotive industry and consisted solely of governmental and oil industry stakeholders.[63] In 1979, the CGSB specified ASTM D3831 as the test procedure to be used in measuring manganese in conjunction with the maximum MMT® limit.[64]

In 1985, Transport Canada acted to align Canadian vehicle exhaust standards with equivalent standards in the U.S. (Tier 0 exhaust standards), with harmonization of exhaust standards beginning with the 1988 model-year. At that time, Environment Canada requested that the CGSB review the impact of the continued use of MMT® on

[*] In 1978, the CGSB was known as the Canadian Government Specification Board; the name of the agency changed to Canadian General Standards Board in 1979.

vehicles and emissions in light of the emission control technology required for compliance with the Tier 0 standards. In response, a Working Group within the CGSB issued a 1986 report recommending that MMT® use be continued at current levels and that the issue should be reexamined, as needed, if more data became available or if vehicle emission control technologies changed. Other findings of the Working Group included an estimate that vehicle HC exhaust emissions would increase under MMT® use by between 0.03 and 0.11 g/mi (relative to the Tier 0 standard of 0.41 g/mi, i.e., by 7 to 27%), that the expected increase in HC emissions represented a "miniscule" increment to atmospheric HC, and that continued MMT® use would not compromise vehicle emissions control system operation or durability based on the then-available data.[65]

In 1992, a Memorandum of Understanding was signed between the automotive industry and the Canadian government continuing the harmonization of 1994 and 1995 model-year Canadian standards with those in the U.S. (Tier 1 exhaust standards). Shortly thereafter, Environment Canada announced it would control MMT® use through the Manganese-based Fuel Additives Act due to concern that MMT® use could compromise the effectiveness of vehicle OBD and vehicle emissions control systems, thereby indirectly harming the health of Canadians.[66] The Act, which prohibited the importation of MMT® into Canada and the trade of MMT® between provinces, was enacted in April 1997 and became effective in June 1997.[67*] Following the effective date of the Act, the Government of Alberta filed a complaint against the Government of Canada under the Canadian Agreement on Internal Trade.[68] The panel convened to hear the dispute concluded in June 1998 that the Manganese-based Fuel Additives Act was indeed inconsistent with the AIT.[69] Also while the Act was in force, Ethyl Corporation filed a constitutional challenge and a suit under Chapter 11 of NAFTA, disputing the legality of the Manganese-based Fuel Additives Act. After the AIT ruling, the Canadian government rescinded the Act in July 1998 and settled with Ethyl Corporation before the NAFTA ruling was issued and the constitutional proceedings were completed.[67] With the rescission of the Manganese Based Fuel Additives Act in July 1998, the CGSB 18 mg Mn/l maximum specification remains the only limit on MMT® use in Canada.[61]

In 1998, authority to regulate motor vehicles emission standards was transferred from Transport Canada to Environment Canada. For model-year 2001, a National LEV program was implemented in Canada through a second Memorandum of Understanding on light-duty vehicles with automobile manufacturers. Environment Canada then enacted Canada-specific Tier 2 exhaust standards in 2002 pursuant to subsection 332(1) of the Canadian Environmental Protection Act of 1999[70] to take effect in January 2004 for 2004 and later model vehicles. These actions and the rescission of the Manganese Based Fuel Additives Act created a situation where MMT®-containing gasoline was likely to be used in vehicles with advanced emission control systems.

[*] MMT® has been and is currently manufactured only in the U.S. and imported into Canada for use in Canadian gasoline.

5.3 Levels of MMT® in Commercial Unleaded Gasolines in the United States and Canada

Data regarding MMT® usage in commercial gasolines sold in the U.S. and Canada are available from fuel surveys conducted by the Alliance of Automobile Manufacturers (Alliance) and its predecessor organization the American Automobile Manufacturers Association (AAMA).[71] This survey has been conducted by performing detailed analyses of gasoline samples taken at service stations in a number of cities in the United States, Canada, and Mexico during the summer and winter months. Testing to quantify manganese levels in unleaded gasoline in Canada was initiated for the winter 1994 survey and has been conducted during every survey since. There was also a supplemental survey in the fall of 1997 when the Canadian gasoline survey was conducted by the CVMA rather than AAMA. In addition to the biannual fuel surveys, there was a special Alliance fuel survey conducted in the spring of 2004 that evaluated MMT® use in Canadian gasolines and gasolines marketed in selected areas of Utah, New Mexico, and New York.

United States – As indicated previously, MMT® use in conventional unleaded gasolines sold in the United States has been allowed since the end of 1995; however, the first use of MMT® in unleaded gasoline in the U.S. was not observed in the Alliance fuel survey data until the winter of 2002. In the winter 2002 survey, Mn was detected at the level of 5 mg Mn/l in one of eight unleaded regular gasoline samples taken in Albuquerque, New Mexico. Since that time, Mn has continued to be observed in 10% to 20% of the regular and premium unleaded gasoline samples taken in Albuquerque at levels between 3 and 7 mg Mn/l. In addition, the spring 2004 survey found Mn in regular and premium unleaded gasolines sampled in Farmington, New Mexico; Salt Lake City, Utah; and at Constable, New York, just across the U.S. border with Canada. Mn levels in these samples ranged from 0.3 to about 10 mg Mn/l. Subsequent surveys indicate that MMT® use in the U.S. has been limited and most of the few samples observed to contain Mn have been from the Albuquerque, New Mexico area.

Canada – MMT® use has been observed on a widespread basis in Canadian unleaded gasolines included in the AAMA and Alliance surveys since testing began in the winter of 1994. These survey data are summarized over time by city and gasoline grade in Tables 5-1 through 5-4. The number of samples in each survey, as well as the average, minimum, and maximum Mn level, are reported. The values reported assume that fuels with Mn levels below the detection limit in the Alliance survey (0.3 mg Mn/l) contained no MMT®. The data are also presented graphically for the cities of Toronto and Montreal for regular and premium fuel in Figures 5-2 and 5-3, and for the cities of Vancouver and Edmonton for regular and premium fuel in Figures 5-4 and 5-5.

As indicated in the tables and shown for some of Canada's major cities in the figures, the presence of MMT® in Canadian gasoline over the period from 1994 to the present has varied considerably in any given location at any point in time in both regular and premium unleaded gasoline. Over the time period for which data are available, average Mn levels in each sampling location have generally been lower than 10 mg Mn/l and most often in the range of 6 to 8 mg Mn/l. Maximum observed values have varied widely up to the CGSB limit of 18 mg Mn/l, with minimum values also showing considerable

Table 5-1
Auto Industry Gasoline Surveys of Canadian Cities
Manganese Minimum, Maximum & Average Concentrations
Regular Gasoline, Winter 1994 – Summer 2000
(mg Mn/l)

Canadian City		W '94	S '94	W '95	S '95	W '96	S '96	W '97	S '97	F '97	W '98	S '98	W '99	S '99	W '00	S '00
Edmonton, AB	Avg	7.5	7.4	6.3	3.5	3.0	9.5	0.0	4.4	0.9	1.1	7.5	5.2	2.5	4.9	7.6
Edmonton, AB	Max	9.0	13.5	13.2	4.5	7.4	12.7	0.0	8.7	2.1	1.8	13.7	16.4	4.8	7.7	8.7
Edmonton, AB	Min	3.7	2.9	0.0	2.1	0.0	5.3	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.1	6.3
Number of Samples		4	4	5	5	5	5	3	5	4	5	5	5	5	5	5
Halifax, NS	Avg	6.9	5.3	3.1	1.7	0.5	9.6	6.8	1.2	0.0	0.0	0.0	11.6	2.1	6.0	3.9
Halifax, NS	Max	9.5	10.8	15.3	5.5	2.6	11.4	10.0	5.8	0.0	0.0	0.0	16.1	3.2	7.4	5.5
Halifax, NS	Min	0.8	0.0	0.0	0.0	0.0	6.3	2.1	0.0	0.0	0.0	0.0	3.4	0.0	5.3	0.8
Number of Samples		5	5	5	4	5	5	5	5	5	5	5	5	5	5	5
Kamloops, BC	Avg															
Kamloops, BC	Max															
Kamloops, BC	Min															
Number of Samples		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Montreal, PQ	Avg	6.0	10.6	6.1	5.2	3.1	1.4	4.4	3.0	2.3	3.4	1.2	3.5	4.5	4.0	6.3
Montreal, PQ	Max	14.8	14.5	12.9	9.8	7.7	2.6	12.2	15.1	11.1	16.9	6.1	9.2	7.1	10.3	12.7
Montreal, PQ	Min	0.0	7.4	1.1	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8
Number of Samples		5	5	5	5	5	5	5	5	5	5	5	5	5	5	4
Regina, SK	Avg									2.7						
Regina, SK	Max									5.3						
Regina, SK	Min									0.0						
Number of Samples		0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Saint John, NB	Avg									0.0					5.5	2.5
Saint John, NB	Max									0.0					11.1	4.0
Saint John, NB	Min									0.0					0.0	1.1
Number of Samples		0	0	0	0	0	0	0	0	2	0	0	0	0	2	2
Toronto, ON	Avg	3.7	8.6	8.4	7.2	5.7	6.6	6.6	8.8	8.3	5.8	4.5	3.1	4.8	4.1	2.3
Toronto, ON	Max	4.5	13.5	10.3	10.0	6.9	9.2	9.2	15.3	13.7	10.6	8.2	5.0	8.5	5.5	4.2
Toronto, ON	Min	2.4	1.3	5.3	1.6	2.9	3.4	2.9	3.7	1.8	1.3	0.8	1.6	3.2	2.6	0.5
Number of Samples		5	5	5	5	5	5	5	5	4	5	5	5	4	5	7
Vancouver, BC	Avg	6.8	10.6	9.5	3.0	4.0	4.5	3.1	2.8	6.3	0.2	0.0	2.1	4.3	0.5	2.0
Vancouver, BC	Max	13.2	12.9	15.1	8.5	7.1	6.1	10.3	6.3	9.8	0.8	0.0	3.2	7.4	1.3	4.2
Vancouver, BC	Min	3.7	6.6	4.5	0.0	0.0	0.5	0.5	0.0	0.2	0.0	0.0	0.0	1.8	0.0	0.0
Number of Samples		5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
All Samples	Avg	6.1	8.5	6.7	4.2	3.3	6.3	4.5	4.0	3.1	2.1	2.6	5.1	3.6	4.0	4.1
All Samples	Max	14.8	14.5	15.3	10.0	7.7	12.7	12.2	15.3	13.7	16.9	13.7	16.4	8.5	11.1	12.7
All Samples	Min	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		24	24	25	24	25	25	23	25	27	25	25	25	24	27	28

Table 5-2
Auto Industry Gasoline Surveys of Canadian Cities
Manganese Minimum, Maximum & Average Concentrations
Regular Gasoline, Winter 2001 – Winter 2007
(mg Mn/l)

Canadian City		W '01	S '01	W '02	S '02	W '03	S '03	W '04	SP'04	S '04	W '05	S '05	W '06	S '06	W '07
Edmonton, AB	Avg	1.4	7.2	2.6	5.0	2.8	7.8	5.5	5.4	0.0	0.0	0.0	0.0	0.0	0.0
Edmonton, AB	Max	3.7	12.2	7.9	7.1	7.7	13.7	7.7	11.4	0.0	0.0	0.0	0.0	0.0	0.0
Edmonton, AB	Min	0.0	4.0	0.0	3.4	0.0	2.4	2.9	1.3	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		5	5	5	5	5	5	3	3	3	3	3	3	3	3
Halifax, NS	Avg	5.8	2.9	1.4	10.6	3.8	13.8	5.2	6.6	0.0	0.0	0.0	0.0	0.0	0.0
Halifax, NS	Max	7.4	3.2	1.6	12.9	7.1	15.6	6.9	7.4	0.0	0.0	0.0	0.0	0.0	0.0
Halifax, NS	Min	0.5	2.4	1.1	7.7	2.1	12.7	3.4	5.8	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		5	5	5	5	5	5	2	2	2	2	2	2	2	2
Kamloops, BC	Avg							1.7	4.2	0.0	0.2	0.0	0.0	0.0	0.2
Kamloops, BC	Max							2.1	11.1	0.0	0.5	0.0	0.0	0.0	0.3
Kamloops, BC	Min							1.3	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		0	0	0	0	0	0	3	3	3	3	3	3	3	3
Montreal, PQ	Avg	2.1	6.2	6.9	3.9	4.7	5.4	1.8	0.7	0.0	0.0	0.0	0.0	0.0	0.0
Montreal, PQ	Max	10.6	9.5	15.1	10.0	11.9	15.3	5.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
Montreal, PQ	Min	0.0	3.4	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		5	5	5	5	5	5	4	4	4	4	4	4	4	4
Regina, SK	Avg							4.1	5.2	9.1	4.6	13.3	3.2	0.0	0.0
Regina, SK	Max							5.0	6.9	11.4	5.5	14.3	6.3	0.0	0.0
Regina, SK	Min							3.2	4.2	6.9	3.7	12.4	0.0	0.0	0.0
Number of Samples		0	0	0	0	0	0	2	3	2	2	2	2	2	2
Saint John, NB	Avg	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saint John, NB	Max	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saint John, NB	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		2	2	2	2	2	2	1	1	1	1	1	1	1	1
Toronto, ON	Avg	2.3	6.4	7.6	5.6	3.3	13.2	5.3	9.8	1.2	0.0	0.0	0.0	0.0	0.0
Toronto, ON	Max	4.2	11.1	14.0	10.8	5.3	16.4	9.0	18.2	1.6	0.0	0.0	0.0	0.0	0.0
Toronto, ON	Min	0.8	2.9	2.1	0.0	0.0	11.4	1.6	0.0	0.8	0.0	0.0	0.0	0.0	0.0
Number of Samples		5	5	5	5	5	4	6	5	5	5	5	5	5	5
Vancouver, BC	Avg	2.1	1.3	0.1	0.5	2.1	5.3	1.8	4.2	0.0	0.0	0.0	0.0	0.0	0.0
Vancouver, BC	Max	5.3	4.0	0.5	2.6	3.2	6.9	2.6	6.1	0.0	0.0	0.0	0.0	0.0	0.0
Vancouver, BC	Min	0.0	0.0	0.0	0.0	0.0	3.2	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		5	5	5	5	4	5	3	3	3	3	3	3	3	3
All Samples	Avg	2.7	4.4	3.4	4.7	3.1	8.3	3.5	5.1	1.1	0.4	1.2	0.3	0.0	0.0
All Samples	Max	10.6	12.2	15.1	12.9	11.9	16.4	9.0	18.2	11.4	5.5	14.3	6.3	0.0	0.3
All Samples	Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		27	27	27	27	26	26	24	24	23	23	23	23	23	23

Table 5-3
Auto Industry Gasoline Surveys of Canadian Cities
Manganese Minimum, Maximum & Average Concentrations
Premium Gasoline, Winter 1994 – Summer 2000
(mg Mn/l)

Canadian City		W '94	S '94	W '95	S '95	W '96	S '96	W '97	S '97	F '97	W '98	S '98	W '99	S '99	W '00	S '00
Edmonton, AB	Avg	10.8	9.1	3.4	6.6	5.5	8.6	0.0	0.2	0.1	0.0	0.0	7.6	6.5	5.9	6.8
Edmonton, AB	Max	15.9	12.4	5.3	8.5	8.7	10.0	0.0	0.5	0.2	0.0	0.0	17.2	9.0	8.5	8.5
Edmonton, AB	Min	2.9	2.9	1.6	4.2	0.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0	3.2	1.1	4.8
Number of Samples		4	4	3	3	3	3	2	3	4	3	3	3	3	3	3
Halifax, NS	Avg	12.0	8.9	16.0	7.7	6.8	9.4	10.7	2.5	0.1	0.0	0.0	7.1	6.7	8.3	7.2
Halifax, NS	Max	14.3	11.6	17.2	9.2	8.7	13.5	11.1	7.4	0.2	0.0	0.0	10.8	10.6	10.8	11.6
Halifax, NS	Min	9.2	5.3	14.8	6.6	3.2	5.5	9.8	0.0	0.0	0.0	0.0	3.2	0.0	4.2	0.0
Number of Samples		3	3	3	3	3	3	3	3	5	3	3	3	3	3	3
Kamloops, BC	Avg															
Kamloops, BC	Max															
Kamloops, BC	Min															
Number of Samples		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Montreal, PQ	Avg	10.0	10.4	12.8	6.8	6.3	5.3	6.5	0.5	4.3	1.9	0.0	1.0	5.1	3.3	5.9
Montreal, PQ	Max	11.9	14.3	16.6	8.7	6.9	6.6	6.6	1.6	15.1	5.8	0.0	1.6	6.9	5.0	7.7
Montreal, PQ	Min	8.2	8.2	10.8	5.5	5.5	4.5	6.3	0.0	0.0	0.0	0.0	0.5	2.9	0.5	4.2
Number of Samples		3	3	3	3	3	3	3	3	5	3	3	3	3	3	3
Regina, SK	Avg									5.6						
Regina, SK	Max									11.1						
Regina, SK	Min									0.0						
Number of Samples		0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Saint John, NB	Avg									0.0					11.1	4.2
Saint John, NB	Max									0.0					22.2	8.5
Saint John, NB	Min									0.0					0.0	0.0
Number of Samples		0	0	0	0	0	0	0	0	2	0	0	0	0	2	2
Toronto, ON	Avg	7.8	10.5	8.4	7.8	6.6	7.9	8.8	6.7	5.5	4.7	4.0	6.5	3.5	6.1	4.8
Toronto, ON	Max	9.8	12.7	10.3	12.9	7.9	10.3	9.8	9.5	9.8	10.8	7.1	11.6	6.1	8.7	9.2
Toronto, ON	Min	6.1	9.2	5.3	2.1	4.2	5.0	7.1	1.8	0.0	0.0	1.1	1.6	1.3	1.6	0.0
Number of Samples		3	3	3	3	3	3	4	3	4	3	3	4	4	5	4
Vancouver, BC	Avg	11.7	14.3	10.4	2.4	3.5	4.7	4.7	1.2	3.6	3.3	0.0	9.0	6.5	4.0	7.5
Vancouver, BC	Max	14.5	16.9	11.9	7.1	7.1	8.5	11.6	2.1	7.7	8.2	0.0	13.7	7.9	6.1	12.9
Vancouver, BC	Min	6.6	12.7	7.7	0.0	0.0	1.1	0.5	0.0	1.1	0.5	0.0	3.2	6.1	0.0	0.0
Number of Samples		3	3	3	3	3	3	4	3	5	3	4	4	4	5	5
All Samples	Avg	10.5	10.5	10.2	6.3	5.7	7.2	6.6	2.2	2.7	2.0	0.7	6.4	5.6	6.0	6.2
All Samples	Max	15.9	16.9	17.2	12.9	8.7	13.5	11.6	9.5	15.1	10.8	7.1	17.2	10.6	22.2	12.9
All Samples	Min	2.9	2.9	1.6	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		16	16	15	15	15	15	16	15	27	15	16	17	17	21	20

Table 5-4
Auto Industry Gasoline Surveys of Canadian Cities
Manganese Minimum, Maximum & Average Concentrations
Premium Gasoline, Winter 2001 – Winter 2007
(mg Mn/l)

Canadian City		W '01	S '01	W '02	S '02	W '03	S '03	W '04	SP'04	S '04	W '05	S '05	W '06	S '06	W '07
Edmonton, AB	Avg	7.6	8.5	9.3	7.9	6.8	7.4	6.4	4.9	0.0	0.0	0.0	0.0	0.0	0.0
Edmonton, AB	Max	12.9	12.2	17.4	9.5	11.9	10.0	8.5	8.7	0.0	0.0	0.0	0.0	0.0	0.0
Edmonton, AB	Min	1.3	5.0	3.7	5.8	0.0	4.5	2.9	1.8	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		3	3	3	3	3	3	3	3	3	3	3	3	3	3
Halifax, NS	Avg	9.5	7.3	10.6	12.0	11.0	14.4	12.5	10.0	2.6	0.0	0.0	0.0	0.0	0.0
Halifax, NS	Max	12.9	9.0	11.1	12.7	11.6	16.1	15.3	12.4	5.3	0.0	0.0	0.0	0.0	0.0
Halifax, NS	Min	3.7	5.8	10.0	11.6	10.6	11.1	9.8	7.7	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		3	3	3	3	3	3	2	2	2	2	2	2	2	2
Kamloops, BC	Avg							7.4	4.0	1.2	0.0	0.0	0.0	0.0	0.3
Kamloops, BC	Max							11.6	8.7	2.4	0.0	0.0	0.0	0.0	0.3
Kamloops, BC	Min							4.2	0.5	0.0	0.0	0.0	0.0	0.0	0.3
Number of Samples		0	0	0	0	0	0	3	3	3	3	3	3	3	3
Montreal, PQ	Avg	4.9	8.5	10.0	9.4	9.7	8.4	4.6	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Montreal, PQ	Max	7.7	10.6	13.5	14.0	14.3	14.3	7.1	6.3	0.0	0.0	0.0	0.0	0.0	0.0
Montreal, PQ	Min	2.4	6.3	5.5	5.3	6.1	5.3	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		3	3	3	3	3	3	4	4	4	4	4	4	4	4
Regina, SK	Avg							11.9	10.3	14.4	12.0	14.4	1.2	0.0	0.0
Regina, SK	Max							12.2	12.9	14.8	15.1	14.8	2.4	0.0	0.0
Regina, SK	Min							11.6	7.9	14.0	9.0	14.0	0.0	0.0	0.0
Number of Samples		0	0	0	0	0	0	2	3	2	2	2	2	2	2
Saint John, NB	Avg	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Saint John, NB	Max	9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Saint John, NB	Min	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		2	2	2	2	2	2	1	1	1	1	1	1	1	1
Toronto, ON	Avg	9.1	10.8	10.6	10.6	3.1	15.2	7.8	8.3	0.6	0.0	0.0	0.0	0.0	0.2
Toronto, ON	Max	15.9	14.8	17.4	14.3	5.0	15.9	10.6	16.1	1.1	0.0	0.0	0.0	0.0	0.8
Toronto, ON	Min	1.3	1.8	0.0	6.1	0.0	14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		4	4	3	3	3	2	5	5	5	5	5	5	5	5
Vancouver, BC	Avg	7.5	5.5	10.1	5.9	5.8	9.1	2.6	2.6	0.0	0.0	0.0	0.0	0.0	0.0
Vancouver, BC	Max	11.1	9.5	17.4	8.7	7.7	12.4	6.9	5.3	0.0	0.0	0.0	0.0	0.0	0.0
Vancouver, BC	Min	2.4	3.2	4.2	4.5	3.4	6.1	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		4	5	4	4	3	5	3	3	3	3	3	3	3	3
All Samples	Avg	7.5	7.2	9.0	8.0	6.4	9.2	6.8	5.7	1.8	1.0	1.3	0.1	0.0	0.1
All Samples	Max	15.9	14.8	17.4	14.3	14.3	16.1	15.3	16.1	14.8	15.1	14.8	2.4	0.0	0.8
All Samples	Min	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Samples		19	20	18	18	17	18	23	24	23	23	23	23	23	23

Figure 5-2
Auto Industry Gasoline Surveys of Canadian Cities
Manganese Minimum, Maximum, and Average Concentrations
Montreal vs. Toronto − Regular Fuel

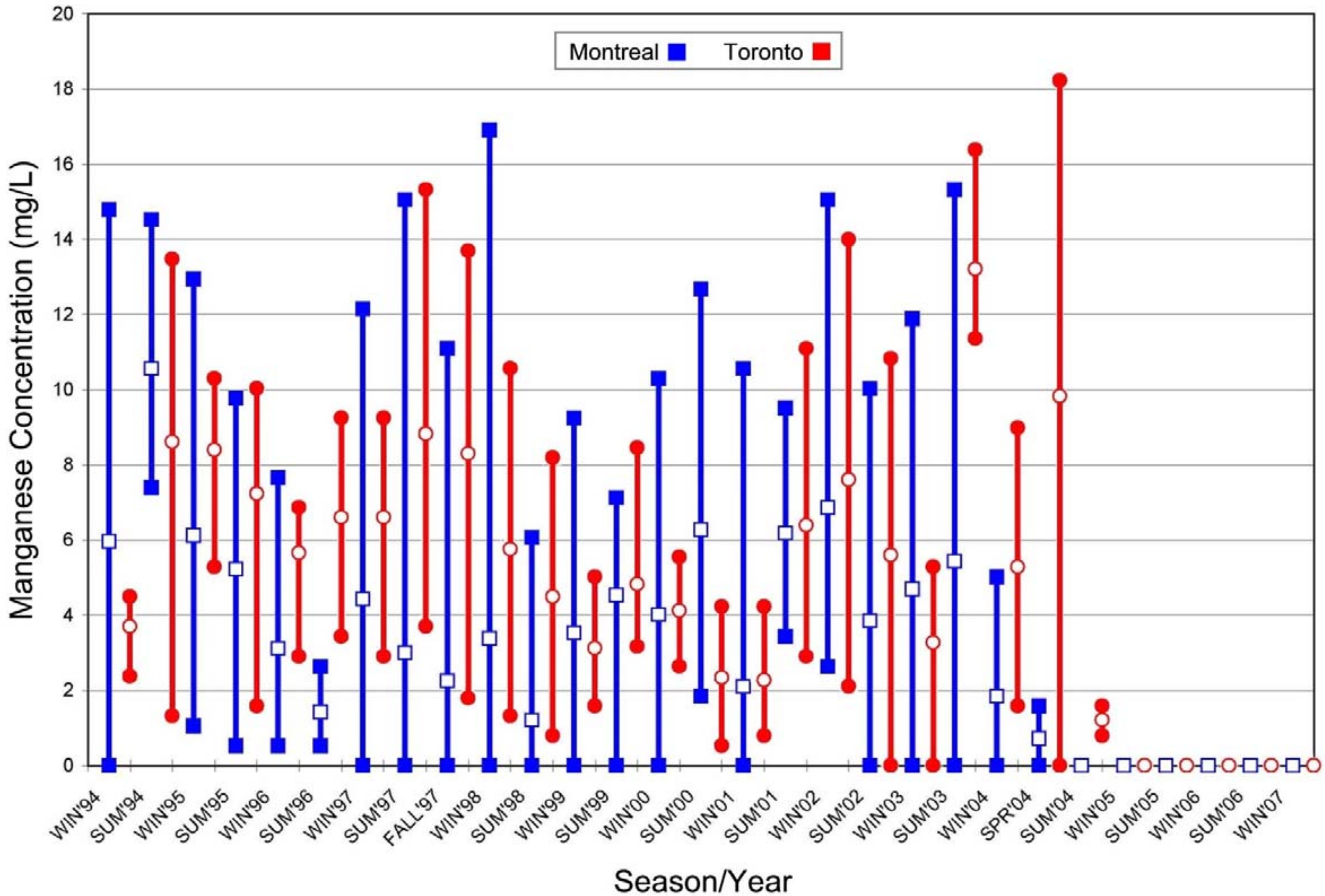


Figure 5-3
Auto Industry Gasoline Surveys of Canadian Cities
Manganese Minimum, Maximum, and Average Concentrations
Montreal vs. Toronto − Premium Fuel

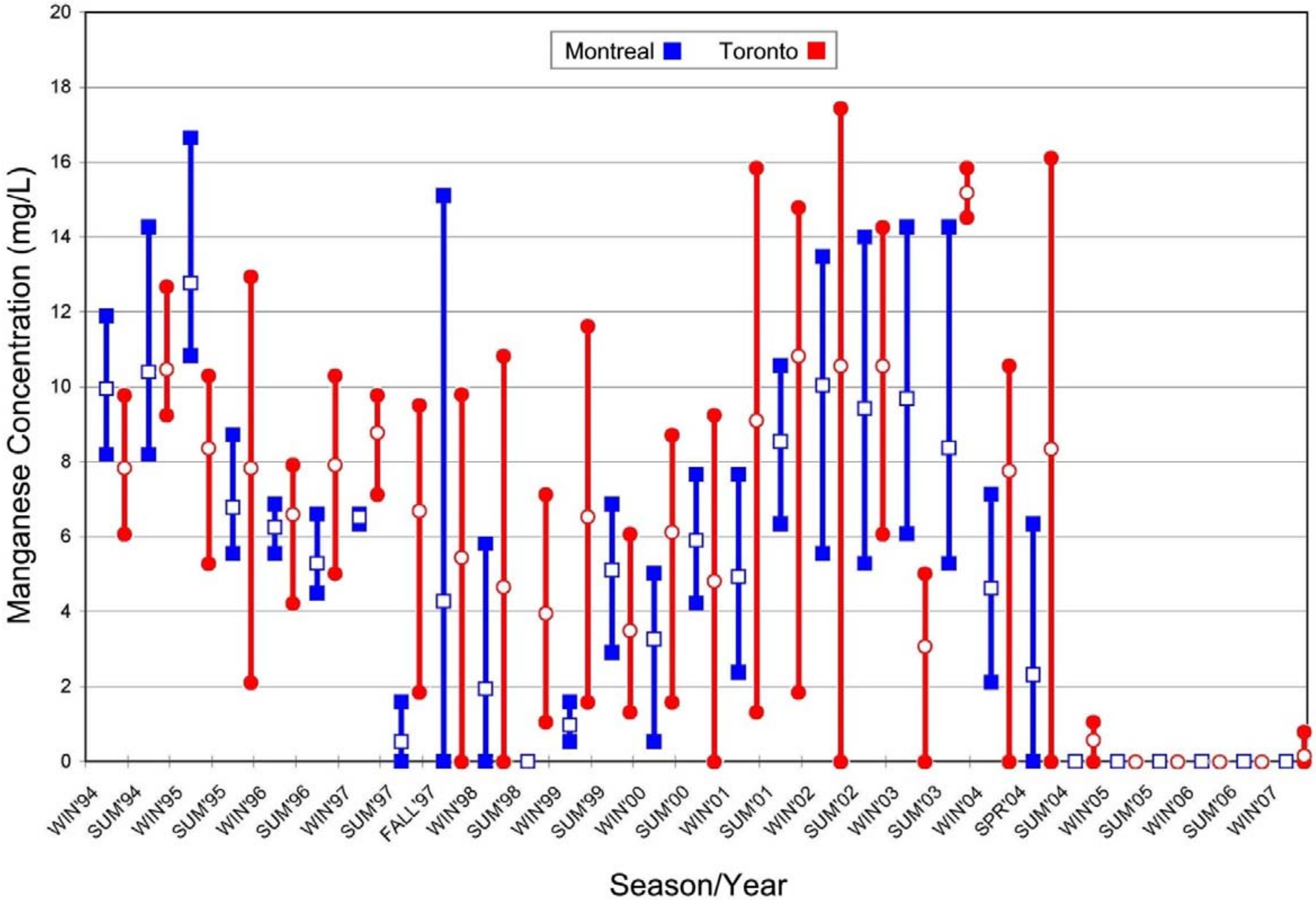


Figure 5-4
Auto Industry Gasoline Surveys of Canadian Cities
Manganese Minimum, Maximum, and Average Concentrations
Vancouver vs. Edmonton − Regular Fuel

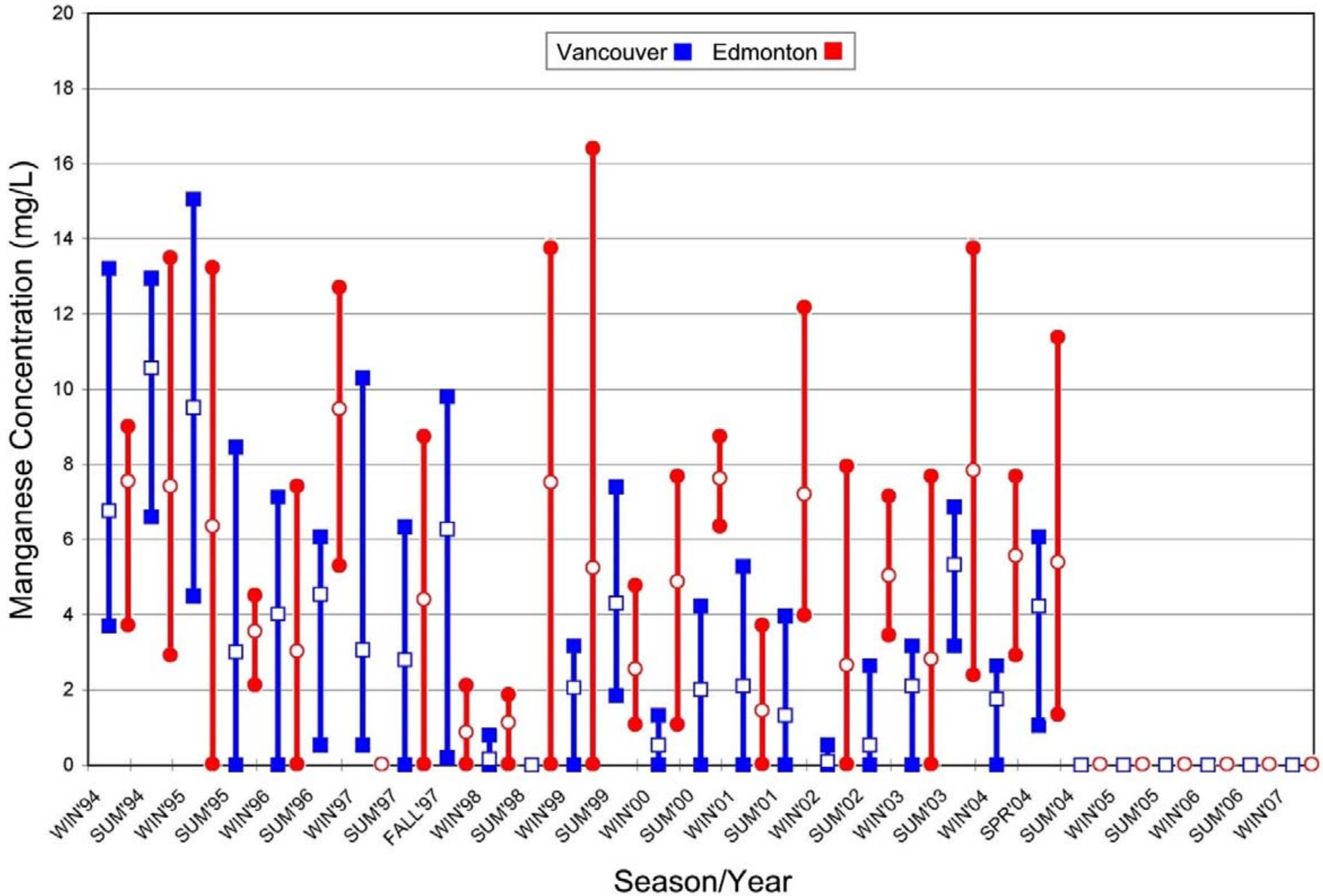
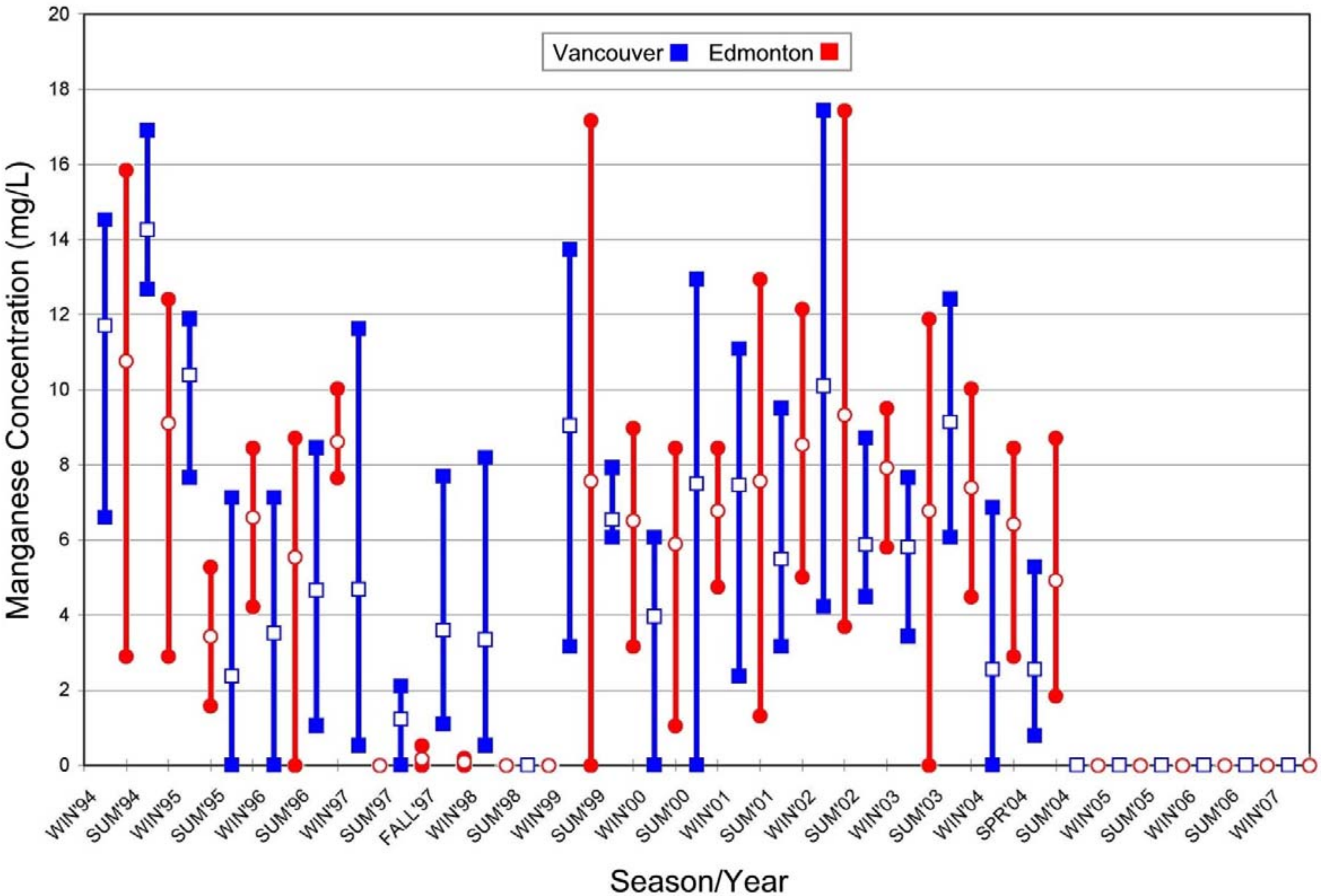


Figure 5-5
Auto Industry Gasoline Surveys of Canadian Cities
Manganese Minimum, Maximum, and Average Concentrations
Vancouver vs. Edmonton − Premium Fuel



variation over time. Given this, it is likely that the amount of Mn ingested by Canadian vehicles due to MMT® use in gasoline has also varied widely depending on the grade of gasoline used, brand loyalty issues, and the area of the country in which the vehicles were operated. Also evident in the data for summer 2004 through winter 2007 is that MMT® use in Canadian gasoline has virtually ceased as a result of voluntary actions on the part of major refiners,[72] although MMT® use did persist longer in Saskatchewan than in other areas.

###

6. OVERVIEW OF POLLUTANT FORMATION AND EXHAUST EMISSION CONTROL TECHNOLOGY

Chapter 2 of this report reviewed the increasingly stringent exhaust emission standards that have been imposed on new gasoline-fueled motor vehicles sold in North America over the past 40 years. Similarly, Chapter 3 reviewed the development of industry standards for gasoline to ensure consistent vehicle performance and the regulations of gasoline composition to facilitate and/or improve the performance of catalysts as well as directly reduce pollutant emissions. In this chapter, the principles associated with exhaust pollutant formation and emission control technologies are reviewed.

6.1 Overview of Emission Control Technologies

As discussed previously, the need to reduce emissions in order to comply with exhaust emission standards led vehicle manufacturers to seek innovative ways both to reduce engine-out pollutant levels and to maximize the efficiency of exhaust aftertreatment devices to achieve reductions in tailpipe emissions. This has been accomplished by, among other things, improved engine design and control, and improvements in the effectiveness and durability of catalysts.[73,74] The success of these efforts has been enhanced by the regulation of fuel composition.

To comply with current emission standards, manufacturers have developed improved combustion chamber systems and sophisticated computerized engine control systems. Improvements in combustion chamber designs include use of multiple spark plugs, various methods of improving air-fuel mixing, changes in the design of pistons and head surfaces to improve the combustion process, and minimization of engine crevice volumes and oil consumption, to name a few.

Computerized engine control systems use input from a multitude of sensors to precisely control all aspects of engine operation. Key among these sensors is the oxygen or air/fuel ratio sensor (or sensors), which is used to maintain precise control over the relative amounts of fuel and air delivered to the cylinders of the engine. These computerized engine control systems both reduce the levels of emissions coming directly out of the engine and facilitate the use of highly effective exhaust aftertreatment devices to further lower pollutant levels before they exit the tailpipe.

At present, three-way catalytic converters (which oxidize HC and CO and reduce NOx) are the primary aftertreatment device. In order to meet the emission regulations, these catalysts must reduce engine-out emission levels by up to 98-99% for approximately 190,000 km of operation. In addition, manufacturers have developed OBD systems capable of identifying emission-related malfunctions or deterioration, alerting vehicle owners that malfunctions or deterioration exist, and facilitating the repair of those problems.

Compliance with Tier 2 emission standards requires the use of increasingly sophisticated and advanced emission control technologies, which reduces the allowable tolerances with respect to increases in emissions over the lifetime of vehicles. Commensurate improvements in OBD systems will also be required.

6.2 Pollutant Formation

Gasoline engines used in automobiles generally operate on a “four-stroke” cycle**.** The strokes are as follows:

1. The “intake stroke,” which involves the induction of air and fuel (hydrocarbons) into the cylinder of the engine with the intake valve open and the piston moving downward in the cylinder;

2. The “compression stroke,” where the upward movement of the piston in the cylinder after the close of intake compresses the mixture of air and fuel, which is referred to as the “charge”;

3. The “power stroke” that forces the piston downward, which is caused by the rapid expansion of gases in the cylinder created by spark ignition of the charge somewhere near the top of the compression stroke; and

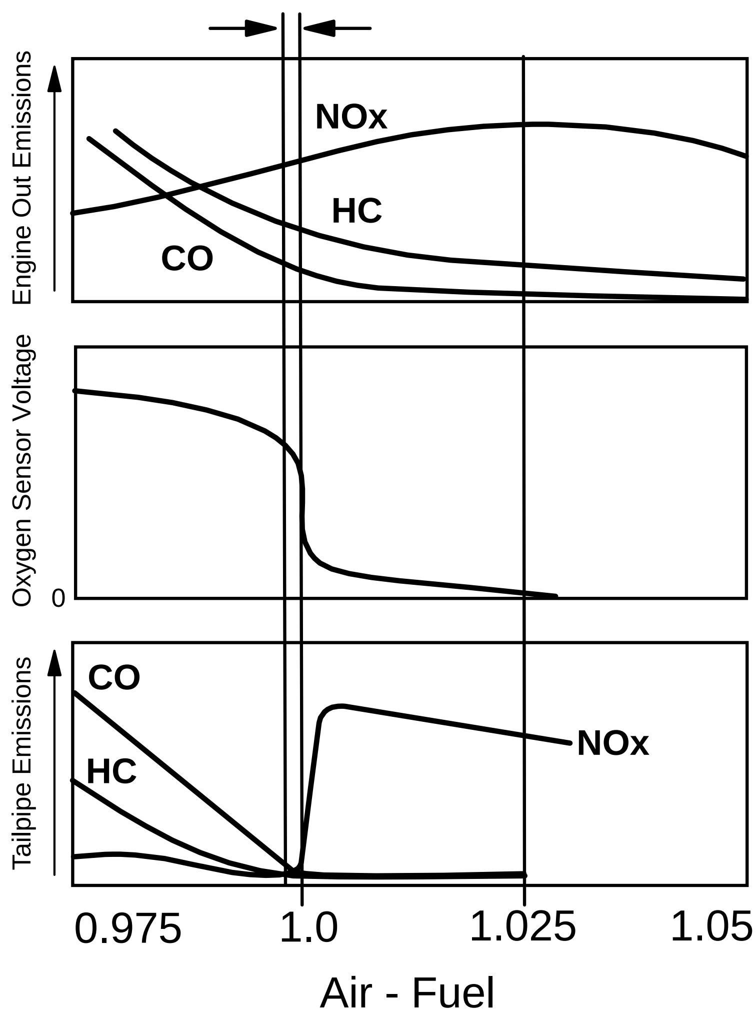
4. The “exhaust stroke,” where the upward movement of the piston with the exhaust value open drives the products of combustion out of the cylinder and into the exhaust system.

The chemical composition of the exhaust gases is determined by a number of factors related to engine design and operation. Factors of significance with respect to engine design are relatively complex and primarily affect HC and NOx emissions.[75] Design factors impacting HC emission levels include combustion chamber characteristics, including mixing, chamber shape and ratio of surface area to volume, chamber crevice volume, the control of lubricating oil in the cylinders, and spark timing. Spark timing, compression ratio, and exhaust gas recirculation are some of the engine design factors that can affect engine-out NOx emission levels.

For a given engine design, the most important factors with respect to pollutant formation are the ratio of air to fuel in the charge and whether the charge has been properly ignited by the spark plug. If proper ignition does not occur, HC emissions will tend to be higher and CO and NOx emissions will tend to be lower than they would be if proper ignition had occurred. Improper ignition is also referred to as misfire. Misfire may be caused by a number of factors, including spark plug failure* and fouling, as well as excessive combustion chamber deposits.

Assuming that proper ignition has occurred, relative engine-out emissions of HC and CO will be high and NOx emissions will tend to be low if there was excess fuel present in the charge (rich operation); NOx emissions will tend to be high and HC and CO emissions will tend to be low if there was excess air present in the charge (lean operation). A conceptual representation of engine-out emission levels for HC, CO, and NOx as a function of air-fuel ratio is shown in the top portion of Figure 6-1.

Figure 6-1
Stoichiometric Window



The air-fuel ratio is controlled by the fuel management system. On most pre-1980 model-year vehicles, carburetors were used to add fuel to the air being drawn into the

* It should be noted that spark plug durability has improved substantially over time, with plug life being about 25,000 km on mid-1970s vehicles and on the order of up to 160,000 km on current model-year vehicles.

engine. Usually, a single carburetor located on the top of the intake manifold prepared the air-fuel mixture that was introduced into all cylinders of the engine. During the 1980s, there was a transition from carburetors to fuel-injection systems. While there are many different designs, fuel injection systems can be broken down into two basic types: single-point (or throttle-body) and multi-point. In single-point systems, a single large fuel injector is used to replace the carburetor and is located at the top of the intake manifold. As is the case with a carburetor, this single injector is used to prepare the air-fuel mixture that is introduced into all cylinders of the engine. With multi-point systems, an individual fuel injector is provided for each cylinder of the engine. The injectors are located in the runners of the intake manifold leading to each cylinder. In general, multi-point systems provide much more precise control of air-fuel ratio than do carburetors or single-point systems. Multi-point systems have been used on most new vehicles since the early 1990s.

In addition to the type of fuel metering device that is used on a vehicle, another important factor with respect to air-fuel ratio is whether there is a feedback system used to control fuel metering. These feedback systems use data from measurements of actual engine air-fuel ratio to adjust the operation of the fuel metering device. Most pre-1980 model-year vehicles did not have any type of feedback control and were generally designed to run with a moderately to slightly rich air-fuel ratio. Beginning in the late 1970s, closed-loop, feedback control fuel metering devices began to be used. These systems generally use one or more oxygen sensors placed in the exhaust stream to control air-fuel ratio. These systems were introduced more slowly in Canada due to the less stringent emission requirements discussed previously.

As the name suggests, oxygen sensors measure the amount of oxygen remaining in the exhaust after all of the HC, CO, and other reducing species have been oxidized. The sensor consists of a small, highly efficient catalyst that performs the oxidation function and a detector that measures the oxygen content of the gas sample after it has passed through the sensor catalyst. A generalized representation of the output voltage of an oxygen sensor is shown in the second graph of Figure 6-1. The very steep portion of the response curve shown in Figure 6-1 is referred to as the switch point of the sensor, which occurs when the air-fuel ratio is in the stoichiometric window.[*]

The goal of the closed-loop control system on a modern vehicle is usually to maintain air-fuel ratios in the stoichiometric window using the output signals from the oxygen sensor(s) in the exhaust stream along with signals from other sensors. As shown in Figure 6-1, at near-stoichiometric air-fuel ratios, engine-out emissions of HC, CO, and NOx are all lower than their maximum values. However, as discussed in the next chapter, the main benefit of precise stoichiometric air-fuel ratio control is that it allows for rapid shifting of the chemical environment in the exhaust system between oxidizing

[*] The stoichiometric point is defined as the air-fuel ratio at which there is exactly enough oxygen present to convert all of the fuel present to water and carbon dioxide (the products of complete combustion), and is denoted by a value of one for the air-fuel ratio metric of lambda. The stoichiometric window generally refers to air-fuel ratios close to the stoichiometric point as shown in Figure 6-2. Note also in Figure 6-2 that values of lambda less than one indicate a fuel rich air-fuel ratio while values greater than one indicate a fuel lean air-fuel ratio.

(oxygen rich) and reducing (fuel rich) conditions required for the proper functioning of three-way catalytic converters.

In summary, pollutant formation in a gasoline-fueled engine is inevitable, but over time manufacturers have made substantial improvements in engine design and control that have minimized pollutant formation in the engine. Despite these improvements, however, pollutant formation will increase if the performance of key engine components like spark plugs and oxygen sensors is compromised or if unexpected deposits form in the combustion chamber.

6.3 Aftertreatment Devices

Oxidation Catalysts − The use of exhaust aftertreatment devices began in earnest with the use of oxidation-type catalytic converters. Catalysts of this type were introduced with the 1975 model year and were found on most passenger cars and light-duty trucks through the 1980 model year in the U.S. and to a lesser degree in Canada (non-catalyst-equipped vehicles were available through the mid-1980s). However, they continued to be used in some applications for a considerably longer period of time, particularly on heavier gasoline-fueled trucks.

Oxidation catalysts oxidize HC and CO in vehicle exhaust under conditions where there is excess oxygen in the exhaust gas stream. Given that many vehicles using oxidation catalysts operated with somewhat rich air-fuel ratios, air pumps or other systems were used to add air to the exhaust stream to create the oxidizing atmosphere necessary for the catalyst to oxidize engine-out emissions of HC and CO.

Three-Way Catalysts − The dominant type of catalytic converter that is still installed on virtually every new gasoline vehicle sold since the late 1980s in North America is the three-way catalyst. In contrast to oxidation catalysts, three-way catalysts are designed to be highly efficient at simultaneously oxidizing HC and CO and reducing NOx. This is achieved through proper catalyst formulation and by rapidly switching the air/fuel ratio of the engine back and forth between rich (excess fuel) and lean (excess air) operation in a narrow window around the stoichiometric point using the closed-loop feedback fuel control system. This is illustrated in the bottom portion of Figure 6-1, which shows relative tailpipe emission levels of HC, CO, and NOx from a three-way catalyst equipped vehicle as a function of air-fuel ratio.

Although oxidation and three-way catalysts use different formulations of the noble metals platinum (Pt), palladium (Pd), and rhodium (Rh), as well as chemicals that promote catalytic activity (promoters) and that prevent sintering of the finely dispersed noble metals (stabilizers), their basic construction and principles of operation are similar. The catalytic materials, including promoters and stabilizers and a high surface area coating, usually alumina, are commonly applied in several steps to a ceramic or metal monolith substrate or in some cases on ceramic beads or pellets. Historically, beaded catalysts have seen only limited use and monolith substrates have been and will continue to be used in most, if not all, catalytic converters. In the past, the most common monoliths had 400 cells per square inch (cpsi); however, as described in more detail in later chapters, advanced catalysts are employing higher cell densities to reduce thermal mass and therefore decrease light-off times and to provide greater catalyst surface area.

The high surface area coating allows for the creation of a large number of “active sites,” which are formed by small clusters of noble metal atoms. In general, the greater the number of active sites, the greater the number of catalytic reactions that can take place. The available surface area of a typical automotive converter (which has a volume on the order of 1 to 2 litres) is on the order of 45,000 square meters or about 500,000 square feet. In addition, as noted above, other compounds besides the noble metals are also incorporated into the catalyst formulation for a variety of reasons, including to enhance (or promote) the activity of the noble metals, to stabilize the noble metals, or to reduce the sensitivity of the catalyst to poisons such as sulfur.

With respect to stabilization, it is the available noble metal surface area that is important in automotive catalysts, rather than simply the total mass of the noble metals.[*] Therefore, in catalyst preparation, great attention is paid to assure that the noble metals are present in the smallest particle sizes possible (i.e., dispersed to the greatest possible extent) in order to maximize surface area. Larger noble metal particle sizes are more thermodynamically favored; as a result, when catalysts are exposed to high temperatures, the noble metals can sinter into larger particles and thus reduce the available surface area and the efficiency of the catalyst. Stabilizers are therefore used to minimize sintering. Catalyst placement is also directly related to sintering as the closer the catalyst is placed to the engine the higher the maximum temperature to which it will be exposed. During the 1980s and 1990s, most automotive catalysts were designed for a maximum temperature of around 800º C.[76] As discussed in Chapter 11, catalysts intended for incorporation into advanced technology emission control systems are designed for maximum temperature in excess of 1,000°C.

Catalyst poisoning is a term generally used to describe a reduction in or the complete loss of catalyst efficiency as the result of the interaction of compounds present in the exhaust stream with a catalyst. However, the term is not applied to macroscopic physical processes such as the blockage of the channels of a monolithic support or the breakage or melting of monolith or pelleted supports. Catalyst poisoning is generally categorized as selective or non-selective, and poisoning may be classified as reversible or irreversible.

Selective poisoning involves a chemical interaction between the poison and the noble metal. Examples of this are the reaction of lead with Pt to form an alloy with no catalytic activity or the chemisorption of sulfur dioxide onto Pt, which effectively prevents other molecules from reaching the surface of the noble metal. In the former case, the poisoning is irreversible, while in the latter case exposure of the catalyst to high temperatures and a reducing environment will cause the desorption of sulfur dioxide and restoration of catalytic activity.

[*] While it is surface area rather than total mass that is important, it must be noted that for a given size of metal particles, the total surface area will increase as the number of metal particles, and hence the total mass, or “loading,” of precious metals, is increased.

Non-selective catalyst poisoning (also known as masking or fouling) involves the formation of microscopic deposits or films on the catalyst wash coat that either cover the precious metals or block the pores of the wash coat, preventing the diffusion of pollutant molecules to the noble metals. This type of poisoning may also be reversible or irreversible.

Three-way catalyst technology has developed significantly since it was introduced in the late 1970s. This development has been driven by the need to develop catalysts with higher efficiency, greater durability, and the capability of being monitored by OBD systems, as well as the need to reduce the cost of catalysts through changes in the noble metals used in catalysts and efforts to minimize noble metal use. However, given the increasingly stringent emission standards and durability requirements (e.g., requiring compliance at increasingly higher mileages), the key issues have been minimizing the time required for the catalyst to come up to operating temperature when the engine is started (referred to as catalyst light-off) and retaining high catalyst efficiency at high mileage.

Unfortunately, these goals have been mutually exclusive to some degree. For example, the most direct way to reduce light-off time is to move the catalyst closer to the engine so that it gets hot fast (but is also exposed to extremely high temperatures) and to minimize the thermal mass of the catalyst by using monoliths with large numbers of very small channels and thin walls (but this poses a durability concern). In contrast, however, the most direct way to ensure long-term catalyst efficiency is to make sure that catalysts are not exposed to high exhaust temperatures and that the ceramic monoliths on which they are based are as mechanically durable as possible, which means smaller numbers of larger cells with thick cell walls.

Despite the above, compliance with the Tier 2 emission standards requires both a very short light-off time as well as high catalyst efficiency for 200,000 km and beyond. Given this, in 1999 when the Tier 2 standards were adopted, the U.S. EPA expected that compliance would require further advances in catalyst technology, including changes in formulation, improved washcoats, greater use of close-coupled catalysts, catalysts capable of withstanding temperatures up to 1100º C, increases in catalyst cell densities up to as much as 1200 cpsi, and higher precious metal loadings. These expectations were subsequently confirmed in a paper published by the Manufacturers of Emission Controls Association (MECA) in 2003,[76] which presented an extensive review of literature available regarding the development of advanced emissions control systems.

Anything that interferes with a manufacturer's ability to use a close-coupled catalyst or that adversely affects either light-off time or catalyst efficiency or impairs catalyst durability over the 200,000 km regulatory "useful life" of a vehicle is likely to impede or preclude compliance with the Tier 2 emission standards, particularly on in-use vehicles.

Lean NOx Adsorbers – Given the potential for improvement of fuel economy, there is considerable interest in the development of gasoline-direct injection engines and other lean-burn engine technologies. While control of HC and CO emissions from engines of these types is straightforward, the lean (oxidizing) exhaust environment precludes the use of three-way catalysts for NOx control. Lean NOx adsorbers can provide a means to reduce NOx emissions with these types of engines. The devices adsorb and store NOx molecules present in the exhaust stream during lean operation. The adsorption is reversible and NOx is simply stored until reducing conditions are established by briefly shifting the air-fuel ratio of the engine from lean to rich. During rich operation, the NOx adsorber is “regenerated” by the reduction and desportion of NOx species. To date, however, NOx adsorbers have seen only very limited use on commercially available vehicles.

In practice, NOx adsorption is accomplished by first oxidizing nitric oxide (NO, the primary NOx species present in engine-out exhaust) to nitrogen dioxide (NO_2) under lean conditions using Pt dispersed on the alumina catalyst support. Hydrocarbons and CO present in the exhaust are also oxidized by the Pt catalyst during lean operation. The NO_2 formed by this process then reacts, again under lean conditions, with an alkaline earth metal oxide that has been converted to a carbonate, forming the nitrate analog with the release of CO_2. In most cases, the alkaline earth metal used is barium (Ba). Under exposure to rich conditions, NO_2 is desorbed and undergoes reduction, still under rich conditions, on either a Pt or other noble metal catalyst. The alkaline earth oxide is then again converted to a carbonate and the process is repeated. In terms of NOx conversion efficiency, the process depends on two factors: the fraction of NO that is converted to NO_2 and adsorbed, and the conversion efficiency of the reduction step involving NO_2 on the precious metal catalyst.

Lean NOx adsorbers are generally based on ceramic monolith supports and will therefore also be susceptible to physical blockage of the monolith channels. Lean NOx adsorbers are very susceptible to poisoning by sulfur, which, while reversible under some conditions, may be irreversible given actual vehicle operating conditions.

Hydrocarbon Traps − Hydrocarbon traps are devices that are used to trap and store engine-out HC emissions upstream of a catalytic converter during cold start and then desorb them once the catalyst has reached operating temperature. Hydrocarbon traps may be placed in special exhaust system loops where diverter valves are used to control the conditions under which exhaust is directed to the trap, or may be present in line in exhaust systems. Integration of the trapping materials into three-way catalysts is also being pursued. As with NOx adsorbers, this technology has seen only relatively limited use on commercially available vehicles and its use is not expected to be widespread. Most hydrocarbon traps developed to date have been based on the use of zeolites of different types.

6.4 On-Board Diagnostic (OBD) Systems

In May 1984, CARB adopted the first regulations requiring that most 1988 and later model-year California-certified vehicles be equipped with on-board diagnostic (OBD I) systems that can monitor the performance of emission control system components, illuminate a dashboard indicator light when performance problems were identified, and store and display “fault codes” that allow repair technicians to readily identify and replace faulty components. These regulations required that OBD I systems be designed to detect and identify the source of malfunction of:

1. The on-board engine control computer; and

2. Any computer-sensed emission related component, including oxygen sensors, air flow, throttle position, and temperature sensors, as well as components in the ignition, exhaust gas recirculation (EGR), and fuel metering systems.

In September 1989, CARB adopted the OBD II regulations to be phased in on 1994 to 1996 model-year vehicles. These regulations expanded monitoring requirements to include catalyst performance, misfire monitoring, and evaporative purge system flow; and established requirements that malfunction indicator lights (MILs) be illuminated when emissions levels reached or exceeded approximately 1.5 times the emission standard to which the vehicle was certified. OBD regulations were also promulgated by the U.S. EPA, but the federal requirements are more general than CARB's. The U.S. EPA has agreed to accept CARB-certified OBD II systems as being in compliance with federal requirements. Therefore, CARB has assumed the primary role in this area and has modified the OBD II regulations on numerous occasions since 1989 to further expand monitoring requirements and to increase the stringency of existing requirements. OBD II systems are in widespread use on 1996 and later-model vehicles in the United States and 1998 and later model-year vehicles in Canada. The OBD systems used on Canadian vehicles must conform to either CARB or U.S. EPA requirements.

As noted above, the general OBD requirement imposed by CARB and U.S. federal regulations is that the MIL be illuminated whenever a malfunction occurs that causes the emissions of any pollutant to exceed a level equal to 1.5 times the applicable emission standard. As a result, compliance with the OBD requirements becomes more difficult for vehicles certified to more stringent standards, because the system must illuminate the MIL in response to smaller and smaller changes in emissions. For example, the NOx standard for a Tier 2 Bin 8 vehicle at 50,000 miles is 0.14 grams per mile, while that for a Tier 2 Bin 5 vehicle is 0.05 grams per mile. Therefore, for situations where the 1.5 times the standard requirement applies, MIL illumination at or before 50,000 miles should occur when emissions reach 0.21 grams per mile on the Tier 2 Bin 8 vehicle and at 0.075 grams per mile on the Tier 2 Bin 5 vehicle. In this example, the effective increase in NOx emissions associated with MIL illumination is 0.07 grams per mile for the Tier 2 Bin 8 vehicle but only 0.025 grams per mile for the Tier 2 Bin 5 vehicle.

From the perspective of exhaust emissions, the two most important monitoring requirements are those associated with catalyst efficiency and oxygen sensor performance. Although the OBD regulations specify that manufacturers must monitor "catalyst efficiency," the actual property being monitored is the "oxygen storage capacity" of the catalyst. Oxygen storage capacity in automotive catalytic converters is provided mainly by cerium. Catalyst monitoring strategies are based on the concept that high levels of oxygen storage capacity correlate with high HC conversion efficiencies and, on LEV II/Tier 2 vehicles, higher NOx conversion efficiencies. Catalyst monitoring systems rely on oxygen sensors placed upstream and downstream of the monitored catalysts to detect changes in the oxygen storage properties of the catalysts.

In general, oxygen storage is measured using one of two methods. The first method relies on the fact that the primary function of the front oxygen sensor is to facilitate the rapid switching of the air/fuel ratio necessary for stoichiometric operation and the sensor's output voltage switches rapidly between its rich and lean limits in a cyclic pattern. This cyclic pattern is caused by the variations in the oxygen content of the exhaust gas created with the shifting of the air-fuel ratio. Because oxygen is alternatively adsorbed (during lean conditions) and released (during rich conditions) as the exhaust gas passes through the catalyst, this results in a change in the oxygen content of the exhaust. Therefore, the response pattern of a sensor in or downstream of a catalyst with high oxygen storage is considerably different from that of the front sensor. Conversely, if the catalyst has little or no oxygen storage capacity, the downstream sensor response pattern is similar to that of the upstream sensor. This approach to catalyst monitoring is generally known as the dual oxygen sensor method.

Another approach to monitoring catalyst efficiency or engine fuel/air control based on oxygen storage involves the use of calibrated excursions to rich and lean conditions specifically for monitoring purposes. The delay period between the time at which an excursion is ordered or observed at the front oxygen sensor and the time at which it is observed at the rear oxygen sensor can be used to infer catalyst oxygen storage capacity. High oxygen storage capacity causes the delay period to be longer than it would be if there were little or no oxygen storage capacity. This approach to monitoring is generally known as the titration method.

In addition to catalyst monitoring, OBD monitoring must be performed for all of the oxygen sensors on a vehicle. The malfunction criteria require MIL illumination if the operating characteristics of the sensor have been degraded such that emissions of any pollutant exceed 1.5 times the applicable standard or if the sensor can no longer function adequately enough to be used for monitoring catalyst efficiency.

###

7. EARLY ASSESSMENTS OF THE IMPACT OF MMT® USE IN UNLEADED GASOLINE ON ENGINES, EMISSION CONTROL SYSTEM COMPONENTS, AND EMISSIONS

This chapter presents an overview of the studies and reports undertaken and published in the 1970s to early 1980s that investigated the impact of MMT® use in unleaded gasoline in 1970s-vintage vehicles.

As noted in Chapters 3, 5, and 6, in response to the need to comply with performance-based emission standards beginning with the 1975 model year, vehicle manufacturers introduced oxidation-type catalytic converters during the mid-1970s. In addition, manufacturers responded to California standards by equipping vehicles with three-way catalytic converters beginning in the late 1970s. The use of catalysts required the use of unleaded gasoline, and MMT® was considered as one means of making up the octane decrease associated with the elimination of lead from gasoline.

Given that the use of lead in gasoline was incompatible with catalytic converters, there were concerns from the outset regarding the use of another organo-metallic compound, MMT®. Test programs were therefore undertaken to study the issue, and the results were summarized in a number of technical papers published through the Society of Automotive Engineers. Based in part on data from early assessments of the impacts of MMT® use in unleaded gasoline on engines, emissions, and emission control components, concerns regarding the use of MMT® quickly developed. This culminated in the U.S. with the California Air Resources Board's July 1977 vote to ban the use of MMT® in unleaded gasoline, which was quickly followed by the changes to the federal Clean Air Act that effectively banned the use of MMT® in unleaded gasoline up until the mid-1990s. As noted previously, however, MMT® continued to be used in unleaded gasoline in Canada.

The early studies conducted on MMT® use in unleaded gasoline during the 1970s focused on the new vehicles and emerging emission control systems of the time, primarily oxidation catalysts and, later, three-way catalysts. Studies conducted by Ethyl Corporation, automobile companies, and cooperative research organizations focused mainly on the following:

1. The effect of MMT® use in unleaded gasoline on engine deposits, spark plug life, engine life, and engine-out emissions;

2. The effects of MMT® combustion products on catalysts and other emission control components; and

3. The effect of MMT® use on tailpipe emissions levels.

As discussed in detail in this chapter, these studies revealed a number of negative effects that were attributed to MMT® use at levels as low as 8.3 mg Mn/l. The main effects, which tended to increase with increasing MMT® content in gasoline, can be summarized as follows:

1. Formation of manganese oxide deposits in combustion chambers and on spark plugs, which increased engine-out HC emissions and, in many cases, tailpipe HC emissions; and

2. Physical plugging of catalytic converters by manganese oxides.

Other negative effects associated with MMT® use that were suggested by the early studies include spark plug fouling leading to misfire, degradation of oxygen sensor performance and durability on vehicles with closed-loop fuel management systems, and increases in PM emissions. The only positive effect of MMT® use reported in some studies was a reduction in the rate of deterioration of catalytic converter efficiency as vehicles accumulated mileage and catalysts aged. However, this effect was not large enough to result in identifiable improvements in tailpipe CO or NOx emissions, nor was it sufficient to offset the effects of the increase in engine-out HC emissions associated with MMT® use.

7.1 Overview of Early Studies of MMT® Impacts

As described below, data on MMT® impacts were generated during the 1970s from controlled laboratory studies, controlled vehicle studies, and observation of in-use fleet vehicles. The key findings are discussed in the next section of this chapter.

Ethyl Studies – Ethyl published four technical papers regarding the impacts of MMT® on the engines, emission control system components, and emissions from 1970s and earlier vehicles along with the waiver requests it filed with the U.S. EPA in 1978 and 1981. (See the discussion in Chapter 5.)

The first of these papers was published in 1975[77] and presented results from a number of studies that had been conducted between the late 1950s and the early 1970s. Most of the data presented in this paper were based on the use of MMT® at the level of 33 mg of Mn/l or higher, although there was some work done using MMT® at the level of 17 mg Mn/l. The impact of MMT® was evaluated using both engine dynamometer-based laboratory procedures, as well as fleets of vehicles that accumulated up to about 80,000 km on specified driving cycles using MMT®-containing and MMT®-free unleaded fuels. Test vehicles were usually equipped with oxidation-type catalytic converters employing either ceramic monoliths or ceramic pellets as supports. In general, vehicle testing was based on use of a number of vehicles of a given model that were operated in paired or triplet sets, with one set operated on a clear fuel and the other operated on MMT®-

containing fuel. MMT®-containing fuels were prepared by simply adding MMT® to the clear fuels used in the test programs. The addition of MMT® to otherwise clear fuels was the only change made in fuel composition, which allows MMT® impacts to be isolated from the impacts of other changes in fuel properties. In addition to investigating MMT® impacts on engines, emission control components, and emissions, some of the studies documented in this paper addressed the octane response of gasoline to the addition of MMT®, the likely ambient concentrations of manganese due to MMT® use in urban areas, and the health effects of exposure to manganese.

The second paper published by Ethyl in 1977[78] presented some of the same data addressed in the first paper, as well as data from additional studies of the impact of MMT® on engine-out and exhaust emissions and on emission control system components of fleets of 1972 to 1977 model-year vehicles that accumulated about 80,000 km of driving either as the result of normal in-use operation or by being operated over specified driving cycles. Again, vehicles were equipped with oxidation-type catalysts employing either ceramic monolith or ceramic pellet supports (see Figure 6-3 for an illustration). Fleet vehicles of a given model were generally operated in paired sets, with each set being operated on either a clear or an MMT®-containing fuel. The MMT®-containing fuels in the studies described in this paper had Mn levels of either 33 mg/l or 17 mg/l. Again, MMT®-containing fuels were prepared by simply adding MMT® to the same unleaded gasoline used as the clear fuel.

Ethyl's third paper, published in 1978,[79] presented additional data again focused primarily on the impacts of MMT® use on engine out and exhaust emissions as well as on emission control components. Most of the data presented were generated from fleets of 1970s model-year vehicles operated over specified driving cycles that had accumulated about 80,000 km using the same types of catalysts and experimental program designs employed in the previous Ethyl studies. The MMT®-containing fuels in the studies for which results were reported ranged from 33 mg of Mn/l at the upper end to a lower level that was extended downward for the first time in an Ethyl study from 17 mg of Mn/l to 8 mg of Mn/l. In addition, MMT® impacts on three-way catalytic converters and oxygen sensors were evaluated.

The fourth paper published by Ethyl in 1980[80] presented results of a statistical analysis of available data on MMT® impacts on engine-out hydrocarbon emissions and catalytic converter efficiency generated by Ethyl and other industry studies.

<u>Auto Industry and Joint Studies</u> − The first paper from an automobile manufacturer regarding the impacts associated with MMT® use in unleaded gasoline on engines, emissions, and emission control components was published by General Motors (GM) in 1977.[81] This study involved two 1976 and three 1977 model vehicles equipped with oxidation-type catalysts employing either ceramic monolith or pellet supports. The vehicles accumulated up to about 80,000 km driving on chassis dynamometers using either a clear fuel or the same fuel containing MMT® at concentrations ranging from about 9 to 33 mg Mn/l.

Two additional papers on MMT® impacts were published by GM during 1978,[82,83] as were papers from an automotive catalyst supplier, Matthey Bishop,[84] and a joint study published by employees of Ford, Amoco, and Standard Oil of Ohio.[85] One of the GM papers[83] and the Matthey Bishop paper presented results from engine dynamometer based studies where the test fuels used MMT® at concentrations ranging from about 5 to 33 mg of Mn/l in combination with oxidation-type ceramic monolith, ceramic pellet, and metal-supported catalysts. Another GM study[82] focused primarily on data from studies of fleet vehicles comparing four different models using either ceramic monolith or pellet-supported catalysts that accumulated up to about 80,000 km of operation on either clear or MMT®-containing fuels over several different prescribed on-road driving cycles. The MMT®-containing fuels were clear fuel to which MMT® had been added at levels equivalent to either 17 or 33 mg Mn/l. The cooperative study involved fleets of 1976 and 1977 model-year vehicles operated in-use as part of a roadside service fleet that accumulated mileage rapidly. These vehicles were equipped with monolith-supported three-way catalysts. The vehicles were all driven approximately 80,000 km. The MMT® fuel in this study was prepared by adding MMT® to one of the clear fuels used in the program at a concentration equivalent to 15 mg Mn/l.

Finally, in 1979, the results of an extensive research program conducted by the Coordinating Research Council (CRC) were published.[86] This statistically designed program involved 63 vehicles from seven different 1977 and 1978 model production vehicles that were grouped into triplet sets and operated on either a clear fuel or one of two MMT®-containing fuels. Five of the seven models were equipped with oxidation catalysts while the other two were equipped with three-way catalysts. The MMT®-containing test fuels were produced by simply adding MMT® to the clear base fuel at levels equivalent to 8 and 17 mg Mn/l. Test vehicles accumulated about 80,000 km by being driven on a test track following a specified driving cycle.

<u>Government Studies</u> − The U.S. EPA published a paper in 1975[87] that summarized the then-available information related to the impact of MMT® on emissions, catalysts, visibility, and public health. U.S. EPA also published a paper in 1979[88] that presented the results of a statistical analysis of the available data on MMT® effects on exhaust emissions. In addition, a paper was published by the New York State Department of Environmental Conservation in 1977[89] that reported on MMT®-related catalyst plugging observed on a limited number of police vehicles during normal in-use operation.

7.2 MMT® Impacts on Engines and Engine-Out Emissions

Studies performed by Ethyl as well as studies performed by others showed that MMT® use in unleaded gasoline had adverse impacts on engine-out HC emissions. There were no positive impacts reported for engines or engine-out emissions of CO or NOx due to the use of MMT®.

Specific findings included the following:

1. Increases in engine-out HC emissions were reported for vehicles using MMT®-containing fuels at concentrations ranging from 8 to 33 mg Mn/l by Ethyl in the 1977 and 1978 papers. The fact that engine-out HC emissions increase with the use of MMT® and that the magnitude of the increase increased with the MMT®

usage rate was confirmed by Ethyl in the statistical analysis presented in its 1980 paper. Higher engine-out HC emissions resulting from the use of MMT® were also reported by GM in its 1977 and 1978[82] papers addressing vehicle emissions, as well as by the CRC. These studies also involved MMT® usage rates ranging from 8 to 33 mg Mn/l and showed that the magnitude of the increase in engine-out HC emissions increased at higher MMT® usage rates.

2. Manganese oxide deposits were reported in combustion chambers and/or on spark plugs by Ethyl in its 1975, 1977, and 1978 papers. Misfire due to the accumulation of manganese oxides on spark plugs was reported in the 1975 paper. Combustion chamber and spark plug deposits consisting of manganese oxides resulting from the use of MMT®-containing fuels were reported by GM in 1977 and 1978.[82] Deposit removal resulted in a reduction in engine-out HC emissions. Spark plug function was reported to be impaired in some cases by the presence of manganese oxide deposits.

7.3 MMT® Impacts on Catalytic Converters

There were two consistent findings reported in the 1970s papers related to the impact of the use of MMT® in unleaded gasoline on catalytic converters: the plugging of both monolith and pelleted catalysts by manganese oxide deposits under certain conditions; and some reduction in the deterioration of catalyst efficiency over time, particularly HC conversion efficiency.

Catalyst Plugging – Catalyst plugging by manganese-based deposits was reported and studied by Ethyl during the 1970s, with the results discussed in Ethyl's 1975, 1977, and 1978 papers. Plugging was confirmed by both visual inspection as well as by use of flow tests, as it was in later work by Ethyl. In the earliest paper, plugging of close-coupled catalysts with monolith supports by manganese-based deposits was reported during engine dynamometer tests with a fuel containing MMT® at the 33 mg Mn/l level. Plugging was determined to be a physical rather than a chemical process. Additional study showed that moving the close-coupled catalysts further downstream from the engine (by 30 inches), keeping exhaust temperatures below about 800º C, and reducing the manganese content of the fuel to 17 mg Mn/l all reduced the incidence of plugging. This paper also reported that catalyst plugging was observed on vehicles equipped with close-coupled catalysts following 15,000 to 20,000 km of high-speed operation using MMT®-containing fuel at the 33 mg Mn/l level. It was reported that no plugging was observed for the pelleted converters studied.[*]

The 1977 Ethyl paper reported that plugging of converters using monolith supports could be minimized by reducing the MMT® content of gasoline from 33 mg Mn/l to 17 mg Mn/l, eliminating the use of close-coupled catalysts (this time by moving catalysts to at least 15 inches from the exhaust manifold), as well as by eliminating the use of

[*] Also mentioned in this paper is an "experimental additive A" that is reported to reduce manganese deposits on catalyst faces. However, this additive is not identified nor is it mentioned in the subsequent papers.

expansion chambers and/or incorporating parallel plate flow straighteners in the exhaust system upstream of converters. However, Ethyl provided no data regarding the impact of these changes on exhaust emissions levels in general or on the ability of the vehicles to comply with the exhaust emission standards they were designed to meet. This is a critical omission, as changes in the location of the converter and elimination of the use of expansion chambers would both be expected to result in increased emissions. For example, moving the converter further away from the engine would increase catalyst light-off time and cold start emissions, and elimination of expansion chambers would prevent uniform exhaust mixing and distribution throughout the catalyst.

The 1977 paper also reported problems with respect to plugging of pelleted converters, but these problems were dismissed by Ethyl as artifacts of the rapid mileage accumulation schedule used in the test program. The 1978 Ethyl paper reported that catalyst plugging was not observed during 80,000 km of operation on eight vehicles operated on fuel containing MMT® at 33 mg Mn/l nor at lower levels of MMT®.

Manganese-related plugging of both converters with ceramic pelleted and monolith supports was also reported in auto industry papers[81-84] when MMT®-containing gasoline was used. Plugging of both pelleted and monolithic catalyst converters is reported at MMT® levels in the range of about 5 to more than 33 mg Mn/l. In general, the results of these studies were similar to those reported in the Ethyl studies. As with the Ethyl studies, catalyst plugging was determined both visually and by flow testing.

Focusing on the more widely used monolith-type converters, the two engine dynamometer based auto industry papers[83,84] provide considerable detail regarding the physical processes associated with plugging. The paper published by Matthey Bishop reported that at a temperature of about 870º C, manganese plugging increased as the cell density of the monolith increased. Increasing cell density translates into decreasing flow area for each individual channel of the monolith. GM reported data showing that exhaust temperature and MMT® levels were significant factors with respect to catalyst plugging, with both higher exhaust temperatures and higher MMT® levels leading to increased problems with monolith plugging. The effect of MMT® concentration in the fuel was found to be linear, while the impact of temperature was found to be linear at temperatures above about 750º C and appeared to be non-linear below that temperature. The paper hypothesized a mechanism for monolith plugging based on the fact that the melting point of pure Mn_3O_4, the primary manganese oxide observed as a combustion product of MMT®, could be lowered by mixing with other materials in the engine exhaust to the point where the particles in the exhaust could actually be liquid droplets under certain high-temperature conditions. These droplets would then impinge and stick to the surface (rather than tending to bounce off as they would if they were solid) at the inlet end of the catalyst inlet. Given sufficient time, enough material would accumulate to block the cells of the monolithic converter.

Recently the data from the GM paper have been revisited and used to develop a mechanism that relates monolith plugging to MMT® concentration in the fuel, duration of operation on MMT®-containing fuel, the area of the individual cell openings on the face of the catalyst, and trapping efficiency of the monolith for manganese oxide particles, which is assumed to be a function of exhaust temperature.[90] This model, which is based on the theory that solid-state sintering of manganese oxide particles is the mechanism by which plugging occurs, predicts that plugging will increase linearly with increasing MMT® concentration, time of exposure to MMT®, and decreasing area of the monolith channel openings. Catalyst plugging is predicted to increase logarithmically with increasing temperature above a threshold temperature of 700º C, below which solid state sintering is not expected to occur.

Turning to the other studies, the U.S. EPA[87] reported plugging of a close-coupled catalyst by manganese oxides at temperatures greater than 760º C, attributed to testing performed by Ford. Plugging problems were also reported by the New York State Department of Environmental Conservation[89] on several 1975 model-year in-use police vehicles with monolith-supported catalysts that were operated on fuels containing as much as 55 mg Mn/l for what appears to have been a relatively short period of time. No catalyst plugging was reported from the CRC study with MMT® at levels of 8.3 and 16.5 mg Mn/l in vehicles for 80,000 km of operation nor from the cooperative study[85] of in-use fleet vehicles operated over 80,000 km on an MMT® fuel with 15 mg Mn/l.

Catalytic Converter Efficiency − The four Ethyl papers all address the issue of the impact of MMT®-containing fuels on catalytic converter efficiency for both HC and, to a lesser extent, CO conversion. All report that the use of MMT® in gasoline results in either a small increase in conversion efficiency or a somewhat lower deterioration in catalyst conversion efficiency over time as mileage is accumulated relative to that observed with clear fuel. Ethyl reported that this effect increased for HC conversion efficiency with increasing MMT® concentration up to 25,000 km, but that by 80,000 km MMT® concentration did not seem to be a factor.

Papers published by GM[81] and particularly by CRC[86] and a detailed post-mortem analysis of the catalysts from the CRC program[91] confirmed that MMT® use resulted in small improvements in the retention of catalyst efficiency for HC and CO conversion as mileage was accumulated. This effect was attributed to the scavenging of oil-derived catalyst poisons, particularly phosphorus and zinc, and residual Pb in unleaded gasoline by manganese oxide deposits on the inlet ends of monolith converters. However, the authors stressed that their findings held only so long as the manganese oxide deposits on the catalysts resulting from MMT® use were not heavy enough to cause mass transfer limitations that would lead to decreased catalyst efficiency.

7.4 MMT® Impacts on Other Emission Control System Components

The most notable adverse impacts associated with MMT® on other emission control system components observed during the 1970s studies were related to the oxygen sensors required for the early closed-loop emission control systems that were introduced in the late 1970s on California vehicles. The 1978 Ethyl paper indicated that the use of MMT® at the 17 mg Mn/l level had an adverse impact on oxygen sensor performance after as few as 16,000 km of operation, but this problem was not observed when the MMT® concentration was reduced to the 8 mg Mn/l level. The CRC study reported shortened oxygen sensor life in one vehicle model when MMT® was used at both the 8 and 17 mg

Mn/l levels relative to clear fuel, and MMT® was suspected of causing shortened sensor life in another vehicle model.

7.5 MMT® Impacts on Tailpipe Emissions

Turning to the issue of the impact of MMT® use on tailpipe emissions, in the 1977 paper Ethyl found that use of MMT® at the 33 mg Mn/l level results in higher exhaust HC emissions than with MMT®-free gasoline over the course of 80,000 km of vehicle operation, while also reporting that there was no impact on tailpipe emissions associated with the use of MMT® at 17 mg Mn/l. The 1975 paper reported lower CO emissions with the use of MMT® at 33 mg Mn/l, but this finding was not explained nor reported in the later Ethyl papers. The 1975 Ethyl paper also reported results from testing to assess the impact of MMT® use on PM emissions. Higher PM emissions were observed with MMT® at 33 mg Mn/l relative to MMT®-free fuel, but the differences were reported to be within the variability of the measurement procedure.

With respect to tailpipe emissions, the 1977 and 1978[82] GM papers and the two papers reporting on the cooperative studies[85,86] all reported higher tailpipe HC emissions in response to the use of MMT®-containing gasolines. The magnitude of the emissions increase was generally observed to increase as MMT® levels increased from 8.3 to 33 mg Mn/l. There were no discernible impacts of MMT® use on tailpipe CO and NOx emissions. Finally, limited data reported in the 1977 GM paper showed that MMT® use at 33 mg Mn/l resulted in PM emissions that were approximately double those observed with MMT®-free fuel.

Finally, as noted above, the U.S. EPA published the results of a statistical analysis in 1979[88] of the then-available data regarding MMT® impacts on vehicles, which included data submitted by Ethyl as part of its first waiver request. The published results of that analysis indicated that MMT® use did have an adverse impact on HC emissions at levels as low as 8.3 mg Mn/l. Based on this, the U.S. EPA concluded that MMT® use would result in, or contribute to, motor vehicles failing to comply with the HC emission standards to which they were certified. This analysis, like the others noted above, did not identify any effects of MMT® on CO or NOx emissions and the U.S. EPA did not consider PM emissions.

###

8. ASSESSMENTS OF THE IMPACT OF MMT® USE IN UNLEADED GASOLINE ON ENGINES, EMISSION CONTROL SYSTEM COMPONENTS, AND EMISSIONS ON 1980 TO MID-1990 MODEL-YEAR VEHICLES

This chapter presents an overview of the studies that investigated the impact of MMT® use in unleaded gasoline on 1980s to mid-1990s model-year vehicles.

Following the U.S. EPA's rejection in 1981 of Ethyl Corporation's second application for permission to use MMT® in unleaded gasolines in the U.S., there was little additional research published regarding the impact of MMT® on engines, emission control system components, and emissions until the late 1980s. As MMT® was not in use in the U.S. and Ethyl was not actively seeking a waiver allowing the use of MMT® from the U.S. EPA, discourse on this issue centered on whether the continued use of MMT® in gasoline could be tolerated as vehicle emission control technology evolved in Canada.[65,92]

Beginning in the late 1980s, however, there was a resurgence in research into MMT® impacts on engines, emission control system components, and emissions. This was due in large part to renewed efforts by Ethyl Corporation to secure a waiver that would allow the use of MMT® in gasoline in the U.S., as discussed in Chapter 5. In these new waiver requests, Ethyl proposed a maximum concentration of MMT® of 8 mg Mn/l.

The research programs conducted during this period involved studies of MMT® impacts on late 1980s to mid-1990s model-year vehicles (including some vehicles certified to CARB TLEV standards), as well as on individual emission control system components and OBD II monitoring strategies that were being developed at that time. The designs of these research programs were similar to those of the earlier programs described in Chapter 7. Several of these programs involved fleets of vehicles where subsets were operated on clear and MMT®-containing fuels. Others were laboratory-based studies of MMT® impacts on oxygen sensors, catalysts, and OBD II catalyst monitoring strategies. Research on MMT® impacts during the 1990s culminated with the Alliance-AIAM-CVMA vehicle test program that is the subject of Chapter 9 of this report.

As discussed in detail below, studies conducted on MMT® impacts in late 1980s to mid-1990s model-year vehicles generally show similar effects as those associated with the use of MMT® at higher concentrations in earlier model vehicles that were reviewed in Chapter 7. These include increased engine-out and tailpipe HC emissions with MMT® use and observations that the apparent catalyst conversion efficiency for some pollutants may be improved or deterioration slowed by the use of MMT®. Moderate reductions in tailpipe NOx emissions were also observed in some studies. Plugging of monolith-type converters by manganese oxides was observed on in-use Canadian vehicles as well as on vehicles in a Ford test fleet that accumulated 160,000 km on MMT®-containing fuel.

8.1 Overview of Studies of MMT® Impacts

As described below, data on MMT® impacts were generated from controlled laboratory studies, controlled vehicle studies, and, to a limited degree, the study of components from in-use vehicles operating on MMT®-containing fuels in Canada. The key findings are discussed in the next section of this chapter.

Ethyl Studies – Ethyl published a paper in 1990[93] that describes an MMT® evaluation program developed with input from the U.S. EPA involving 48 1988 model-year vehicles produced by Ford, GM, and Chrysler, each of which accumulated approximately 120,000 km over about 18 months on either a clear fuel or the same fuel containing MMT® at the 8 mg Mn/l level. The test fleet consisted of triplet sets of vehicles from eight models. FTP emissions testing, including PM measurements, was performed at 8,000 km intervals. In addition, the 1990 paper reports on a limited test program involving two vehicles that accumulated about 50,000 km under high-speed driving conditions on either a clear fuel or the same fuel containing MMT® at the 8 mg Mn/l level. A second paper was published in 1994 that reported on the results of laboratory studies of the catalyst properties and performance from some of the vehicles from the 48-vehicle test fleet[94] described in the 1990 paper. Another laboratory study of catalytic converters from some early 1990s model-year vehicles that accumulated 160,000 km of operation on a fuel containing MMT® at the 8 mg Mn/l level was published in 2000.[95]

Although not published in the technical literature, Ethyl also conducted fleet testing of 1992 and 1993 model-year vehicles over as much as 160,000 km of operation on either a clear fuel or the same fuel containing MMT® at the 8 mg Mn/l level[96] using triplet sets of vehicles as well as other test programs involving mid-1990 model-year vehicles.

Ethyl also published two papers regarding the impact of MMT®-containing fuels on the performance of OBD systems in 1994[97] and 1997.[98] The first of these involved laboratory study of catalysts and oxygen sensors removed from vehicles that had accumulated approximately 160,000 km of operation on either a clear fuel or a version of the clear fuel containing MMT® at the 8 mg of Mn/l level. The second also focused on laboratory testing of catalysts and oxygen sensors that had been aged in various ways, including through controlled on-road operation over 80,000 km on a fuel containing MMT® at the 8 mg of Mn/l level.

Finally, in 2002, Ethyl[99] published a paper reporting on the results of another study of three triplet sets of vehicles operated for 80,000 km on either one of two clear "reformulated" gasolines or a "reformulated" gasoline containing MMT® at the 8 mg Mn/l level. FTP emissions were measured during the mileage accumulation period and testing of each set of vehicles on a number of reformulated fuels, some containing MMT® at the 8 mg Mn/l level, was performed following the mileage accumulation period.

Auto Industry and Cooperative Studies – Ford Motor Company published five papers related to MMT® use during the late 1980s and early 1990s. The first of these papers, published in 1989,[100] described the results of the laboratory characterization of catalysts removed from nine 1984–1986 model-year in-use Canadian vehicles. The catalysts examined in the study had been replaced under warranty after customer operation ranging from 35,000 to 70,000 km. The then Chrysler Corporation also investigated MMT® impacts on catalysts from in-use vehicles replaced under warranty in Canada during this period.[101]

The next three Ford papers published during 1991[102,103] and 1992[104] reported results from a fleet study of eight test vehicles. There were four vehicles from each of two 1991 Ford models, Escort and Explorer, equipped with prototype engines and emission control systems being evaluated for use in 1993 model-year vehicles. The experimental design of this study was based on paired sets of vehicles operated on either a clear fuel or the same fuel containing MMT® at the 8 mg Mn/l level. The vehicles accumulated 160,000 km through on-road operation on either the clear or MMT®-containing fuel. FTP emissions measurements included engine-out and PM emissions, and laboratory studies were conducted to evaluate MMT® impacts on catalysts and other emission control system components.

The final Ford paper during this period was published in 1993[105] and presented the results of a laboratory study of the effects of MMT® use on the performance of OBD II catalyst efficiency monitoring systems.

Government Studies − There were only two government studies (other than those U.S. EPA studies related to analysis of data contained in Ethyl's various waiver requests) during this period. The first of these was an assessment of the impact that the use of MMT® would have on vehicles certified to Tier 0 emission standards conducted by a work group of the Canadian General Standards Board Petroleum Committee at the request of Environment Canada. The potential impacts of MMT® on Tier 0 vehicles were assessed using data from the CRC study described in the previous chapter and low mileage testing of 15 in-use 1983 to 1985 model-year Canadian vehicles calibrated to comply with the Tier 0 standards. The other study was a U.S. EPA sponsored laboratory evaluation[106] of MMT® impacts on catalyst conversion efficiencies at an MMT® level equivalent to 17 mg of Mn/l.

8.2 MMT® Impacts on Engines and Engine-Out Emissions

None of the Ethyl studies described above addressed the issue of MMT® impacts on engines or engine-out emissions. The Ford fleet study involving the Escort and Explorer models described in the 1991 and 1992 papers showed that MMT® use, at 8.3 mg Mn/l, caused a substantial increase in engine-out HC emissions relative to the clear fuel vehicles. The magnitude of this emissions increase was observed to increase with increasing vehicle mileage (i.e., greater accumulation of manganese oxides resulting from MMT® combustion). Data regarding effects on engine-out CO and NOx emissions were inconclusive, again consistent with the results from earlier studies.

8.3 MMT® Impacts on Catalytic Converters

Catalyst Plugging – The results of the 48-vehicle fleet study described in the 1990 Ethyl paper[107] included catalyst backpressure data for 42 of the 48 vehicles. All of the vehicles that were not monitored were from the same model (model F), the only model indicated as having close-coupled catalysts. The reason for the lack of monitoring on these vehicles was stated to be that "this model was not equipped with a pressure gauge tap." The results presented indicated that no catalyst plugging had occurred over the course of the 120,000 km of operation. However, no data regarding exhaust or catalyst temperatures were collected and it is not known whether temperatures on these models reached the 800º C range over the driving cycles used in the Ethyl study. As noted in the previous chapter, catalyst temperatures on the order of 800º C or higher were established by research performed during the 1970s as being correlated with the plugging of catalysts by manganese oxides.

Also described in the 1990 Ethyl paper was an evaluation of plugging on the model F vehicles for which backpressure was not monitored during the fleet testing. In this case, however, only two vehicles were used—one operated on clear fuel and one on the same clear fuel containing MMT® at the 8 mg Mn/l level. In addition, these were rental vehicles, not vehicles from the 48-vehicle test fleet that were equipped with pressure taps. Backpressure was observed over only 50,000 km (as opposed to the 120,000 miles of operation by the fleet vehicles) of "high speed" operation on both vehicles and no catalyst plugging was reported. Once again, no data regarding exhaust or catalyst temperatures were collected.

One of the 1994 Ethyl papers[94] presented results from laboratory studies of core samples of some of the catalysts from the 48-vehicle test fleet described in the 1990 paper. In addition, similar results were presented for core samples of catalysts removed from two paired sets of 1991 Ford Escorts that accumulated about 40,000 km on either a clear fuel or a fuel containing MMT® at the 8.3 mg Mn/l level. The goal of this study was to examine whether manganese oxides plugged the pores of the catalysts, in contrast to the gross physical plugging of monolith channels reported in previous studies. Based on measured catalyst conversion efficiencies and surface area measurements of the catalysts from the clear fuel and MMT® vehicles, the authors concluded that plugging of catalyst pores by manganese oxides did not occur. However, as noted above, no catalyst temperature data were collected for the vehicles in the 48-vehicle fleet and none were reported for the 1991 Ford Escorts described in this paper.

Later Ethyl studies of 1992-1993 model-year vehicles that accumulated up to 160,000 km of operation on MMT®-containing fuel at 8 mg Mn/l, and one 1997 model-year vehicle that accumulated 80,000 km, also on a fuel containing 8 mg Mn/l, did not report any incidences of catalyst plugging. However, none of these studies provided any data regarding catalyst temperatures experienced by the test vehicles during the studies.

In its 1989 paper, Ford reported, based on visual examination, light to moderately heavy manganese oxide plugging of the channels of monolith-type catalysts removed from in-use Canadian vehicles after 22,000 to 43,000 km of operation. Manganese oxide plugging of monolith channels was also reported based on visual examination by Ford in its 1992 paper describing the Escort/Explorer fleet study. Plugging of the close-coupled catalysts of the Escorts was described as more severe than that observed on the faces of the under-floor catalysts of the Explorers. No catalyst plugging was reported for the clear-fuel Escorts or Explorers.

As noted above, Chrysler Corporation conducted an evaluation involving visual inspection of 400 catalysts removed from in-use Canadian vehicles and replaced under warranty by Chrysler, and reported physical plugging of the inlet ends of monoliths that ranged from minor to severe.

<u>Catalytic Converter Efficiency</u> – The 1990 paper published by Ethyl addresses the issue of catalyst conversion rate for seven of the eight models in the 48-vehicle fleet. Catalyst conversion efficiency was evaluated for some of the vehicles involved in the 48-vehicle fleet in one of the 1994 Ethyl papers.[94] However, only averaged differences in conversion efficiencies were presented and only the differences for one model were claimed to be statistically significant—in that case, the results suggested that efficiencies were higher for the catalyst exposed to MMT®. However, this comparison was based on catalysts for only two vehicles—one clear fueled and one MMT® fueled—and the results are further obscured by the fact that while each vehicle had two catalysts, no information was provided as to how the differences in catalyst efficiencies were averaged. Despite the substantial issues associated with the data from the 48-vehicle test fleet, Ethyl purported that the use of MMT® reduces catalyst exposure to oil-borne catalyst poisons.

The other 1994 Ethyl paper[97] presented catalyst conversion rate data for ten 1992 and 1993 model-year vehicles from two models involved in that fleet study. Higher catalyst conversion rates were generally reported for vehicles that operated on MMT®, but again it must be stressed that conversion rate data are not appropriate for use in evaluating the impacts of MMT® use on catalyst performance. Catalysts from these vehicles were also subjected to laboratory evaluation, and an analysis of those data was published by Ethyl in 2000. The data show much lower levels of phosphorus deposition on catalysts from vehicles using MMT®-containing fuels relative to catalysts from clear fuel vehicles. The paper presents correlations of differences in what is described as catalyst "inefficiency" between catalysts from MMT® and clear fuel vehicles with differences in deposited phosphorus levels. The authors conclude that MMT® combustion products bind phosphorous in the form of manganese phosphates, minimizing phosphorus deposition on catalysts and reducing the degree of deterioration in conversion inefficiency as mileage is accumulated. However, the data upon which these conclusions were based are again catalyst conversion rates, which are not appropriate for use in rigorously evaluating the impacts of MMT® on catalyst performance relative to clear-fueled vehicles.

Ethyl's 2002 paper also showed that the use of MMT®-containing fuel over 80,000 km resulted in reduced deterioration of catalyst conversion efficiency on a 1997 model-year Ford model relative to non-MMT®-containing fuels. Once again, this finding was based on inappropriate comparisons of averaged catalyst conversion rates rather than actual conversion efficiency measurements.

The effects of MMT® use on catalyst conversion efficiency from newer vehicles were evaluated in Ford's 1989 paper that presented results from a study of catalytic converters taken from in-use Canadian vehicles.[103] In this laboratory study, in-use converters exposed to MMT® exhibited reduced catalyst efficiency for HC, CO, and NOx compared to a similar laboratory-aged catalyst that had not been exposed to MMT® combustion products. However, it is not clear, in comparing the laboratory-aged, MMT®-free catalyst with the in-use catalysts exposed to MMT®, that all relevant factors that could impact the results were properly taken into account.

The Ford study of Escorts and Explorers documented in Ford's 1991 and 1992 papers also assessed the impact of MMT® on catalyst performance. Although catalyst efficiency was not directly determined, tailpipe HC emissions were observed to increase on vehicles that accumulated mileage on MMT®-free fuels when their catalysts were replaced by those from the vehicles that accumulated mileage on the fuel with MMT®. Similarly, the reverse procedure (i.e., MMT® vehicles with MMT®-free catalysts) generally resulted in lower tailpipe HC emissions. Results for CO were varied, but there was a trend toward lower tailpipe NOx emissions with the MMT®-exposed catalysts.

The U.S. EPA laboratory study of MMT® impacts on catalytic converters reported a degradation of NO conversion efficiency with MMT® use and no impact on HC and CO conversion efficiencies.

8.4 MMT® Impacts on Other Emission Control System Components

The studies of MMT® impacts during this period also focused on MMT® impacts on oxygen sensors and the performance of OBD II monitoring systems particularly as they relate to engine misfire and catalyst efficiency monitoring.

The 1990 Ethyl paper purported to demonstrate that MMT® has no impact on oxygen sensor performance by conducting emissions tests after replacing the sensor in the most stable vehicle operated on MMT®-free fuel with sensors from each of the other five vehicles. Testing was performed on MMT®-free fuel, and the results showed no statistically significant difference in tailpipe emissions when comparing oxygen sensors from the MMT® vehicles with those from the MMT®-free vehicles. While these results indicate that oxygen sensor function was not severely impaired, it would have been more meaningful if sensor performance had been evaluated based on changes in engine-out, rather than tailpipe, emissions. Furthermore, it is difficult to understand why such data were not presented since engine-out emissions were measured in order to estimate catalyst efficiency. There was no evaluation of MMT® impacts on OBD II systems in this study as none of the eight models were equipped with such systems.

Ethyl's 1994 paper[97] reporting on the impact of MMT® on several models of 1992 and 1993 model-year vehicles dealt with both MMT® impacts on oxygen sensors as well impacts on the efficacy of an OBD II catalyst monitoring strategy. As discussed in Chapter 6, OBD II catalyst monitoring systems do not actually monitor the catalyst efficiency, but rather catalyst oxygen storage capacity. Given this and the fact that manganese oxides have been shown to have limited oxygen storage capacity, the potential of MMT® use to effectively mask actual catalyst deterioration from detection by the OBD II system has been a major concern.

In this paper, the fact that oxygen sensors are not adversely impacted by MMT® use was again purported to be demonstrated by comparing tailpipe emissions results from MMT®-exposed sensors to those from sensors exposed only to MMT®-free fuel on vehicles otherwise operated exclusively on MMT®-free fuel. Again, it would have been more instructive to include comparisons of engine-out and tailpipe emissions. With respect to OBD systems, the results were purported to show that manganese oxides deposited on catalytic converters have no impact on either the oxygen storage properties of the catalysts or the ability of OBD catalyst monitors to identify degraded catalysts.

MMT® effects on oxygen sensors and OBD II monitoring systems were again evaluated in Ethyl's 1997 paper. Based on data collected from static response testing of sensors exposed to MMT® and clear fuels, Ethyl concluded that MMT® exposure does not alter the operation of oxygen sensors because the switch point of the sensor was the same on aged sensors regardless of exposure to MMT®. However, no data were presented from other methods used to characterize oxygen sensor performance, which include dynamic response testing and an evaluation of sensor response rates. With respect to OBD systems, Ethyl used a somewhat different approach from that used in the 1994 paper, but the results are again represented as indicating that manganese oxides do not alter catalyst oxygen storage properties or the ability of the OBD catalyst monitoring strategies to detect degraded catalysts. There are some issues associated with the data presented in the 1997 paper. First, the "degraded" catalysts used in this study had high conversion efficiencies and should not have been identified as being defective by the OBD II system. Second, the laboratory aging process used by Ethyl to degrade catalysts did not appear to be representative of in-use aging because the laboratory-aged catalysts had far lower oxygen storage capacities at a given level of conversion efficiency than did catalysts from in-use vehicles examined by Ethyl. Therefore, the relevance of the laboratory-aged catalysts is questionable. Finally, the only truly "degraded" catalysts examined by Ethyl were "dummy" catalysts without washcoats or noble metals, which means that the efficiency and oxygen storage capacity of the catalysts were either zero or very near zero. In order for the OBD II system to be "fooled" by MMT® in this case, the amount of oxygen storage resulting from the accumulation of MMT® combustion products on the catalyst supports would have to approach that of a fully formulated catalyst (i.e., with washcoat and noble metals) with a high HC conversion efficiency. Therefore, using this procedure, MMT® would be found to adversely impact the OBD catalyst monitor only if there were a large increase in oxygen storage capacity.

Ethyl's 2002 paper noted that there were no emission-related problems identified by the OBD II system present on the 1997 model-year vehicles used in this test fleet using either clear fuels or MMT®-containing fuels.

Ford's 1992 paper describing the Escort/Explorer fleet evaluated the impacts of MMT® use on oxygen sensors using component switching. Oxygen sensor exchange led to inconsistent changes in engine-out levels on both the paired sets of Escorts and Explorers.

With respect to OBD II systems, Ford's laboratory study of MMT® impacts on oxygen storage published in 1993 showed that Mn_3O_4 could be reduced under conditions commonly encountered in automotive exhaust streams and that the additional oxygen storage capacity provided by Mn_3O_4 could lead to a situation where the substantially degraded catalysts were not detected by the monitoring system. Oxygen sensor response data were also presented to confirm that manganese oxides were in fact providing additional oxygen storage capacity.

8.5 MMT® Impacts on Tailpipe Emissions

Data published in 1990 from Ethyl's 48-vehicle fleet study showed that there was a statistically significant increase in HC emissions and a statistically significant decrease in NOx emissions due to the use of MMT® at the 8 mg Mn/l level. The difference in tailpipe CO emissions was not statistically significant. Particulate emissions were also measured and are discussed below.

The 22-vehicle fleet study conducted by Ethyl, for which data were published in 1994,[97] showed tailpipe emissions results similar to those of the 48-vehicle fleet study wherein higher tailpipe emissions of HC and lower tailpipe emissions of CO and NOx were observed for the vehicles using gasoline with MMT®. However, no statistical analyses of the data were presented.

Tailpipe emissions data from the 1997 model-year vehicles that were the subject of Ethyl's 2002 paper showed higher tailpipe HC emissions for the MMT® fleet and lower CO and NOx emissions with MMT® after 80,000 km of operation. These differences were, in general, statistically significant at the 95% confidence level.

Of the auto industry studies, only the Ford Escort/Explorer study addressed the impact of MMT® use on tailpipe emissions. The results presented in Ford's 1992 paper showed that tailpipe HC emissions were substantially higher for the MMT® vehicles and that the results was statistically significant at the 95% confidence level. The impact of MMT® use on tailpipe CO and NOx emissions was variable and not statistically significant. Particulate emissions were also measured on these vehicles and those results are discussed below.

The CGSB study of MMT® impacts on Tier 0 vehicles concluded that MMT® use would increase HC emissions by between 0.03 and 0.11 g/mi (relative to the Tier 0 standard of 0.41 g/mi). For comparison, today's Tier 2 Bin 5 vehicle is certified not to exceed 0.075 g/mi through 50,000 miles. The CGSB study characterized this increase in HC emissions as representing a "miniscule" increment in atmospheric HC levels, and expressed the opinion that continued MMT® use would not compromise vehicle emissions control system operation or component durability. It also recommended a re-examination of MMT® use in Canadian unleaded gasoline should the adverse impact of MMT® use be greater than recognized at the time the report study was performed.

As noted above, the impact of MMT® use on particulate emissions was studied as part of the work reported in the 1990 Ethyl paper as well as one of the 1991 Ford papers.[100]

While the magnitude of the total particulate emissions measured from the vehicles in both studies was similar, there were fundamental differences in the results. The Ethyl paper reported that total particulate emissions were about 50% lower from vehicles using MMT®-containing gasoline relative to MMT®-free gasoline and that only about 0.4% of the Mn in the fuel consumed by the vehicle was emitted from the tailpipe as particulate matter. In contrast, the Ford study found that total particulate emissions were about two times higher from the vehicles using gasoline with MMT® and that emissions of manganese particles increased with increasing mileage accumulation on the MMT®-containing fuel. In addition, in this study, between 5 and 45% of the manganese consumed by the engine was found to be emitted as particulate matter.

###

9. ALLIANCE-AIAM-CVMA MMT® VEHICLE TEST PROGRAM

During the latter part of the 1990s, a large-scale test program was conducted in two parts[108,109] by the North American automobile industry to investigate the impact of the use of MMT®-containing gasoline on the engine and emission control system components and the emissions of the new vehicle fleet of the time. The study was sponsored by the Alliance of Automobile Manufacturers (Alliance and its predecessor the American Automobile Manufacturers Association [AAMA]), the Association of International Automobile Manufacturers (AIAM), the Canadian Vehicle Manufacturers Association (CVMA), and individual vehicle manufacturers, and is referred to here as the Alliance-AIAM-CVMA study. The objectives, design, execution, and results of both parts of the Alliance-AIAM-CVMA study are summarized in this chapter.

9.1 Summary of Study Objectives, Design, and Execution

The basic design of the study involved the on-road accumulation of mileage on a number of sets of four identical new vehicles of a given make and model under highly controlled conditions. Two of the four vehicles in each set were operated on MMT®-free gasoline (referred to as "clear fuel") and the other two were operated on a gasoline containing MMT® at the 8 mg Mn/l level (referred to as the "additive" fuel). These two fleets were closely monitored over the course of 80,000 to 160,000 km of operation and subjected to engine-out and exhaust emissions tests at regular intervals during mileage accumulation. After mileage accumulation had been completed, additional testing of various types was performed to determine the impact of the use of MMT®-containing fuels on individual emission control system components as well as combinations of components and complete engine and exhaust systems.

Study Objectives – As indicated in reference 108, the purpose of Part 1 of the Alliance-AIAM-CVMA fleet study was to investigate the impacts of the use of MMT®-containing gasoline on engine and emission control system components as well as emissions from fleets of vehicles with emission control systems certified to Tier 1, CARB TLEV, and CARB LEV emission standards that were also equipped with OBD II systems.

To quote reference 108,

> *Specifically, the program was statistically designed to determine whether or not MMT causes vehicle emissions to change or has any effect on engine component durability or OBD II systems. Among the questions the program seeks to answer are the following:*

- *Does MMT cause vehicle emissions to increase and/or impair the performance of any emission control device?*
- *Does MMT cause spark plugs to misfire?*
- *Does MMT degrade oxygen sensor performance?*

The purpose of Part 2 of the Alliance-AIAM-CVMA study was generally the same, but the vehicles included in the program all had emission control systems designed to comply with CARB LEV I emission standards. Vehicles designed to comply with the CARB LEV I standards were chosen because they were equipped with the most advanced emission control technology available at the time.

Statistical Study Design − The Alliance-AIAM-CVMA study was designed by a statistician under contract to the study sponsors. Data from previous studies investigating the effect of MMT® on vehicle emissions were used to evaluate vehicle-to-vehicle variability in emission test results. Based on this evaluation, it was determined that four vehicles subdivided into two matched pairs subjected to identical operating conditions, with one vehicle in each pair operating on clear fuel and the other operating on fuel with MMT®, would be required.

Using these same data, as well as data on test-to-test variability from previous studies, statistical power calculations were made to determine the number of pairs of vehicles and replicate emissions tests that would be required to detect different changes in mean emission levels between fleets of vehicles operated on MMT® and on clear fuel. Using an iterative process with input from the project sponsors, a design involving ten vehicle models, two pairs of vehicles from each model, and duplicate emission tests of each vehicle at each mileage point was selected.

The predicted power of the experimental design for Part 1 of the program is summarized in Table 9-1, which was developed from reference 108. The power of the experiment can be observed from the probability of detection of the differences in mean emissions of the MMT® and clear fleets shown in Table 9-1. For example, the probability that a difference in the mean HC emissions of the MMT® fleet of 0.05 grams per mile could be determined to be statistically significant at the 95% confidence level at both 8,000 and 80,000 km of testing was greater than 99%. Also shown in Table 9-1 are the actual mean clear fleet emissions at 6,500 and 80,000 km.[*] These values, which were obviously not available at the time the experiment was designed, are provided so that the magnitude of the differences in mean emissions used in designing the study can be put into better perspective. As shown, the differences in mean emissions used in designing the study generally reflect increases in emissions of 50% or more from the observed mean clear fleet emissions levels of each pollutant. This same basic experimental design was used for the Part 2 test program.

[*] For reasons that are not explained, the statistical analysis was performed at 5,000 miles while baseline emissions testing was performed at 4,000 miles.

Table 9-1
Power of the Alliance-AIAM-CVMA Test Program to Detect Changes in Emissions Due to the Use of MMT®[a]

Pollutant	Clear-Fleet Mean Emissions at 6,500 km	Clear-Fleet Mean Emissions at 80,000 km	Difference in Mean Emissions of the MMT® and Clear Fleets	Probability of Detection at 8,000 km	Probability of Detection at 80,000 km
HC	0.070	0.088	0.03 g/mi	0.93	0.89
HC	0.070	0.088	0.05 g/mi	>0.99	>0.99
CO	0.824	1.166	0.5 g/mi	>0.99	0.99
CO	0.824	1.166	1.0 g/mi	>0.99	>0.99
NOx	0.139	0.178	0.04 g/mi	0.80	0.66
NOx	0.139	0.178	0.08 g/mi	>0.99	0.99

[a] Based on Table 1 and Table 4 of Part 1 report of reference 108.

The design of the Alliance-AIAM-CVMA study was subjected to a review by Robert Maxwell, former Director of the U.S. EPA's Certification Division and an independent consultant on issues related to mobile source emissions, under contract to the study sponsors.[110] Maxwell stated:

> *The program design of using vehicles operating in pairs, receiving simultaneous and identical treatment is a power technique which will minimize variables and should allow statistically significant conclusions.*

and:

> *The significance of the actual detectable difference will depend on the actual test results and variance seen in the emission testing of this program. However, from an experimental design perspective, the task force appears to have a rational basis for its sample size selection.*

The design of the Alliance-AIAM-CVMA study was also reviewed by Ethyl Corporation.[111] Ethyl Corporation offered no direct criticism of the study design other than to state that the study was not based on "sound engineering and statistical principles" because it was not consistent with recommendations that the study sponsors had previously made with respect to the design of Ethyl test programs intended to investigate the effects of MMT®.

One point raised obliquely by Ethyl at this stage, and more directly after the completion of the study, was that the design should involve three or four vehicles per model operated on both the MMT® and clear fuels. However, this recommendation was based on previous comments from the study sponsors directed at previous studies of MMT® impacts that had not used the paired design developed for this study. There was no information provided by Ethyl that addressed how the power of the study would be improved by the addition of more test vehicles or that demonstrated that the improvement in power would have been commensurate with the higher cost of the study, which would have increased proportionally to the total number of test vehicles.

9.2 Execution of Part 1 Study

The Part 1 study was executed according to a protocol developed by the study sponsors. The protocol was also reviewed by Robert Maxwell prior to the commencement of the testing. He concluded:

> *The emission testing program is well thought out and should be able to allow credible conclusions to be drawn regarding the differential effect of MMT on emissions. While no major improvements are recommended in the technical design of the program a few recommendations are made for consideration . . . to improve the quality control aspects of the program and better defend the program's end results.*

According to reference 108, "*several of those recommendations* . . . *were implemented and documented*"* in the study protocol. The general execution of the study following that protocol is described below.

Part 1 of the Alliance-AIAM-CVMA study involved ten types of new 1996 and 1997 model-year vehicles produced by five different vehicle manufacturers and equipped with the most advanced emission control technology in use at that time**.** As noted above, four vehicles of each model type were included in the program, for a total of 40 test vehicles. Each set of four vehicles was randomly divided into two vehicle pairs, with one vehicle in each pair being operated on a gasoline containing MMT® at the 8 mg Mn/l level and the other on MMT®-free fuel. The vehicle operating on Mn-containing fuel was given a designation of AEXY, where X is the model designation number of the vehicle (0 through 9 for the ten models) and Y denotes the pair (either 1 or 2). Clear-fuel vehicles were similarly denoted using a designation of the form CEXY. Vehicle mileage accumulation with clear or Mn-containing fuel commenced after the initial "zero mile" FTP emissions testing.

Two models were certified to Tier 1 emission standards, seven to CARB TLEV emission standards, and one to CARB LEV emission standards. Six models had four-cylinder engines, three models had V-6 engines, and one model had a V-8 engine. The vehicles were all equipped with varying numbers of catalysts in close-coupled (CC) and/or under-floor (UF) locations. All catalysts used ceramic monoliths with cell densities of 400 cells per square inch. All ten models were equipped with on-board diagnostic systems that complied with CARB OBD II regulations. The characteristics of the ten models are summarized in Table 9-2.

Table 9-2
Summary of Part 1 Test Vehicle Characteristics

Mfr	MY	Model	Engine	Catalyst	Std.
DC	1996	Neon (0)[a]	2.0L L4	CC	TLEV
DC	1996	Intrepid (1)	3.3L V6	2-CC	TLEV
DC	1996	Caravan (2)	3.3L V6	CC	TLEV
Ford	1997	Escort (3)	2.0L L4	CC	TLEV
Ford	1996	Crown Victoria (4)	4.6L V8	2-CC+2-UF	TLEV
GM	1997	Saturn (5)	1.9L L4	CC+UF	TLEV
GM	1997	Cavalier (6)	2.2L L4	UF	TLEV
GM	1996	S10 Blazer (7)	4.3L V6	UF	Tier 1
Honda	1996	Civic (8)	1.6L L4	CC	LEV
Toyota	1996	Corolla (9)	1.8L L4	UF	Tier 1

[a] Number in parenthesis denotes the model designation number in Part 1 of the Alliance-AIAM-CVMA study.

* See page 10 of reference 108.

FTP emissions testing* of all vehicles was performed prior to any mileage accumulation and then at intervals of about 6,500; 24,000; 40,000; 56,000; and 80,000 km. Emissions testing that used the U.S. EPA Cold CO procedure was also conducted at 80,000 km. The Honda Civics (model designation number 8) were also tested after 120,000 km of mileage accumulation.† At least two emissions tests were performed on each vehicle at each test point, and in some cases a third test was conducted based on the application of a statistically based protocol. FTP emissions testing at all points was performed using California Phase 2 certification test fuel, which does not contain MMT®. FTP emissions tests at 6,500 and 80,000 km were also performed using the certification fuel (known as Indolene) specified by U.S. EPA in federal regulations, which also does not contain MMT®. The use of MMT®-free test fuel in all vehicles means that any differences in emissions performance between vehicles would be solely related to vehicle performance and not the fuel use at the time of testing. In addition to standard tailpipe emission measurements, engine-out emission measurements‡ were made during FTP emissions testing. Analysis of the engine out and tailpipe emissions data also allowed the calculation of catalyst conversion efficiencies for HC, CO, and NOx.

Mileage accumulation was conducted on a test track using a version of an EPA proposed driving schedule for mileage accumulation known as the "Standard Mileage Accumulation" (SMA) cycle modified in response to concerns raised by Ethyl Corporation.[112] This cycle involves a number of moderate and light acceleration events and high-speed cruise operation. Both vehicles of a given pair were driven on the test track at the same time and mileage accumulation of both vehicles was halted during emissions testing. Mileage accumulation for both vehicles in a given pair was also halted if the malfunction indicator light (MIL) of the OBD II system turned on or if either vehicle needed service or repair. Once every 1,600 km the vehicle was stopped for an eight-hour period and then restarted. During this period, data from the vehicle's OBD II system were obtained and recorded. The same regular unleaded gasoline with and without the addition of MMT® was used during all mileage accumulation.

At the end of 80,000 km of accumulated operation, one pair of vehicles from models with designation numbers 0, 2, 3, 5, 6, and 7 (see Table 9-2) were subjected to post-mortem analysis. This included inspection of components and FTP emissions testing following interchange of emission control system components from clear to additized fuel vehicles and vice versa, as well as after the removal of combustion chamber deposits.

9.3 Execution of Part 2 Study

Part 2 of the Alliance-AIAM-CVMA study involved four different types of 1998 and 1999 model-year vehicles produced by four different vehicle manufacturers, which again were equipped with the most advanced emissions control technology available in-use at the time. All four models were certified to CARB LEV emission standards and equipped

* Tailpipe emissions of total hydrocarbons (THC), NMHC, NMOG, CO, NOx, and CO_2 were measured.
† Mileage accumulation was extended on these vehicles because NMOG emissions of both additive vehicles exceeded the 50,000-mile LEV certification emission standard while emissions of both clear-fueled vehicles did not.
‡ Engine-out emissions of THC, CO, NOx, and CO_2 were measured.

with OBD II systems. As with the Part 1 program, four vehicles of each model type were included in the program, for a total of 16 test vehicles. Again, each set of four vehicles was randomly divided into two vehicle pairs, with one vehicle in each pair being operated on a gasoline containing MMT® at the 8 mg Mn/l level and the other on MMT®-free fuel. The vehicle operating on Mn-containing fuel was given a designation of AEXY, where X is the model designation number of the vehicle (0 through 3 for the four models) and Y denotes the pair (either 1 or 2). Clear-fuel vehicles were similarly denoted using a designation of the form CEXY. The characteristics of the four models included in the Part 2 program are summarized in Table 9-3.

Table 9-3
Summary of Part 2 Test Vehicle Characteristics

Mfr	MY	Model[a]	Engine	Catalyst	Std.
DC	1998	Breeze (0)	2.0L L4	CC	LEV
Ford	1998	Escort (1)	2.0L L4	CC	LEV
GM	1999	Tahoe (2)	5.7L V8	2-UF	TLEV
VW	1999	Beetle (3)	2.0L L4	UF	LEV

[a] Number in parenthesis denotes the model designation number in Part 2 of the Alliance-AIAM-CVMA study.

Execution of the Part 2 study was identical to that of the Part 1 study, with the following exceptions:

1. FTP emissions testing of all vehicles was also performed after 120,000 and 160,000 km of operation;
2. All emission testing was performed with California Phase II certification fuel;
3. No emissions testing was performed using the U.S. EPA Cold CO procedure; and
4. OBD II system data were not collected at 1,600 km intervals.

Also, as discussed below, component inspections and post-mortem FTP emissions testing were not performed as part of the Part 2 test program, but such testing was later performed by Ford on one pair of the Escort vehicles and, subsequent to the Part 2 test program, some of the test vehicles from the program were subjected to emissions testing that included measurement of particulate emissions.

9.4 Ethyl Corporation Criticism Regarding the Execution of Part 1 and Part 2 of the Alliance-AIAM-CVMA Study

Following the completion of the Alliance-AIAM-CVMA study, Ethyl Corporation published critical analyses of the Alliance-AIAM-CVMA study.[113,114] Criticisms related to the execution of the studies were as follows:

1. The addition of MMT® to the same regular unleaded gasoline used as the "clear" fuel, which resulted in the MMT®-containing fuel having a higher octane rating than the clear fuel;
2. The use of "uneven" maintenance practices on test vehicles during the execution of the study;
3. The use of the modified SMA driving cycle for mileage accumulation; and
4. Failure to break in vehicles through operation on clear fuel for about 6,500 km prior to the use of any MMT®-containing fuel.

These criticisms have been addressed recently by MacKay and Benson.[115] With respect to the first criticism, MacKay and Benson note that the higher octane of the MMT®-containing fuel would not be expected to increase emissions[*] or adversely affect engine or emission control system components. Further, as alluded to by MacKay and Benson, equalizing the octane rating of the MMT®-containing and clear fuels would have required that the MMT®-containing fuel differ from the clear fuel in ways other than Mn content and octane rating, which would have been more likely to confound the study results.

Turning to "uneven" maintenance procedures, MacKay and Benson point out that all scheduled maintenance was conducted at the same mileage on both test vehicles using both the clear and additized fuel. They further note that unscheduled repairs that could affect emissions, such as oxygen sensor replacement, were performed on both vehicles in a pair. In addition, they found no technical basis nor any evidence to support the view that any other unscheduled maintenance performed on only one vehicle in a pair, such as coolant addition, affected the results of the study.

Regarding the modified SMA cycle for mileage accumulation, MacKay and Benson describe in more detail why it was selected for use in the program and note that, because all vehicles were tested using the same mileage accumulation cycle, only MMT®-related impacts on emissions and engine and emission control components would be expected to have been observed in vehicles using the additized fuel. Further, Ethyl's characterization of this cycle as "excessively severe" and suggestion that less severe cycles should have been used implies that adverse MMT® impacts are more likely under certain operating conditions.

Finally, with respect to the lack of a break-in period, MacKay and Benson point out that in real customer service there is no clear-fuel break-in period for vehicles in areas where MMT® is in use. They also indicated that among other reasons for omitting a break-in on clear fuel, there was some concern that early use of clear fuel might alter deposit formation in the engine and exhaust systems of vehicles later operating on MMT®-containing fuel.

[*] It should be noted that neither the U.S. EPA Complex Model nor the CARB Predictive Model, both of which are used to assess the emissions impacts of changes in gasoline composition for regulatory purposes, considers changes in octane rating.

9.5 Summary of Part 1 Results

Based on the design of the Part 1 study, the emissions data collected were analyzed for the 20 sets of paired clear- and additive-fuel vehicles. After 80,000 km of operation, the data showed that emissions of NMOG and CO were higher for the fleet of vehicles that operated on the fuel with MMT® while the NOx emissions from the MMT® fleet were lower relative to the fleet operating on the clear fuel. In addition, the cumulative (or integrated) emissions of NMHC and CO from the MMT® fleet from the start of the program through 80,000 km were higher than those of the clear-fuel fleet, while NOx emissions were lower. All of these differences were found to be statistically significant. Statistically significant increases in NMHC and decreases in NOx emissions at 80,000 km were also reported for the MMT® fleet based on an Analysis of Variance, and regression analysis also found higher NMHC emissions and lower NOx emissions from the MMT® vehicles through 50,000 km. The higher NMHC emissions observed from the MMT® fleet were generally attributed to manganese oxide deposits in combustion chambers, while the lower NOx emissions were generally attributed to a smaller decrease in catalyst efficiency for NOx reduction over the course of the mileage accumulation period. A similar effect was observed with respect to the catalyst efficiency for THC with the MMT® fleet, but its impact on tailpipe emissions was more than offset by higher engine-out emissions. There were no other effects found to be statistically significant.

Turning to individual vehicle model effects, emissions of NMOG from both of the MMT®-fueled Civics (model 8) exceeded the 80,000 km LEV certification emission standard at that point and exceeded the 160,000 km certification emission standard at 120,000 km. NMOG emissions from both clear-fueled vehicles of this model were below the 80,000 km standard through that point and remained below the 160,000 km standard level after 120,000 km of operation. The high NMOG emissions from the MMT®-fueled Civics were attributed to deposits of manganese oxides in the combustion chamber and in particular on the exhaust valves, which caused the exhaust valves to leak. In addition, MIL illumination for intermittent misfire was observed on both MMT®-fueled Cavaliers (model 6) at almost the same point (58,000 km), while MIL illumination for misfire was not observed on either of the clear-fueled Cavaliers.

9.6 Ethyl Corporation Reanalysis of Data from Part 1 of the Alliance-AIAM-CVMA Study

Ethyl Corporation responded to the results of the Part 1 Alliance-AIAM-CVMA study by raising concerns with the statistical methods employed in the analysis of the data and by engaging ENVIRON to perform a reanalysis of the data using different methods.[113,116] Rather than performing a reanalysis of the data for the entire Part 1 fleet, however, as would be consistent with the design of the study, ENVIRON's reanalysis focused on individual models and groups of models based on the emission standards to which they were certified.

The reanalysis of the Part 1 study data published by Ethyl concluded that there were not, in general, statistically significant differences in emissions between vehicles operating on MMT®-containing fuel compared to clear fuel when the vehicles were evaluated on a model-by-model basis. However, in those cases where statistically significant effects were observed, they were the same as those found in the original data analysis: higher NMHC and lower NOx emissions for vehicles operating on MMT®-containing fuels relative to clear fuels. For the analysis performed on groups of vehicles based on the emission standards to which they were certified, the ENVIRON reanalysis found statistically significant increases in NMHC emissions and decreases in NOx emissions for TLEVs at 80,000 km of operation on gasoline containing MMT® relative to clear fuel. ENVIRON's reanalysis also showed that the increase in NMOG emissions observed with the Civics that operated on MMT®-containing fuels was statistically significant.

Ethyl's reanalysis has been reviewed by MacKay and Benson,[115] who conclude that the primary difference in the statistical methods used in the original analysis of the Part 1 data and the reanalysis is that:

> *…the Alliance analysis…is less concerned about erroneously stating that there is a significant difference between the MMT and clear fuel fleet averages, when such a difference does not exist, and more concerned with failing to report such a difference when it does in fact exist. The ENVIRON analysis takes the opposite view.*

In addition to the above, Ethyl has taken issue with the statement that the NMOG emissions from the Civic vehicles operated on the MMT®-containing fuel exceeded the LEV certification standards at 80,000 km and the 160,000 km standard after 120,000 km. As discussed by MacKay and Benson, Ethyl's argument is based on a technicality in the provisions of the California regulations that provided manufacturers with an in-use compliance margin in recognition of the challenges facing manufacturers in developing vehicles capable of meeting LEV standards. CARB offered the following rationale for adopting these short-term interim standards:[117]

> *In the early years of implementation, intermediate in-use standards would provide additional time to verify the in-use durability of vehicle emission control systems. It is envisioned that engineering resources would first be devoted to the design and development of the technologies which would enable vehicles to meet the proposed certification standards, and additional time would be needed to fine tune designs to assure that the vehicles meet all the standards in customer service.*

As the clear-fueled Civics complied with the NMOG certification emission standards through the end of their testing at 120,000 km, Ethyl's discussion of the interim in-use standards arises only because of the failure of the Civics operating on the MMT®-containing fuel to comply with the certification standards.

9.7 Summary of Part 2 Results

The results of Part 2 of the Alliance-AIAM-CVMA study are presented in detail in reference 108 as well as in a peer-reviewed technical paper.[118] Because all four models of Part 2 test vehicles were certified to LEV standards and the Civic was the only model certified to LEV standards in Part 1, two analyses—the first just for the Part 2 study and the second for the five LEV models tested in Part 1 and Part 2—were performed; however, the latter had to be limited to 120,000 km rather than 160,000 km as the Civic vehicles were operated to only 120,000 km in Part 1. In general, inclusion of the Civic vehicles from the Part 1 study only reinforced the conclusions drawn from the Part 2 study vehicles.

Analogous to the Part 1 study, exhaust emissions of NMOG were higher for the Part 2 additive fuel fleet than the clear fleet at 120,000 and 160,000 km, and NOx emissions were lower at 120,000 km. At 160,000 km, however, the NOx emissions for the additive fuel fleet were also higher than for the clear fleet. These differences were statistically significant. The same results were observed with an Analysis of Variance procedure, except that NOx emissions from the additive fleet were not significantly lower than those of the clear fleet at 120,000 km. Regression analysis again showed that NMOG emissions from the additive fleet were higher over the entire period of mileage accumulation; however, while NOx emissions from the additive fleet were lower than those for the clear fleet to 80,000 km, they were higher at 120,000 km and thereafter.

Statistical analyses were also performed on engine-out emissions. These analyses showed higher engine-out THC emissions for the additive fleet over the course of the test program and generally showed lower engine-out NOx emissions for the additive fleet relative to the clear fleet. These effects were generally found to be statistically significant. As with the Part 1 study, the degradation of catalyst efficiency for THC and NOx conversion with increasing mileage was initially found to be lower for the additive fleet than for the clear-fuel fleet. This situation was reversed, however, above 80,000 km for THC and at 120,000 km for NOx, due largely to severe degradation of catalyst performance for the Escorts (model 1) and increased engine-out emissions. The impacts of MMT® on the catalysts of the Escorts in the Part 2 fleet are discussed in more detail later in this chapter.

Finally, the fuel economy of the additive-fuel fleet was lower than that of the clear-fuel fleet both during the city driving that characterizes the FTP driving cycle and also during the on-road mileage accumulation. The finding for city driving was found to be statistically significant. More detailed measurements showed a rich bias in the engine-out air-fuel ratio of the additive fuel fleet and the presence of higher concentrations of oxygen in the engine-out exhaust gases. These findings suggest that the use of MMT® led to deterioration in the quality of combustion in the additive fuel fleet.

With respect to individual vehicle impacts in the additive fleet, in addition to the Part I Civics that had NMOG emissions in excess of the LEV I certification standards, both Breeze vehicles had NMOG emissions that exceeded the LEV I certification standards beyond 80,000 km, and both Escorts exceeded the certification standards at 160,000 km. Only one clear-fueled vehicle, a Breeze, marginally exceeded the LEV I NMOG certification standards, but it had lower emissions than either Breeze in the additive-fuel fleet. Integrated cumulative NMOG emissions through 160,000 km were significantly higher for both the Breeze and Escort models on MMT®-containing gasoline relative to the clear-fuel vehicles.

9.8 Ethyl Corporation Reanalysis of Data from Part 2 of the Alliance-AIAM-CVMA Study

As was the case with Part 1, Ethyl Corporation also reanalyzed the data from Part 2 of the Alliance-AIAM-CVMA study. Most of the issues associated with that reanalysis are the same as those discussed above and are not covered again here. It is important to note, however, that even the ENVIRON reanalysis found statistically significant increases in NMOG emissions for the LEV vehicles operating on MMT® at 120,000 and 160,000 km and, unlike the TLEV vehicles, no statistically significant decrease in NOx emissions was found for the LEV vehicles operating on MMT® at any mileage relative to the clear-fueled vehicles.

One new issue was an assertion by ENVIRON and Ethyl that differences in the initial fuel economy of the clear and additive fuel test fleets formed the basis for the finding that there was a negative impact of MMT® on fuel economy in the Part 2 study. That assertion is rebutted by MacKay and Benson, who found, based on statistical analysis, that differences in the initial vehicles had no impact on the fuel economy finding.

9.9 Additional Testing of Part 2 Test Vehicles

Particulate Matter Testing – Following the conclusion of Part 2 of the Alliance-AIAM-CVMA study, one complete set of paired test vehicles (two vehicles each from each of the four models) was shipped to an independent laboratory and subjected to exhaust particulate emissions testing.[119] The testing was performed using CARB Phase 2 certification gasoline and an additized version of that fuel containing MMT® at the 8 mg Mn/l level**.** Vehicles were tested while being driven over both the driving cycle of the FTP and the REP05 driving cycles. The REP05 cycle ("representative driving cycle number 5") is a higher-speed driving cycle developed by Sierra Research for the U.S. EPA using data collected on actual vehicle operation in the U.S. The REP05 cycle addresses driving patterns observed for light-duty vehicles outside those covered by the FTP,[120] which is also known as "off-cycle" driving. Particulate emissions were characterized as follows:

1. Total PM mass emission rates were measured;

2. Emission rates for specific elements including Mn were determined by high-resolution inductively coupled plasma mass spectrometry after acid digestion of PM samples;

3. Mass-based particle size distributions were obtained using a MOUDI (micro-orifice uniform deposit impactor); and

4. Number-based particle size distributions and number concentrations were obtained using an electrical low-pressure impactor (ELPI) and scanning mobility particle sizer (SMPS).

The results of this study showed that the vehicles operating on MMT®-containing gasoline had much higher PM and Mn emission rates than the clear-fueled vehicles and in general had higher emissions of fine and ultra-fine particles as indicated by both the mass- and number-based size distribution data.

Post Mortem Testing – The data for two pairs of Escorts from the Part 2 study showed that the vehicles operating on MMT® began to have higher emissions of NMOG, CO, and NOx relative to the clear-fuel fleet vehicles beginning at 120,000 km, with that difference increasing greatly at 160,000 km. In its reanalysis of the Part 2 data, Ethyl alleges that the higher emissions of the Escorts in the additive fleet may have been due to coolant replacement, oil pan cleaning, and an observation of transmission slippage. Subsequent analysis, however, showed that this was not the case.

Following completion of Part 2 of the Alliance-AIAM-CVMA study, one pair of the Ford Escorts from that study was examined in detail by Ford.[121,122] The vehicle pair consisted of vehicles AE16 and CE16. The vehicles were inspected and emissions testing was then performed with "swapped" components in a manner similar to the post-mortem analyses conducted for certain models in the Part 1 study. The following components were swapped:

1. Heated Exhaust Gas Oxygen (HEGO) sensors;
2. Spark plugs;
3. Catalysts; and
4. Engine cylinder heads.

Components were swapped individually, and in groups consisting of (1) spark plugs and head to examine effects of engine deposits; (2) the spark plug, HEGO sensors, and catalyst to examine fuel control and aftertreatment effects; and (3) all four components. Engine-out and tailpipe emissions of THC, NMHC, CO, and NOx were measured using the FTP and CARB certification gasoline.[123]

The results of the emissions testing showed that a complete swap of all components from the MMT® vehicle to the clear vehicle resulted in increases in tailpipe NMHC, CO, and NOx emissions to the same levels as originally observed on the MMT® vehicle. Conversely, emissions on the MMT® vehicle decreased to the same level as those originally observed on the clear-fueled vehicle when the clear-fueled vehicle components were installed on the MMT® vehicle.

With respect to specific components, swapping of the head and spark plugs in combination from the MMT® vehicle to the clear vehicle led to a substantial increase in engine-out NMHC emissions. A similar increase in tailpipe emissions was also observed.

The opposite result was obtained for the switch of the clear-fueled vehicle head and plugs to the MMT® vehicle. Further investigation involving swaps of fuel injectors, exhaust gas recirculation (EGR) valves, intake and exhaust valves, as well as spark plugs and detailed analysis of the cylinder heads, indicated that the increase in NMHC emissions was due to exhaust valve leakage resulting from deposits on the valves. The deposits were examined using X-ray fluorescence and X-ray diffraction and found to have a high Mn content and a structure consistent with their being primarily Mn_3O_4. The cylinder head itself also seemed to be the most important component with respect to changes in engine-out and tailpipe CO emissions, and subsequent analysis indicated the higher CO levels were indirectly linked to the valve deposits affecting NMHC emissions.

For tailpipe NOx emissions, the exchange of catalysts by themselves had by far the most pronounced impact on emissions, with installation of the catalyst from the MMT® vehicle on the clear-fueled vehicle resulting in a substantial increase in emissions and the opposite effect being observed for the corresponding switch of the clear-vehicle catalyst to the MMT® vehicle. Examination of the catalyst from the MMT® vehicle showed that approximately 20% of the face of the catalyst from the MMT® vehicle was plugged by reddish brown deposits. These deposits were also examined using X-ray fluorescence and X-ray diffraction and were found to have a high Mn content and a structure consistent with their being primarily Mn_3O_4. The plugging of the catalyst face by the Mn deposits was found to increase catalyst space velocity, with the reduced residence time leading to higher NOx emissions. This effect was not observed to lead to increases in tailpipe levels of NMHC or CO emissions.

It should also be noted that the primary difference between the Escorts of the Part 2 study (certified as LEVs) and those of the Part 1 study (certified as TLEVs) was that catalysts on the Part 2 vehicles had higher precious metal loadings.[123] Therefore, it seems likely that the same effects that were observed in the Part 2 study (increasing emissions beginning at 120,000 km) would have also been observed on the Escorts in the Part 1 study had mileage accumulation not been halted at 80,000 km.

9.10 Significance of Alliance-AIAM-CVMA MMT® Vehicle Test Program

As summarized above, the Alliance-AIAM-CVMA MMT® vehicle test program represents the largest and most sophisticated assessment of the impacts of the use of MMT® on vehicles with advanced emission control systems. The results of that program demonstrate that the use of MMT® as a gasoline additive is not benign. MMT® has been shown to alter the performance of the engine as evidenced by consistently higher engine-out emission levels of hydrocarbons that are related to manganese deposits in the combustion chamber, which in turn cause higher tailpipe hydrocarbon emissions.

In the case of the most advanced emission control technology examined, that capable of allowing vehicles to certify to the LEV I emission standards of CARB's LEV program, vehicles operating on MMT®-containing fuels have been observed to have NMOG emission levels that exceed certification emission standards while identical vehicles operating on clear gasoline do not, and even the reanalysis of the Part 2 data by ENVIRON indicates that these increases in NMOG emissions are statistically significant.

Another major finding was that made for the Escorts of the Part 2 study, where the use of MMT® led to plugging of the close-coupled catalysts and substantial increases in NOx emissions. While catalyst plugging was observed only for this single model, it should also be noted that, based on the changes in NOx emissions, it appears that plugging on the Escorts did not become a significant issue until after 120,000 km. Given that the Part 1 study was, in general, terminated at 80,000 km, the question remains whether additional examples of plugging might have been observed on those vehicles as well. Another question is what would have been observed in all aspects of the Alliance-AIAM-CVMA study had MMT® been used at the 18 mg Mn/l level allowed in Canada compared to the 8 mg Mn/l level allowed in the U.S.

The results of the Alliance-AIAM-CVMA study also indicate that sensitivity of advanced engines and emissions control systems to adverse impacts associated with the use of MMT® will generally increase as the level of sophistication of those systems, and the stringency of the standards they must meet, increases.

9.11 Assessment of Impact on Emissions of the Canadian Vehicle Fleet

In addition to demonstrating that the use of MMT® will have adverse impacts on engines, emission control systems, and emissions of vehicles equipped with what were then advanced emission control technologies, the data generated by the Alliance-AIAM-CVMA study formed the basis of an assessment of the impact of MMT® use on in-use vehicular emissions in Canada.[124]

In this study, the vehicles tested in the Alliance-AIAM-CVMA study were first divided into four groups based generally on vehicle type (e.g., passenger cars or light-duty trucks) and the level of sophistication of emissions control technology. Next, correction factors for application to the MOBILE5 emission factor model were developed for VOC, NOx, and CO emissions for each group that accounted for the impacts associated with MMT® use in those vehicles on emissions of each pollutant. These correction factors were based on analysis of the emissions results obtained during the Alliance-AIAM-CVMA study using the clear and MMT®-containing fuel. It should be noted that this study was conservative in that MMT® was assumed to have no emissions impact on vehicles with emission control systems less advanced than those required to comply with Tier 1 emissions standards and in that vehicles certified to Tier 2 standards would respond to MMT® in the same manner as two test vehicles certified to relatively less stringent LEV standards.

Two different MMT® use scenarios were evaluated: (1) where MMT® was assumed to be used in all Canadian gasoline at a concentration of 8 mg Mn/l, and (2) where MMT® was assumed to be used in all Canadian gasoline at a concentration of 6.0 mg Mn/l (both scenarios being well below the CGSB limit of 18 mg Mn/l). The first scenario reflected the conditions of the Alliance-AIAM-CVMA study, while the second reflected an overall volume-weighted average concentration for actual MMT® use in Canada developed by Environment Canada based on data for fuels marketed in 1999. The study indicated that, in 2010, MMT® use in Canada would be expected to result in increases in VOC+NOx emissions of 1-2% and increases of 8-11% in CO emissions. By 2020, however, with the widespread introduction of vehicles with advanced emission technologies and their accumulation of substantial mileage on MMT®-containing fuel, the magnitude of the emissions increases associated with MMT® would be expected to grow dramatically to 26-36% for VOC+NOx emissions and 35-75% for CO emissions. These results clearly illustrate the hazard posed by MMT® use in gasoline to the effective control of vehicular emissions in Canada.

###

10. OTHER ASSESSMENTS OF MMT® USE IN UNLEADED GASOLINE ON ENGINES, EMISSION CONTROL SYSTEM COMPONENTS, AND EMISSIONS OF LATE MODEL VEHICLES

Since the completion of the Alliance-AIAM-CVMA MMT® vehicle test program, there have been several other studies and reports published regarding the impact of using MMT®-containing gasoline on the engines, emission control system components, and emissions of late-model vehicles. These studies and reports can be divided into three categories: (1) vehicle test programs performed under controlled conditions, (2) laboratory test programs, and (3) evaluations of in-use vehicles. The studies that fall into each category are summarized below.

10.1 Controlled Vehicle Test Programs

Afton Chemical[125] – Afton Chemical performed a controlled vehicle test program that involved an accelerated mileage accumulation program on two models of 2003 model-year vehicles certified to EURO 4 emission standards. The two models used in the Afton program were the 2003 Volkswagen Passat, powered by a 2.0 l, four cylinder, in-line engine; and the 2003 Opel Corsa, powered by a 1.4 l, four-cylinder, in-line engine. The Passat was equipped with a “manifold mounted” metal foil catalyst reported to have a cell density of more than 500 cpsi, while the Corsa was equipped with a 600 cpsi ceramic substrate catalyst, again characterized as “manifold mounted.” The program involved four vehicles of each model, operated in two pairs, with both pairs using a clear fuel for the first 7,000 km of operation and one pair then continuing on that fuel through 100,000 km while the other pair operated on a fuel containing MMT® at the level of 18 mg Mn/l through 100,000 km. The vehicles were driven both on public roads and on a closed test track. Although the operation was characterized as “severe,” only the average speed of 60 km/hr and maximum speeds of 150-160 km/hr were reported. Afton concluded that MMT® was compatible with vehicles equipped with high cell density close-coupled catalysts because emissions measured on the European testing protocol indicated that MMT® use did not result in emissions exceeding the applicable emission standards or illumination of the MIL by the OBD systems present on the vehicles.

Several problems with the Afton study contradict its broad and general conclusions regarding the compatibility of MMT® with vehicles equipped with advanced emission control systems. First, no data were reported regarding average or peak catalyst temperatures experienced by the test vehicles in this study during operation over either standardized driving cycles or in actual operation during the test program. Therefore, one cannot conclude that the catalysts were actually exposed to severe conditions. Second, there are no results from physical or visual inspection of the catalysts from the test vehicles that could be used to determine whether plugging by manganese oxides was in fact occurring. Finally, from poorly documented testing on two European vehicle models, it is not possible to conclude, as Afton does, that the use of MMT® will be compatible with all makes and models of vehicles equipped with advanced emission control technologies.

Afton concluded that the use of MMT®-containing gasoline in vehicles with advanced emission control systems had no impact on exhaust emissions because the MMT® test vehicles did not exceed the EURO 4 standards after 100,000 km of operation. However, closer examination of the limited exhaust emissions data presented suggests fundamental differences in emissions of the clear and MMT®-fueled Opel Corsa vehicles at 100,000 km. As can be seen in Figures 2, 4, and 6 of reference 125 the MMT® vehicles had higher HC and CO emission levels relative to the clear-fueled vehicles, along with lower NOx emissions. While the cause of such results was apparently not investigated by Afton and cannot be determined based on the available data, the results are consistent with an enriched air-fuel ratio in the vehicles exposed to MMT®. The same effect was not observed for the VW Passat vehicles; however, as the Alliance-AIAM-CVMA study showed, the lack of observable MMT® effects after 100,000 km does not mean that impacts will not be observed by 160,000 km.

10.2 Laboratory Studies

Porsche – Researchers at Porsche performed a study of the impact of MMT® on emissions and performance of the 2004 model-year Porsche Carrera, a vehicle with a horizontally opposed six cylinder engine certified to Euro IV emission standards.[126] The emission control system for this vehicle includes two 400 cpsi metal substrate catalysts in series for each of the two banks of cylinders. The test program involved engine dynamometer testing of two identical engine and emission controls systems sets. Both sets were broken in by being operated on a non-MMT®-containing gasoline for 20 hours. After that, one set continued operation for another 179 hours on the clear fuel while the other continued operation on a version of the clear fuel to which MMT® had been added at 15 mg Mn/l. The engine dynamometer test cycle used was one hour in total duration and included operating conditions ranging from idle to near wide open throttle, with exhaust temperatures reaching a maximum of about 900º C. The 179 hours of operation on the engine dynamometer was reported to translate to about 60,000 km of on-road vehicle operation. In addition to engine dynamometer based testing, the engines/emission control system sets were placed into a test vehicle so that chassis dynamometer testing could be conducted.

The results of the study showed that while the emissions and performance of the two sets of engines and emission control systems were nearly identical after the 20-hour break period, there were considerable differences at the end of the service accumulation period. For the engine/exhaust system exposed to MMT®, these differences included the following:

- The presence of reddish-brown combustion chamber deposits that were visually observed on the valves, piston faces, and spark plugs;

- Plugging of some catalyst cells on the faces of both the front and following catalytic converters by reddish-brown material;
- A 5% loss in maximum power and a 3% loss in maximum torque during wide open throttle testing;
- A 6% increase in exhaust system backpressure at rated speed;
- A 5% increase in brake specific fuel consumption and a 3% increase in fuel consumption over the European Union (EU) emission test cycle;
- A substantial increase in engine-out and exhaust hydrocarbon emissions, leading to emission levels that exceeded the EU IV hydrocarbon standard; and
- Reduced catalyst efficiency for conversion of hydrocarbons, carbon monoxide, and oxides of nitrogen.

With respect to the increase in exhaust hydrocarbon emissions, both the higher engine-out emissions resulting from MMT® use plus a delay in the light-off of the front catalysts and degraded catalyst efficiency for hydrocarbons contributed. The delay in catalyst light-off was attributed to the presence of the reddish brown deposits, which blocked part of the catalyst and also increased its thermal mass.

Honda – Researchers at Honda[127] performed an extensive series of engine dynamometer tests to investigate the effects of catalyst temperature and exhaust system geometry on the formation of manganese oxide deposits on high-density catalyst substrates. Results of this study are summarized below.

1. In engine/emission control systems where catalyst plugging was observed, the degree of plugging increased with the amount of fuel containing MMT® consumed.

2. At an exhaust gas temperature of 805º C, introduction of a 90º bend in an exhaust pipe immediately upstream of a HDCC catalyst led to manganese oxide plugging of the catalyst during operation on MMT®-containing fuel (8 mg Mn/l), when no plugging was observed prior to the introduction of the bend.

3. For an engine operating with MMT®-containing fuel (8 mg Mn/l) with a HDCC catalyst and an exhaust gas temperature of 805º C, and where no manganese oxide plugging was observed after 375 hours of operation with a straight exhaust pipe, introduction of a 45º bend in an exhaust system on an engine led to complete plugging with 375 hours of operation; introduction of a 60º bend led to complete plugging in only 275 hours. Deposit growth was in a direction exactly opposite to the direction of exhaust gas flow.

4. The rate of manganese oxide plugging of a HDCC catalyst in the exhaust system increased as a function of increasing temperature over the range from 600 to 805º C.

5. If temperature, exhaust system geometry, and MMT® level remained constant, the rate of catalyst plugging increased as the cell density of the catalyst substrate increased.

Electron probe microanalysis and X-ray diffraction confirmed that the deposits observed on the catalysts in this test program were manganese oxides, primarily, if not exclusively, Mn_3O_4.

Afton – A recently published study[128] performed by Afton also examined the formation of manganese oxide deposits on high-density catalyst substrates under laboratory conditions. Three catalyst types were used in the study. These were reported to be (1) 400 cpsi catalysts used on 1996 Honda Civics, (2) 600 cpsi catalysts used on 2003 Honda Civics, and (3) 900 cpsi catalysts from 2003 Ford Crown Victorias. Although Afton provides little detail regarding its experimental apparatus, it appears that catalysts were attached in some fashion to an exhaust system attached to a Ford 4.6 liter V-8 engine of unspecified age located in a laboratory engine dynamometer test cell. No details regarding the design or configuration of the exhaust system used in this program were provided by Afton. Further, there was no mention of any effort to test any of the catalysts using space velocities or flow geometries representative of the vehicles on which they were intended to be used. The build-up of deposits on the test catalysts was evaluated by monitoring the pressure drop across the catalysts.

Test catalysts were exposed to exhaust from the test engine while operated on the engine dynamometer using either clear fuel, or one of two MMT®-containing fuels additized to the 8.3 and 18 mg Mn/l level, respectively. Two different engine operating regimes were used. The first of these was based on continuous steady-state operation; the second involved steady-state engine operation for five minutes followed by periods of engine "motoring" of either 20 or 60 seconds during which time fuel to the engine was cut off while the engine continued to rotate at a constant but unspecified speed. According to Afton, the "fuel cut off" procedure (which amounts to using the engine as an air pump to rapidly decrease the gas temperature to which the catalyst is exposed by as much as 500º C) was intended to induce a "thermal shock" that represented "particle detachment" forces that Afton claims normally occur on in-use vehicles. However, fuel cut-offs of the duration used by Afton are completely unrepresentative of actual engine operating conditions on in-use vehicles where maximum fuel cut-off periods are on the order of five seconds or less and generally occur only during vehicle deceleration events.

In testing performed without the "fuel cut-off," the data presented by Afton are consistent with the Honda study discussed above and indicate the following:

1. The presence of MMT® in the fuel led to a greater increase in pressure drop across the catalyst than was observed without MMT® in the fuel for 400 cpsi catalysts;

2. With MMT® in the fuel, increases in pressure drop were observed to occur faster as catalyst cell density increased;

3. With MMT® in the fuel, increases in pressure drop were observed to occur faster as exhaust temperature increased; and

4. With MMT® in the fuel, increases in pressure drop were observed to occur faster for the fuel with the higher MMT® concentration.

When the 20- and 60-second "fuel cut-off" were included during testing of the 400 and 600 cpsi catalysts, increases in pressure drop were not observed in testing using fuel with MMT® at the 18 mg Mn/l level at nominal exhaust temperatures of between 800 and 820°C. However, Afton provides no data to support the assertion that the "fuel cut off" technique employed in this study accurately reflects the particle "detachment" process on in-use vehicles other than the unsupported statement that the findings observed with the technique are "consistent with over two decades of successful experience with MMT® use in gasoline in Canada and elsewhere in catalyst equipped vehicles."

This study, which is the most recent published by Afton, is of particular interest because it confirms MMT®-related plugging of catalytic converter faces under laboratory conditions and postulates that plugging on in-use vehicles is not observed because of the action of poorly characterized particle "detachment" processes. An obvious conclusion that can be drawn from the Afton study is that MMT® use in gasoline will lead to catalyst plugging on in-use vehicles whenever Afton's postulated particle "detachment" process is insufficient to clear the accumulated deposits of manganese oxides.

10.3 Evaluations of In-Use Vehicles

Various Auto Manufacturers − Volkswagen has publicly reported catalyst plugging problems in China.[129] The Volkswagen report shows a photo of a single catalyst reported to be from an in-use vehicle operated in China. The face of the catalyst has heavy reddish-brown deposits that appear to be plugging the channels of the catalyst substrate. In addition, BMW, Volkswagen, Opel, Nissan, and Saab have all publicly reported catalyst plugging on in-use vehicles operating in South Africa following the introduction of MMT® into gasoline sold in that country.[130] In general, these reports were based on motorists' complaints of poor vehicle driveability. Photographs have been presented showing reddish-brown deposits on the face of catalytic converters obtained from in-use vehicles operated in South Africa. Samples of deposits from some catalysts were subjected to elemental analysis performed using X-ray fluorescence spectroscopy and energy dispersive spectroscopy. The results indicated the presence of substantial amounts of Mn, and structural analysis using X-ray diffraction indicated the presence of Mn_3O_4.

Afton − As described below, Afton has published the results of two studies that are loosely based on evaluations of in-use vehicles that Afton claims demonstrate the compatibility of MMT® use in gasoline with normal performance of late model vehicles. The first of these[131] was based simply on the results of a telephone survey of owners of 2001 and later model-year vehicles. The survey focused on owner experiences with OBD MIL lights and associated component repair/replacement on their vehicles. Approximately 350 owners were surveyed in the cities of Denver, Colorado; Minneapolis, Minnesota; and Regina, Saskatchewan. Survey results from Regina, where MMT® has been used in gasoline, were compared to those from Denver and Minneapolis, where MMT® has not been used in gasoline, in an attempt to infer impacts of MMT® use on 2001 and later model-year vehicles. Based solely on the telephone survey results, Afton concluded that there are no material differences in OBD MIL illumination rates between Regina and the other two cities, and extended that finding to conclude that MMT® does not have an impact on vehicle engines, emission control systems, or emissions.

The first issue with this study is that it does not demonstrate that a phone survey of vehicle owners is a valid approach for determining differences in the frequency of occurrence of OBD MIL illumination in different areas or in the frequency of specific vehicle repairs in different areas. Perhaps more tellingly, the study does not contain a single reference to any other phone-survey-based study of any issue. This indicates that phone surveys have not been used by researchers in this area and suggests that the phone-survey-based study design is not appropriate for addressing the issues of concern.

Notwithstanding the questionable validity of the entire survey-based study design, the Afton study has a number of flaws that result in a situation where Afton's conclusions are not supported by the analysis upon which they are based. The first flaw with the Afton survey is that there are no details available regarding the survey process. For example, the instructions provided to surveyors and the survey questions asked of participants are not contained in the paper. Other design-related issues include no description of survey controls or other means of assuring data quality. For example, some vehicles have both OBD MIL lights as well as maintenance lights and it isn't clear how the survey differentiated between these lights, if at all. Also, there is no discussion of how the survey identified components replaced as part of routine maintenance as opposed to those that had failed and illuminated the MIL.

A second flaw is that the surveyed vehicles tended to have low mileages, as documented in Table 2 of the paper. The bulk of vehicles in each city had been driven between 0 to 80,000 km, and the average mileage of vehicles in Regina was the lowest of the three cities (46,000 km compared to 55,000 km in Denver and 66,000 km in Minneapolis). Further, approximately 90% of vehicles surveyed in Regina had accumulated less than 80,000 km. This is significant as adverse MMT® impacts have been shown to be related to the amount of MMT® to which a vehicle has been exposed, which increases with mileage and with higher gasoline MMT® concentrations. Therefore, a survey focused on low mileage vehicles would not be expected to reveal the true magnitude of the ultimate impacts associated with MMT® use.

A related issue is that while Afton claims the Regina results demonstrate the compatibility of MMT® with proper vehicle performance, MMT® levels in Regina during 2001 to 2005 were, as shown in Chapter 5, lower than the 18 mg Mn/l limit set by the CGSB, particularly for the unleaded regular gasoline used in most vehicles. Again, this means that exposure of vehicles to MMT® in Regina was limited relative to that which would occur if MMT® were used at the allowable limits.

Another critical issue is that Afton's conclusions rest on the reported lack of evidence of a statistically significant difference in the results from Regina and the two U.S. cities. However, there is no discussion of the statistical analysis to which the collected data were subjected. In addition, even assuming the statistical analysis was performed properly, the conclusion that there is no statistical difference between Regina and the U.S. cities could be due to factors such as inappropriate sample size, improper sample selection, bias introduced by the survey questions, high variability in the results, and customer recollections of OBD-related repairs being an inappropriate metric for use in investigating MMT® impacts. Perhaps most importantly, the study's conclusions with respect to statistically significant differences or lack thereof in the Regina and Denver and Minneapolis data are not supported with details from the statistical analysis.

The second Afton paper[132] in this category compared IM240 test results from British Columbia's AirCare inspection and maintenance program with IM240 test results collected as part of the Wisconsin and Arizona inspection and maintenance programs. The premise of the paper is that comparison of IM240 emission test data collected in British Columbia, Arizona, and Wisconsin can be used to evaluate the impacts of MMT® use on selected 1996 to 2001 model-year vehicle models, including some with advanced emission control technology. Afton's conclusion is that the analysis presented in this study confirms the satisfactory operation of advanced emission control systems and components, including HDCC catalysts on MMT®-containing fuels. There are, however, several fundamental problems with the Afton methodology that render the results of the analysis meaningless with respect to the impact of MMT®-containing fuels on engines, emission control systems, and emissions.

One problem is that inspection and maintenance programs are designed to identify high- and gross-emitting vehicles. IM programs are not designed or calibrated to compare the performance of normal emitters, particularly those certified to extremely low LEV or Tier 2 emission levels. In addition, some programs may use "fast pass" and "fast fail" algorithms (as is the case in British Columbia), which further complicates comparisons of data from different I/M programs.

Another problem with Afton's analysis of the AirCare program data is that the Mn content of gasoline in the Vancouver area was relatively low from the summer of 1995 through the winter of 2004 (the period during which the vehicles selected by Afton would have been in operation). This can be seen from the Auto Industry fuel survey data presented in Chapter 5, which indicate that the average Mn concentration in regular unleaded gasoline in the Vancouver area during this period was about 2.6 mg Mn/l during the summer months and about 1.8 mg Mn/l during the winter months. These values are seven to ten times lower than the CGSB limit of 18 mg Mn/l. Therefore, given the link between MMT® exposure and MMT®-related impacts established in the literature, one would not expect to see MMT®-related impacts on these vehicles until mileages higher than the mileages at which the impacts would appear in areas where higher MMT® concentrations were used. However, Afton's analysis is that the 2000 and 2001 model-year “Tier 2 capable Vehicles” from British Columbia had been in operation for only two to four years and had, by Afton’s own admission, accumulated only about 35,000 km and 65,000 km, on average, by those points in time.

Another problem with Afton’s analysis is that it is based on IM240 test data, which are intended to identify vehicles with very high or gross emissions levels relative to average vehicles of the same vintage. These data are not intended to be used to determine if vehicles meet certification emission standards or to quantify or determine the actual emissions of in-use vehicles. Given this, the IM240 test is simply not suitable for the type of analysis Afton has performed. Further, IM240 testing is done on warmed-up vehicles and does not identify factors leading to high cold start emissions.

Yet another problem with Afton’s methodology is that it has not been demonstrated to be capable of identifying vehicles with emissions component issues. Although Afton discusses defects with the 1998 Honda Civic and 1999 Mazda Protégé and then uses these two instances to conclude that the methodology employed is a valid means of identifying vehicles that suffer from “specific and significant component performance issues,” this was a post-hoc determination that ignores the fact that other models in the data analyzed had similar component performance issues[133] that were apparently not identified by Afton’s methodology.

###

11. MMT®'S ADVERSE IMPACTS ON IN-USE CANADIAN VEHICLES WITH ADVANCED EMISSION CONTROL SYSTEMS

As shown in Chapter 9 of this report, the Alliance-AIAM-CVMA test program demonstrated that the use of MMT®-containing fuels can have adverse impacts on components and exhaust emissions of vehicles with emission control systems designed to meet Tier 1 and the LEV I/NLEV emission regulations as well as in-use emissions from the vehicle fleet. Further, in Chapter 10, data were presented that suggest that MMT® impacts on vehicles with more advanced emission control systems (those with higher cell density catalysts, for example) may be more pronounced than those observed during the Alliance-AIAM-CVMA test program.

Given the fundamentally different conclusions reached by the auto industry and Afton based on the data summarized in Chapters 9 and 10 of this report, some may believe that it has not been sufficiently demonstrated that MMT® will have serious adverse impacts on the engines, emissions control systems, and emissions of advanced technology vehicles. However, additional data are available from in-use Canadian vehicles, and are presented in this chapter, that clearly demonstrate adverse impacts due to MMT® use on advanced technology vehicles. More specifically, these data demonstrate that the use of MMT® in gasoline has adversely impacted 19 models of 1999 to 2003 model-year vehicles produced by nine manufacturers. These data come from real-world experience in Canada where advanced technology vehicles began to be introduced into the market during the late 1990s and where MMT® use continued until the latter part of 2004, as documented in Chapter 5. It must be stressed that there was not a comprehensive effort to investigate the impact of MMT® on all advanced technology vehicles in operation when MMT® was being used in Canada and more makes and models of vehicles could have been impacted by MMT®. In addition, an even greater number of vehicles and models would have been adversely affected by MMT® use as more and more advanced technology vehicles entered the market, had MMT® use not been phased out in Canada.

As concerns have grown regarding MMT® impacts on in-use vehicles equipped with advanced emission control systems, the Canadian Government has considered but has not yet executed a review of MMT®'s impacts. The proposed Terms of Reference (TOR) for what is referred to as the Third Party Review (TPR)[134] asks three overarching questions that probe beyond adverse impacts of MMT®-containing fuels on the Tier 1 and LEVI/NLEV vehicles that formed the basis of the Alliance-AIAM-CVMA study:

1. What are the attributes of advanced emissions control technologies and systems?

2. Does the use of MMT® in gasoline affect vehicle emissions and/or the operation or performance of any advanced emissions control technologies and systems used in vehicles in Canada? If so, do vehicles experiencing effects share common characteristics? What is the magnitude of these effects? If such information exists, do the effects vary with the concentration of MMT® in gasoline?

3. Would the use of MMT® in gasoline affect the introduction of any vehicle combustion or engine technology or emissions control requirement that has been developed to the point where it would otherwise be expected to be in general use in North America?

This chapter addresses each of the three questions raised by the TOR using data collected by vehicle manufacturers in light of events occurring in Canada. Each question is addressed in the order listed above and the data presented clearly demonstrate that the use of MMT® in gasoline has adversely affected the emissions of vehicles incorporating advanced emission control technologies and systems, as well as the operation and performance of both the vehicles and this technology.

11.1 What are the Attributes of Advanced Emissions Control Technologies and Systems?

The first step required to address this question is to define what is meant by the term "advanced emission control technologies and systems." As set forth in the TOR for the TPR, this is defined as follows:

> *"Advanced vehicle emission control technologies and systems" are considered to be those being used by vehicle manufacturers, or those that may be reasonably expected to be used by vehicle manufacturers to meet new vehicle emission standards being phased-in in Canada and the United States beginning with the 2004 model year (i.e. commonly referred to as "Tier 2" emission standards). "Advanced vehicle emissions-control technologies and systems" also includes those that were used on vehicles in advance of the coming into force of the "Tier 2" standards but which has similar characteristics.*

As was shown in Chapter 3 of this report (see Tables 3-2 and 3-5), compliance with the Tier 2 or LEV II standards requires substantial additional reductions in emissions of all pollutants relative to the Tier 1 standards, while compliance with Tier 2 or LEV II emission standards also requires substantial reductions in NOx emissions relative to the California LEV I regulations. More stringent emission levels are not the only additional regulatory requirements imposed by the Tier 2 and LEV II regulations, however. Other requirements include compliance with emission standards for longer duration and distance, additional OBD II requirements, Supplemental Federal Test Procedure Standards, stringent in-use compliance requirements, and compliance of larger light-duty trucks and medium-duty passenger vehicles with standards equivalent to those mandated for passenger cars.

Tier 2 and LEV II emission control technology and system design will be based on these vehicles operating exclusively on low-sulfur gasolines by virtue of the 30 ppm average and 80 ppm maximum sulfur limits that have been established by the U.S. and Canadian governments. This means, among other things, that vehicle manufacturers and emission control system suppliers will be able to design catalyst formulations to maximize efficiency without having to be concerned with sensitivity to exposure to sulfur levels above 80 ppm. Further, these limits on gasoline sulfur content could facilitate the introduction of new emission control technologies such as NOx adsorber catalysts.[135] Despite the progress made with respect to sulfur exposure, however, the potential for advanced emission control technologies and systems to be exposed to other fuel-related contaminants, such as products of MMT® combustion, remains an unresolved issue.

As has been noted by CARB,[136] there were four technological means (in addition to the use of reformulated/Tier 2 low-sulfur gasoline) by which vehicle manufacturers could move from the Tier 1 level to achieving compliance with more stringent Tier 2 or LEV II emission standards:

1. More precise fuel control;
2. Better fuel atomization and delivery;
3. Reduced engine out emissions; and
4. Improved catalytic converter performance.

CARB also noted that vehicle manufacturers, in developing emissions control systems capable of complying with the emission standards of the LEV I regulations, have employed different combinations of the technologies shown in Table 11-1 (reproduced here from reference 136). As shown in Table 11-1, these technologies included, but were

Table 11-1
Low-Emission Vehicle Technologies[a]

Dual Oxygen Sensors	Close-Coupled Catalysts
Universal Exhaust Gas Oxygen Sensors	Engine Calibration Techniques
Individual Cylinder Air-Fuel Control	Leak-Free Exhaust Systems
Adaptive Fuel Control Systems	Increased Catalyst Loading
Electronic Throttle Control Systems	Improved High Temperature Washcoats
Abbreviated Engine Start Systems	Electrically Heated Catalysts
Reduced Combustion Chamber Crevice Volumes	Electric Air Injection
Sequential Multi-Point Fuel Injection	Full Electronic Exhaust Gas Recirculation
Air-Assisted Fuel Injectors	Hydrocarbon Adsorber Systems
Heated Fuel Injectors	Engine Designs to Reduce Oil Consumption
Improved Induction Systems	Heat-Optimized Exhaust Pipes

[a] Reproduced from reference 136, Table II-16.

not limited to, higher catalyst loadings, use of close-coupled catalysts, improved high-temperature catalyst wash-coats, and heat-optimized exhaust pipes. As described in the previous chapter, the use of gasoline containing MMT® at the 8 mg Mn/l level with vehicles certified to LEV I standards has been shown to cause adverse impacts on vehicle emission control systems and increased emissions. CARB did not need to consider the impact of MMT® on these advanced emission control technologies, however, since the State of California banned the use of MMT® in unleaded gasoline during the 1970s.

With respect to the changes required to move from compliance with the LEV I regulations to compliance with the LEV II regulations, CARB again pointed to the four approaches for reducing emissions listed above and the technologies listed in Table 11-1. CARB discusses in detail three catalyst technological changes with respect to compliance with LEV II standards on passenger cars and light trucks of less than about 4,000 kg GVWR:

1. Increased catalyst volume and substrate cell density;

2. Improved catalyst formulations and washcoats, as well as increased catalyst precious metal loadings; and

3. Improved catalyst light-off with secondary air injection and retarded spark timing.

Specifically, CARB indicates that LEV II vehicles will utilize catalysts with cell densities of 600 cpsi, particularly in close-coupled locations, and that it is likely that higher cell density catalysts will also be used, again particularly in close-coupled locations. CARB states that catalyst loadings of noble metals "up to a certain point," namely 100 to 300 grams/ft^3, will be used in combination with improved washcoats. CARB also notes that improved washcoats will increase the upper level of acceptable catalyst operating temperature from around 900º C to around 1050º C, allowing catalysts to be placed in higher temperature locations. With respect to LEV II compliance by medium-duty vehicles with GVWR ratings between about 4,000 kg and 6,400 kg, CARB again focused on the need for catalyst system changes, including placement of catalysts closer to the engine, advanced catalyst formulations with improved washcoat technologies, and higher precious metal loadings.

Given the similarity of the Tier 2 regulations to CARB's LEV II regulations, the U.S. EPA reached conclusions similar to those reached by CARB, publishing its own version of what is essentially Table 11-1 (see Table IV-1 of reference 30) with regard to the technological advances required for compliance with that agency's Tier 2 regulations. Among other factors, the U.S. EPA specifically cited advances in catalyst technology, including changes in formulation, improved washcoats, greater use of close-coupled catalysts, catalysts capable of withstanding higher temperatures (up to 1100º C), increases in catalyst cell densities up to as much as 1200 cpsi, and higher precious metal loadings in the range of 100 to 250 g/ft^3.

The acuity of the 1998 CARB and 1999 U.S. EPA technical assessments regarding the technologies required for compliance with LEV II or Tier 2 emission regulations—particularly the focus on the need for advances in catalyst formulation and washcoats, use of catalysts with higher precious metal loadings capable of withstanding higher operating temperatures (on the order of 1000º C), and the use of higher cell densities—was confirmed by an extensive review of literature available regarding the development of advanced emissions control systems presented in a 2003 publication of the Manufacturers of Emission Controls Association (MECA).[76] More specifically, using data available from the literature, this paper documents the following:

1. The need for the use of close-coupled catalysts to achieve fast catalyst light-off during cold starts in order to achieve higher catalyst conversion efficiencies needed to comply with Tier 2 or LEV II emission regulations;

2. The need for the use of catalyst substrates with higher cell densities and thinner cell walls in order to provide greater catalyst surface area to improve catalyst efficiency and minimize the thermal mass of catalysts for faster light-off; and

3. The need for improved catalyst and washcoat technologies, including precious metal loadings, formulation, materials, and production processes to achieve higher catalyst efficiencies and durability requirements of the Tier 2 and LEV II regulations.

The MECA review paper also presents data regarding the introduction of these advanced emission control technologies into the marketplace. With respect to catalyst substrate design for North America, MECA indicates that for the 2003 model-year, thin wall, high density substrates accounted for about 50% of the market; that value is expected to rise to about 75% by the 2007 model-year.

It is clear that advanced three-way catalysts like those described above will be the predominant technology applied to vehicles for compliance with the LEV II or Tier 2 emission regulations. While there are other technologies identified by CARB and the U.S. EPA that may also be used (e.g., exhaust HC adsorbers[137] and exhaust NOx adsorbers and lean NOx catalysts[138]), none of these technologies have been commercialized to any significant degree in North America to date. That could change as the technologies mature, but a search of the available literature indicates that the impact of MMT® use in gasoline on the performance and durability of these technologies has not been evaluated and therefore the potential exists that serious problems could be encountered if they are used with MMT®-containing gasolines.

11.2 Survey of Vehicle Manufacturers to Collect Data on MMT® Impacts on Canadian Vehicles

Eighteen manufacturers were asked in a confidential survey if they sold vehicles using advanced emission control systems in Canada prior to MY 2004 and, if so, had they experienced catalyst plugging and/or deterioration of emissions performance associated with use of MMT®. Each of these manufacturers was assigned a confidentiality blinding code based on the letters A through R.

Nine of the surveyed manufacturers provided information regarding their field and/or research testing experience with vehicles incorporating advanced emissions control systems that they sold during this critical time period when MMT® remained in widespread use in Canadian gasoline. Separate “blinded” reports summarizing this information are included in Appendix D for manufacturers A, C, D, I, J, K, L, M, and O. These nine companies accounted for about 86 % of the total light-duty vehicle sales in Canada in calendar year 2006.

The other nine manufacturers did not provide detailed information regarding experience with vehicles incorporating advanced emission control systems. These are grouped as follows:

1. Manufacturers F and P reported selling several models with advanced emission control systems during the time period in question. Both reported observing warranty repair cases that involved plugging of the catalyst with deposits that appeared to be predominantly manganese oxide. However, neither of these two manufacturers provided follow-up information regarding the frequency of or investigation of these cases. Hence, there are no blinded reports included for these two manufacturers.

2. Manufacturers E, H, and N indicated that they did not sell any vehicles with advanced emission control systems prior to the 2004 model-year. Therefore they had nothing to report regarding experience with the exposure of such systems to gasoline containing MMT® in the Canadian market. Hence, again, there are no blinded reports included for these three manufacturers.

3. Manufacturers B, G, Q, and R each indicated they had sold one or more vehicle models using advanced emission control systems prior to the 2004 model-year. However, none of these manufacturers provided any information regarding field experience in Canada except to say that they were not aware of any warranty cases that appeared to involve catalyst plugging associated with MMT® use. None reported performing any testing or survey work to further investigate whether there were in fact MMT®-related problems or developing problems. Hence, there are no blinded reports included for these four manufacturers.

Again, it should be stressed that the nine manufacturers not reporting MMT® related issues accounted for less than 14% of the sales of light-duty vehicles in Canada in calendar year 2006.

11.3 Does the Use of MMT® in Gasoline Affect Vehicle Emissions and/or the Operation or Performance of Any Advanced Emissions Control Technologies and Systems Used in Vehicles in Canada?

While it has been known for over 30 years, as documented in Chapters 7 through 10 of this report, that MMT® use in gasoline causes adverse impacts on emission control technologies and systems as well as vehicle emissions, this chapter specifically addresses the evidence regarding the effects of the use of MMT® in gasoline on either the emissions or the operation or performance of vehicles incorporating advanced emission control technologies and systems.

As demonstrated below, there is overwhelming evidence that the use of MMT® in gasoline in Canada as fuel for vehicles with advanced emissions control technologies and systems has led to increased emissions as well as serious operational and performance problems. In addition, data collected from other countries where MMT® is allowed and vehicles with advanced emission control technologies and systems are in use provide additional evidence with respect to the substantial adverse impacts of MMT® on the operation, performance, and emissions of vehicles with advanced emission control technologies and systems.

Overview of Data from Canadian Vehicles − The data demonstrating the adverse impacts of MMT® on exhaust emissions and advanced emission control technologies and systems on in-use Canadian vehicles are documented in the blinded vehicle manufacturer reports attached to this report. These data were collected from the following sources:

1. In-use Canadian vehicles brought to dealerships by motorists for warranty service;
2. In-use Canadian vehicles recruited or obtained for data collection;
3. In-use parts from Canadian vehicles obtained by manufacturers;
4. Laboratory test programs performed in light of problems observed with in-use Canadian vehicles to confirm in-use findings and to investigate causative factors; and
5. Vehicle emissions testing.

Table 11-2 summarizes the data collected by the vehicle manufacturers and identifies the number and model years of those manufacturers' models sold in Canada that have been demonstrated, to date, to be adversely impacted by the use of MMT®. As shown, twenty-five 1999 to 2003 models produced by nine manufacturers have been shown to be adversely impacted by the use of gasoline containing MMT®. Reports documenting the findings of these nine manufacturers, which accounted for about 86% of passenger and light-duty truck sales in Canada in 2006, are presented in Appendix D.

Table 11-2
Sources of Evidence of Adverse MMT® Impacts on Exhaust Emissions, Operation, and Performance of In-Use Canadian Vehicles with Advanced Emission Control Technologies and Systems

MFR	Warranty Claims	In-Use Vehicle Inspection	Laboratory Testing	Emissions Testing	Number of Models Impacted by MMT® Identified	Model Years
A	Yes	Yes	No	No	1	1999
C	Yes	Yes	Yes	Yes	4	2000-2002
D	Yes	Yes	Yes	Yes	2	2003
I	No	Yes	No	No	1	2002
J	Yes	Yes	Yes	Yes	7	2002-2003
K	Yes	Yes	Yes	Yes	1	2003
L	No	Yes	Yes	Yes	3	2001
M	Yes	Yes	Yes	Yes	5	2001-2003
O	No	No	Yes	No	1	2001

Time Period Covered by the Data − It must be noted that the data in Table 11-2 reflect only those vehicles with advanced emission control technologies and systems for which adverse MMT® impacts have been demonstrated to date. Obviously, with the cessation of MMT® use in Canada in 2004, the real-world laboratory for investigating MMT® impacts closed. Tellingly, when MMT® was no longer added to Canadian gasoline, the increasing trend of adverse impacts subsided. This suggests that the adverse impacts through the cessation of MMT® use in Canada reflect only the "tip of the iceberg." The rationale is as follows:

1. As documented in Chapter 5, MMT® use in Canadian gasoline declined rapidly during the spring and summer of 2004 and appears to have been eliminated from Canadian gasoline in the spring of 2005. Therefore, at present, most if not all Canadian gasoline is believed to be MMT® free. Given this, vehicles with advanced emission control technologies and systems are no longer being exposed to MMT® in Canada.

2. As noted above, vehicles with advanced emission control technologies and systems were, in general, being first introduced during the 2001 to 2004 model-year period. As a result, these vehicles had relatively little exposure to MMT® relative to what they would have experienced over their entire service lives had MMT® remained in Canadian gasoline.

3. Vehicles with even more advanced emission control technologies and systems have been introduced since the 2004 model year in order to comply with emissions regulations. Due to the need to comply with Tier 2 and LEV II emission regulations, automotive emission control systems sold in North America have undergone and continue to undergo substantial change. This is required to continue at least through the 2010 model year, when the phase-in

of more stringent standards and longer required performance periods incorporated into the Tier 2 and LEV II regulations will be completed, and potentially longer given the U.S. EPA's recent promulgation of the Mobile Source Air Toxics (MSAT) regulations that create additional stringent vehicle hydrocarbon control.[139] Had the vehicles been exposed to MMT®, even greater adverse effects than discussed below would be expected in these later model-years, as they would incorporate greater use of HDCC catalysts and other technologies that have been demonstrated to be incompatible with MMT® use in gasoline.

While points 1 and 3 above are straightforward, an example illustrating the second point is presented below. Table 11-3 presents data obtained from the State of California's Smog Check program[*] for the month of November 2003 on the mean and maximum mileage accumulation rates of 2001, 2002, and 2003 model-year vehicles.[†] As shown, the highest mileage vehicles of a given model year of relatively new vehicles will have accumulated three to four times as much mileage as the average vehicle of that model year. Therefore, adverse impacts due to MMT® that are related to the amount of MMT® a vehicle has consumed will appear first on that fraction of the population that is driven many more miles than the average vehicle. Further, it follows that the magnitude of a problem related to MMT® consumption relative to the total number of vehicles sold in a given model year will initially appear to be much smaller than its ultimate magnitude should these vehicles be forced to operate on MMT®-containing fuels over the course of their entire service lives.

Table 11-3
Mean and Maximum Odometer Readings for 2001, 2002, and 2003 Model Year Vehicles Observed in the California Smog Check Program in November 2003

Model Year	Mean Odometer (km)	Maximum Odometer (km)
2003	24,800	78,850
2002	44,240	162,300
2001	67,890	240,670

<u>Summary of Data from Canadian Vehicles</u> – The data available from in-use Canadian vehicles that have been demonstrated to be adversely affected by MMT® use prior to its removal from Canadian gasoline are summarized below. Additional details are contained in the reports of each manufacturer in Appendix D of this report.

Manufacturer A − Manufacturer A has demonstrated adverse impacts resulting from the use of MMT®-containing gasoline on one model (Model A-1). The basic characteristics

[*] This is an illustration of mileage accumulation that is expected to be representative of the distribution in mileage accumulation by model year in various jurisdictions. Comparable Canadian data may be available through the annual Canadian Vehicle Survey by Statistics Canada, or other suitable sources.
[†] In general, vehicles are introduced in the fall of the calendar year that precedes their model year. For example, most 2001 model year vehicles were introduced in the fall of 2000.

of this vehicle are summarized in Table 11-4. The data demonstrating the impact of MMT® are discussed in detail below and in the Manufacturer A Report.

Table 11-4
Manufacturer A Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
A-1	1999	Tier 1	I4	No, but close-coupled

In-Use Vehicle Inspection – Manufacturer A has observed, by means of visual inspection, plugging of catalysts used on one 1999 model-year model. Visual inspection of catalysts replaced under warranty on three Canadian vehicles showed plugging by reddish-brown deposits. The catalysts were replaced at dealerships in response to owner complaints of degraded vehicle performance.

Manufacturer C − Manufacturer C has observed adverse impacts resulting from the use of MMT®-containing gasoline on four models (the 2002 version of Model C-1 differs materially from the 2000-2001 version). The basic characteristics of these models are summarized in Table 11-5. The data demonstrating the impact of MMT® on these vehicles are discussed in detail below as well as in the Manufacturer C Report.

Table 11-5
Manufacturer C Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
C-1a	2000-2001	LEV I	In-Line	Yes
C-1b	2002	ULEV I	In-Line	Yes
C-2	2002	LEV I	V	Yes
C-3	2002	LEV I	V	Yes

Canadian Warranty Claims and In-Use Vehicle Inspection – Manufacturer C has observed high catalyst warranty replacement rates in Canada on four models with advanced emission control systems. Using the warranty replacement rates collected through the middle of 2004, Manufacturer C has predicted Canadian catalyst warranty rates at 100,000 km for all four models impacted by MMT®. For Model C-1a vehicles, the warranty rate on Canadian vehicles was observed to be 20 times greater than the U.S. warranty rate for the same model. The Canadian catalyst warranty rate for Model C-1b was about 12 times higher than the U.S. warranty rate for the same model. The Canadian warranty rates for Models C-2 and C-3 were approximately 6 and 12 times higher, respectively, than the U.S warranty rates for these models. Manufacturer C also reported predicted warranty claim ratios for Canada versus the U.S. for all four models after 100,000 km of in-use operation. These ratios were even greater, by a factor of two to three, than those reported above. In addition, warranty replacements of catalysts plugged by manganese oxides on Models C-1b, C-2, and C-3 peaked during the summer of 2003 and subsequently diminished. It should be noted that, as documented in Chapter 5, substantial reductions in MMT® levels in Canadian gasoline also began at about the same time that the Canadian catalyst warranty replacement rate peaked.

Visual inspection of several catalysts replaced in Canada under warranty from Model C-1a, C-1b, and C-3 vehicles after about 45,000 to 106,000 km of in-use operation found that the catalysts were physically plugged by hard reddish-brown deposits. Analysis of the deposits by X-ray diffraction indicated that the deposits contained Mn_3O_4. Further examination of catalysts from these four models replaced under warranty in Canada at between 40,000 and 120,000 km indicated that the bulk of the replaced catalysts examined were more than 50% plugged by hard reddish-brown deposits.

Laboratory Testing – Manufacturer C measured the temperatures experienced near the catalyst face on the 2002 model-year versions of Models C-2 and C-3 during operation on the FTP and US06 driving cycles. Model C-2 experienced peak catalyst temperatures of about 600º C over the FTP and about 800º C over the US06. Model C-3 peak temperatures were higher, about 700º C over the FTP and slightly below 900º C over the SFTP.

The CO conversion efficiency of one plugged catalyst was measured before and after the reddish-brown deposits were physically removed using a mechanical process.* Removal of the deposits increased the CO conversion efficiency of the catalyst from 55% to 95%. This suggests that the decrease in catalyst efficiency was due to a decrease in the effective volume of the catalyst and a corresponding increase in the effective space velocity of exhaust passing through the converter.

Exhaust Emissions Testing – Manufacturer C has performed FTP exhaust emissions testing on one Model C-1a vehicle. The testing was performed by replacing the catalyst on a durability test vehicle that had not been operated on MMT® with a catalyst that was approximately 90% plugged by reddish-brown deposits that had been replaced under warranty in Canada after about 73,000 km of service. Emissions of NOx and CO exceeded both the 50,000-mile and 100,000-mile LEV 1 standards that the vehicle was certified to meet. NMHC emissions were greater than the 50,000-mile LEV 1 standard (73,000 km = 45,000 miles), but not greater than the 100,000-mile standard. In addition to exceeding the 50,000-mile LEV 1 emission standard, emissions from the vehicle tested with the plugged Canadian catalyst were 3 to 3.5 times higher for all three pollutants compared to emissions test data from U.S. Model C-1a vehicles that accumulated about the same mileage.

* Manufacturer C indicates that the MMT removal process involved would not be usable as a "field" repair technique.

Manufacturer D − Manufacturer D has encountered adverse impacts resulting from the use of MMT®-containing gasoline on two models. The basic characteristics of these models are summarized in Table 11-6. The data demonstrating the impact of MMT® on these vehicles are summarized below and discussed in detail in the Manufacturer D Report.

Table 11-6
Manufacturer D Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
D-1	2003	T2B7[a]	V	Yes
D-2	2003	T2B8[b]	V	Yes

[a]Tier 2 Bin 7
[b]Tier 2 Bin 8

Canadian Warranty Claims and In-Use Vehicle Inspection **–** Manufacturer D has observed a high rate of catalyst warranty claims in Canada for one 2003 model with a V-engine configuration (Model D-1). Warranty claims data collected from the introduction of the model through the summer of 2004 show the total number of claims normalized for differences in sales volumes occurring in Canada to be much higher than the total number occurring in the U.S. (scaled to Canadian sales volumes), where MMT® use is very limited. When examined as a function of mileage, the 2003 MY Canadian warranty claims rates are dramatically higher than for the U.S. beginning at about 50,000-60,000 km and remain higher through the 130,000-km limit of the data collected. A comparison of the relative Model D-1 Canadian and U.S. catalyst warranty rates as a function of the time vehicles have been in customer service shows that the Canadian rates grow logarithmically while the U.S. rates grow linearly. For the Canadian claims, the rate of increase in claims begins to slow at the point in time when MMT® began to be removed from Canadian gasoline and declines to be about the same as the U.S. rate of change once MMT® was essentially eliminated from Canadian gasoline. In addition, catalyst warranty data collected in 2007 for the model-year 2006 version of Model D-1, which would not have been exposed to MMT® in Canada, show little difference between the relative Canadian and U.S. return rates.

Catalysts removed from in-use Model D-1 vehicles in Canada that underwent warranty replacements have been subjected to visual examination by Manufacturer D. This visual examination showed that the faces of the catalysts are covered with reddish-brown deposits. Elemental characterization of the deposits using X-ray fluorescence spectroscopy determined that the primary elemental constituent of the deposits was manganese. Structural characterization of the deposits using X-ray diffraction indicates that the deposits contain Mn_3O_4. Microscopic and microprobe analyses of the deposits on the catalyst face showed that deposits have physically blocked the channels of ceramic monolith. Catalysts replaced under warranty in the U.S. have also been collected and inspected. These catalysts show no plugging by reddish-brown deposits nor the presence of such deposits.

Laboratory Testing – Manufacturer D has conducted engine dynamometer testing using MMT®-containing fuel (18 mg Mn/l) and engines and emission control systems from 2003 model-year D-1 vehicles. Testing was also performed on this engine/catalyst combination in which the original equipment HDCC catalysts were replaced by otherwise equivalent 400 cpsi catalysts. Catalyst inlet temperatures during the testing ranged from 780 to 805°C and catalyst plugging was monitored using exhaust system backpressure. Testing of the original equipment HDCC catalysts was suspended after consumption of approximately 1,000 gallons of test fuel after significant increases in exhaust system backpressure were observed relative to the 400 cpsi catalysts. In addition, visual observation of the HDCC catalysts showed progressive plugging of the converter face by brownish-red deposits over the course of the testing. Deposits were also observed on the spark plugs and oxygen sensors from the test engine. Only gradual increases in catalyst backpressure were observed for the 400 cpsi catalysts even after consumption of 3,300 gallons of fuel.

Accelerated whole-vehicle testing was also performed on the 2003 model-year version of Model D-1. This testing was again performed using original equipment HDCC and 400 cpsi catalysts and an MMT®-containing test fuel (18 mg Mn/l). The test vehicles were operated on chassis dynamometers using an EPA-approved "whole-vehicle durability" protocol until the vehicles with the original equipment HDCC catalysts reached about 160,000 km and the vehicles with 400 cpsi catalysts reached about 130,000 km. The impact of MMT® use was assessed visually, with the 400 cpsi systems showing only about 0-5% plugging (depending on which side of the V engine they were located) at 130,000 km while the original equipment HDCC system exhibited 20-50% plugging. At 160,000 km, the degree of plugging of the original equipment HDCC system had increased to 85-95%.

A second 2003 vehicle model produced by Manufacturer D (Model D-2) equipped with a V engine was evaluated using the same EPA-approved protocol as completed for the model above, with test vehicles again being equipped with an original equipment HDDC system and 400 cpsi test catalyst system. In this model, the original equipment HDCC system was about 80-85% plugged following about 110,000 km of in-use operation, while the 400 cpsi system exhibited 0-25% plugging after 130,000 km.

Exhaust Emissions Testing − FTP and US06 exhaust emissions testing was performed on the 2003 model-year version of Model D-1 by Manufacturer D. Emissions data for plugged catalysts were collected by installing plugged catalysts collected by Manufacturer D from Canada on either a U.S. reference vehicle aged to the equivalent of 160,000 km of in-use operation on non-MMT® gasoline in the U.S. or a Canadian reference vehicle that accumulated about the same mileage through in-use operation in Canada. Multiple tests, typically three, were performed on each plugged catalyst, and all testing was performed using Indolene.

The Canadian catalysts examined in this study had been replaced under warranty in Canada. Prior to removal or replacement, the catalysts had been on vehicles in in-use operation in Canada for a period of between about 40,000 and 120,000 km. The catalysts tested were visually observed to be between about 30% and 85% plugged. The U.S. catalysts examined in this study were obtained from U.S. customer fleet samples and had been in operation for about 100,000 to 160,000 km. No U.S. catalysts were observed to be plugged.

FTP emissions of NMHC, NOx, and CO obtained using the Canadian catalysts generally increased above the levels observed with the U.S. catalysts as catalyst plugging exceeded 50%, with the effect being more pronounced for NMHC and CO emissions. On average, NMHC emissions with Canadian catalysts were about double those with the U.S. catalysts; the highest emissions observed with the Canadian catalysts were about four times higher than average emissions with the U.S. catalysts. NMHC emissions levels with several Canadian catalysts exceeded the applicable full useful life Tier 2 Bin 7 standard to which the vehicle was certified. Average CO emissions with the Canadian catalysts were also about double the average CO emissions with the U.S. catalysts. Average NOx emissions with the Canadian catalysts were about 20% higher than with the U.S. catalysts.

The increase in emissions of NMHC, NOx, and CO as a function of the degree of catalyst plugging with the Canadian catalysts was markedly stronger in the US06 test data. For NMHC, average emissions with the Canadian catalysts were more than 10 times higher than average emissions with the U.S. catalysts, while the average increase in CO and NOx emissions with the Canadian catalysts were 2.1 and 3.9 times, respectively, compared to the average levels with the U.S. catalysts.

Manufacturer I − Manufacturer I has demonstrated adverse impacts resulting from the use of MMT®-containing gasoline on one model (model I-1). The basic characteristics of this model are summarized in Table 11-7. The data demonstrating the impact of MMT® on these vehicles are summarized below and discussed in detail in the Report of Manufacturer I.

Table 11-7
Manufacturer I Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
I-1	2002	NLEV (LEV)	In-Line	Yes

Canadian Warranty Claims and In-Use Vehicle Inspection − Manufacturer I obtained catalyst samples from five in-use Canadian I-1 model vehicles replaced under warranty for reasons unrelated to catalyst plugging by MMT®. The five vehicles had accumulated between about 30,000 and 140,000 km of in-use operation in Canada. Visual inspection of the catalysts showed that all five had reddish brown deposits. The deposits had plugged 30-40% of the cells on the face of catalyst taken from the vehicle that had accumulated 140,000 km and plugging was observed to a lesser degree on the catalysts from the vehicles that had accumulated less mileage.

Manufacturer J − Manufacturer J has experienced adverse impacts resulting from the use of MMT®-containing gasoline on three models (Models J-1, J-2, and J-3). Their basic characteristics are summarized in Table 11-8. The data demonstrating the impact of MMT® are summarized below and discussed in detail in the Report of Manufacturer J.

Table 11-8
Manufacturer J Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
J-1	2002-2003	NLEV (LEV)	V	Yes
J-2	2003	LEV I	In-Line	Yes
J-3	2001-2002	LEV I	In-Line Turbo	No but Close Coupled
J-4	2001-02	NLEV (LEV)	In-Line	No but Close Coupled
J-5	2001-02	NLEV (LEV)	V	Mid-Underfloor
J-6	2001-03	Tier 1	V	No but Close Coupled
J-7	2001	NLEV	In-Line	Yes

Canadian Warranty Claims and In-Use Vehicle Inspection – Manufacturer J has observed high catalyst warranty replacement rates in Canada on three models. Beginning with Model J-1, warranty data collected through mid-November 2005 show Canadian catalyst warranty replacement rates for the 2002 model-year version peaked at approximately 35 times higher than those observed in the U.S. The same data for the 2003 model-year version peaked at approximately 14 times the rate observed in the U.S. This finding is again consistent with the fact that the 2003 model-year vehicles experienced a shorter period of exposure to the potential for operation on MMT®-containing fuel given the voluntary phase-out of MMT® use in Canada documented in Chapter 5. In addition to the above, the data show that the rate of Canadian catalyst warranty replacements for 2002 and 2003 model-year Model J-1 slowed in response to the phase-out of MMT® use. This was observed by examining Canadian catalyst warranty data for Manitoba and Saskatchewan, where MMT® use persisted separately from that for the rest of the country, where MMT® use was phased-out in 2004.

Visual examination of a sample of approximately 200 catalysts replaced under warranty in Canada on J-1 vehicles with odometer readings ranging from 4,000 to 130,000 km showed that 94% exhibited heavy reddish-brown deposits on the face of the catalysts. Deposits from two of these catalysts were subjected to elemental and structural analysis using X-ray diffraction. It was found that Mn accounted for approximately 68% of the deposits by weight and these were identified as being primarily composed of Mn_3O_4. Cold-flow backpressure testing of the Canadian catalysts with deposits showed that most of the catalysts with reddish-brown deposits exhibited much higher than normal backpressure. No reddish-brown deposits were found on a sampling of 190 catalysts replaced under warranty from 2002 and 2003 J-1 vehicles in the U.S. and high backpressure was observed on catalysts replaced under warranty in the U.S. only in those cases where the catalyst substrate was broken or melted.

Turning to Model J-2, Canadian catalyst warranty replacement rates peaked at a level approximately 37 times higher than those observed in the U.S., based on warranty data collected through mid-November 2005. As with Model J-1, the rate of Canadian warranty claims was observed to slow across the east and west of Canada, followed by Manitoba-Saskatchewan, as MMT® use was phased out.

With respect to Model J-3, the incidence of replacement of the close-coupled catalysts on 2000 and 2001 is more than nine times greater than for replacement of the non-close-coupled catalyst on the earlier model-year vehicle, based on a comparison of Canadian catalyst warranty replacement rates for 2000 and 2001 model-year versions of Model J-3 with Canadian catalyst warranty replacement rates for an earlier model year without a close-coupled catalyst.

In addition to the data on the three Manufacturer J models documented above, Manufacturer J has collected catalyst warranty replacement data for all of its products sold in Canada during the period from March 1998 through May 2006 for 2000 to 2007 model-year vehicles. These data show a decrease in the rate of Canadian catalyst warranty replacements that coincides with the voluntary removal of MMT® from Canadian gasoline during this period both in the Manitoba-Saskatchewan regions and the rest of Canada.

Manufacturer J also conducted visual catalyst inspections on a sample of five models of 2001 to 2003 vehicles leased to consumers in Canada after the vehicles had been returned. This program involved inspections of 72 vehicles. The characteristics of the models as well as the results of the inspections are summarized in Table 11-9. As shown, a substantial number of the vehicles examined for all of the models except Model J-8 (of

Table 11-9
Manufacturer J Survey of In-Use Canadian Vehicle Catalysts

Model	Model-Year(s)	Engine	Catalyst	% With Deposits (Light-Heavy)	Number Examined
J-4	2001-02	In-Line	CC	90	20
J-5	2001-02	V	Mid-Underfloor	50	20
J-6	2001-03	V	CC	63	14
J-7	2001	In-Line	HDCC	100	16
J-8	2002-03	In-Line	HDCC	0	2

which only two were examined) were observed to have deposits on their catalysts ranging from light to heavy. Manufacturer J also reported that the frequency of medium and heavy deposits on Models J-4 and J-7 was greater than 50%.

Laboratory Studies – Manufacturer J measured catalyst face temperatures experienced by the 2002/2003 version of Model J-1 for which high Canadian warranty catalyst replacement rates were observed on the US06 driving cycle. Peak catalyst temperatures observed were about 875º C.

Vehicle Emissions Testing – Manufacturer J performed an emissions testing program that involved 49 2002 model-year Model J-1 vehicles. The test program involved 24 vehicles from Canada and 25 vehicles from the U.S. coming off lease from non-fleet owners between February 1 and June 1, 2004. No vehicle acceptance criteria were imposed other than requiring that test vehicles could not have had a catalyst or engine replacement in their repair history.

All vehicles were subjected to FTP emissions testing along with catalyst flow testing to determine backpressure. With respect to flow testing results, all of the U.S. and a portion of the Canadian vehicles had normal exhaust system backpressure. However, 13 of the 24 Canadian vehicles had high exhaust system backpressure and higher exhaust emissions than either the U.S. or Canadian vehicles with normal system backpressure.

Results of this testing program are summarized in Table 11-10. As shown, average as well as minimum and maximum emissions of NMHC, NOx, and CO from the U.S. and normal backpressure Canadian fleet were comparable. In contrast, both the average as well as the minimum and maximum emissions of all three pollutants were higher from the high backpressure Canadian fleet. In particular, average NMHC emissions from the high backpressure Canadian fleet were 40% higher than the U.S. fleet average while average NOx emissions were two times higher for the Canadian vehicles. Several of the Canadian vehicles with high backpressure that had accumulated less than 80,000 km had NMHC emission levels above the 50,000-mile emission standards to which this model was certified. One high-backpressure vehicle had NMHC and NOx emissions at approximately 60,000 miles that exceeded the 120,000-mile standard to which the model was certified. For vehicles with high backpressure, emissions of all three pollutants generally increased with increasing backpressure. Average engine-out emission levels for all pollutants were similar for the U.S., low backpressure Canadian, and high backpressure Canadian vehicles**.**

Following the completion of testing, catalysts from all the Canadian vehicles were subjected to elemental analysis**.** Manganese was detected in varying amounts on the face of all the Canadian catalysts and in all cases in much greater amounts than the trace amounts found on the faces of any of a sample of catalysts from the U.S. fleet. Increased exhaust system backpressure and increased emission levels were positively and non-linearly correlated with the amount of Mn found on the catalyst.

Table 11-10 Summary of Emission Test Program Conducted by Manufacturer J on 2002 Model-Year Model J-1 Vehicles	U.S. Vehicles	Canadian - Normal Backpressure	Canadian - High Backpressure
Number	25	11	13
Average Odometer (km)	64,000	45,000	73,000
Min/Max Odometer (km)	30,000/108,000	10,000/102,000	22,000/137,000
Average NMHC (g/mi)	0.076	0.072	0.105
Min/Max NMHC (g/mi)	0.05/0.10	0.05/0.09	0.07/0.20
Average NOx (g/mi)	0.169	0.154	0.341
Min/Max NOx (g/mi)	0.10/0.33	0.10/0.20	0.20/1.0
Average CO (g/mi)	0.645	0.580	1.598
Min/Max CO (g/mi)	0.3/1.3	0.4/0.8	0.75/5.0
Average Restriction (inches H_2O)	8.7	9.1	30.3
Min/Max Restriction (inches H_2O)	7.5/10.0	8.2/11.4	13.6/81.7

Manufacturer K − Manufacturer K observed adverse impacts resulting from the use of MMT®-containing gasoline on one model (Model K-1). The basic characteristics of this vehicle are summarized in Table 11-11. The data demonstrating the impact of MMT® are summarized below and discussed in detail in the Report of Manufacturer K.

Table 11-11
Manufacturer K Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
K-1	2003	NLEV (LEV)	In-Line	Yes

Canadian Warranty Claims and In-Use Vehicle Inspection – High warranty replacement rates for catalysts under warranty in Canada have been observed for Model K-1 equipped with an advanced emissions control system. A high incidence of catalyst plugging on Model K-1 relative to total catalyst warranty claims was determined through visual inspection of all catalysts replaced under warranty in both the U.S. and Canada. This visual inspection revealed that a large percentage of the Canadian catalysts replaced under warranty were substantially plugged (defined by Manufacturer K as blockage of more than 70% of the cells on the face of the catalyst) by heavy reddish brown deposits.

No such deposits were observed on any catalysts replaced under warranty on U.S. vehicles. Plugged catalysts were replaced under warranty at mileages as low as 5,000 km or less to as high as 65,000 km. The peak incidence of plugging was observed on vehicles that accumulated between 25,000 and 60,000 km. The deposits plugging Canadian catalysts were found to contain approximately 55% Mn by weight using x-ray diffraction analysis, and both Mn_3O_4 and manganese phosphate ($Mn_3(PO_4)_2$) were detected.

Laboratory Studies – Manufacturer K performed laboratory studies of catalyst plugging involving both engine dynamometer based testing and controlled mileage accumulation on specific test vehicles. The engine dynamometer testing was performed using a Model K-1 catalyst. The engine was run using a high load test cycle and a test fuel containing MMT®. Testing was halted after 17 hours of engine operation because catalyst plugging was observed. The deposits were analyzed and found to consist of 70% Mn by weight in the form of Mn_3O_4.

The vehicle testing program involved mileage accumulation on three vehicles that were operated on an MMT®-containing fuel. The vehicles were subjected to accelerated mileage accumulation by being driven on a test track for approximately 16 hours a day at a constant speed of about 150 km/hr. One of the three vehicles was Model K-1, while the other two vehicles were of a related model (Model K-2). The Model K-2 vehicles were equipped with a slightly different HDCC catalyst located further from the engine than the catalyst on Model K-1, and there were differences in exhaust system geometry between the two models. Catalyst plugging by brownish-red deposits was observed on the Model K-1 vehicle after approximately 16,000 km of operation**.** Some brownish-red deposits were observed on the two Model K-2 vehicles, but catalyst plugging did not occur during approximately 100,000 km of operation.

Catalyst temperature measurements were also made on Model K-1 and Model K-2 during two different operating modes. Peak temperatures of more than 800°C were observed on both models and somewhat higher peak temperatures were observed for Model K-1 over the US06 and SC03 dynamometer driving cycles and during steady-state cruise operation over a range of cruise speeds from 80 to 160 km/hr.

Vehicle Emissions Testing – Manufacturer K performed exhaust emissions testing using one plugged catalyst replaced under warranty from an in-use Canadian Model K-1 vehicle. This catalyst was installed on a Model K-1 test vehicle and FTP emissions testing was performed using the FTP. Emissions of CO exceeded applicable standards by a factor of six, while HC and NOx emissions remained below the emission standards.

Manufacturer L − Manufacturer L has experienced adverse impacts resulting from the use of MMT®-containing gasoline on three models (Model L-1, L-2, and L-3). The basic characteristics of these vehicles are summarized in Table 11-12. The data demonstrating the impact of MMT® are summarized below and discussed in detail in the Report of Manufacturer L.

Table 11-12
Manufacturer L Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
L-1	2001	NLEV (LEV)	In-Line	Yes
L-2	2001	NLEV (LEV)	V	Yes
L-3	2004	T2B5[a]	V	Yes

[a] Tier 2 Bin 5

In-Use Vehicle Inspection – This manufacturer obtained catalysts from four in-use Canadian vehicles representing two different model types from dealers in Canada. One of these vehicles was the 2001 model-year version of Model L-1. The 2001 Model L-1 was equipped with an in-line engine and HDCC catalyst and was certified to U.S. EPA NLEV standards. The other three vehicles were the 2001 versions of Model L-2, which was equipped with a "V" engine and also certified to U.S. EPA NLEV standards.

The catalyst from the Model L-1 vehicle was removed at a dealership in Alberta. This vehicle had accumulated about 55,000 km of in-use operation. Visual inspection of this catalyst showed that reddish-brown deposits had plugged some of the cells on the face of the catalyst.

The catalysts (six in total) from the 2001 model-year Model L-2 vehicles were removed at dealerships in Manitoba and Alberta. These vehicles had accumulated between 50,000 and 60,000 km of in-use operation. Visual inspection showed that reddish-brown deposits were present on all of the catalysts and that, in some cases, cells on catalyst faces were plugged or partially plugged by the deposits.

Laboratory Studies – Manufacturer L performed an accelerated mileage accumulation program on one 2004 model-year Model L-3 vehicle. (The 2004 Model L-3 vehicle used the same catalyst and exhaust system as the 2001 Model L-2.) The vehicle operated for 6,000 km on clear fuel and then accumulated another 74,000 km on gasoline containing MMT® at 17 mg Mn/l. The vehicle was operated six days a week over a designated route on public roads that included city, suburban, and highway driving. The vehicle's HDCC catalysts were visually inspected. This inspection revealed substantial plugging of the catalyst channels, particularly on the left catalysts, by reddish-brown deposits that were confirmed to be manganese oxides. In addition to the mileage accumulation, Manufacturer L measured catalyst temperatures on Model L-3 over the FTP and US06 driving cycles. This testing showed that peak catalyst temperatures on both catalysts reached at least 850º C over the US06. Higher temperatures were observed on the left catalyst where temperatures of 800º C or more were frequently observed on both the US06 and FTP cycles.

Vehicle Emissions Testing – FTP emissions testing was performed on the Model L-3 vehicle subjected to accelerated mileage accumulation described above. There were two tests after 44,000 and 74,000 km of operation on MMT®-containing gasoline, respectively. Emission results were compared to projected certification emissions at each mileage point. At 44,000 km, emissions from the test vehicle showed an increase in NMOG and CO emissions of more than 50% relative to projected certification emissions, with the increase in NOx emissions being about 25%, again relative to projected certification emissions. A similar comparison at 74,000 km showed an increase in NMOG emissions of about 100%, coupled with increases in CO and NOx emissions of about 50% and 15%, respectively.

In addition, Manufacturer L performed emissions testing using the catalysts taken from the three Model L-2 vehicles described previously. The data from these tests were compared to certification emission levels for Model L-2. Emissions of NMOG and CO were at or below the certification emissions level while NOx emissions increased, with the increases ranging from 2 to more than 2.5 times the certification emission level. NOx emissions, however, were still below the applicable certification emission standard.

Manufacturer M − Manufacturer M has encountered adverse impacts resulting from the use of MMT®-containing gasoline on five models (Model M-1, M-2, M-6, M-7, and M-8). The basic characteristics of these vehicles are summarized in Table 11-13. The data demonstrating the impact of MMT® are summarized below and discussed in detail in the Report of Manufacturer M.

Table 11-13
Manufacturer M Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
M-1	2001-2003	ULEV	In-Line	Yes
M-2	2002-2003	T2B5[a]	In-Line	Yes
M-6	2003	T2B5	In-Line	Yes
M-7	2003	T2B5	V	Yes
M-8	2003	T2B5	V	Yes

[a]Tier 2 Bin 5

Canadian Warranty Claims and In-Use Vehicle Inspection – Manufacturer M has observed high Canadian catalyst warranty replacement rates for two models. The first of these are 2001 to 2003 model-year versions of Model M-1 with automatic transmissions. Based on warranty data collected through the third quarter of 2005, total Canadian catalyst warranty replacement rates for the 2001 model-year version of Model M-1 with automatic transmissions were approximately three times higher than those observed in the U.S. MIL illumination was the primary reason for plugged catalyst replacements under warranty on 2001 model-year Canadian Model M-1 vehicles up to the first quarter of calendar year 2004.

Although there were no differences in the automatic transmission versions of Model M-1 over the course of the 2001 to 2003 model-years, there were differences in Canadian catalyst warranty claims rates after similar periods of time from the start of sales. The Canadian warranty rate of the 2002 version of Model M-1 began to deviate from that of the 2001 version after the use of MMT® in Canada was voluntarily suspended in mid-2004 and was lower thereafter. Similarly, the Canadian warranty claim rate for the 2003 version of Model M-1 was lower than that of the 2002 version, with the deviation again becoming apparent following the elimination of MMT® in Canadian gasoline. In addition, all Canadian catalysts replaced under warranty for 2001 to 2003 model-year automatic transmission versions of Model M-1 were inspected for plugging and flow restriction. The rates of occurrence of plugging on 2001 and 2002 versions of Model M-1 decreased dramatically following the elimination of MMT® from Canadian gasoline, and plugging rates for the 2003 model-year version, which saw only limited exposure to MMT®-containing gasoline, remained low after MMT® was eliminated. The average odometer reading at the time of warranty catalyst replacement on Canadian 2001 to 2003 model-year vehicles was between 80,000 and 100,000 km.

The differences in the ratio of Canadian and U.S. warranty rates is, as described below, attributed to MMT®-related plugging; the lower ratios for later model years is explained by the more limited mileage accumulated by the 2002 and 2003 model-year vehicles through the middle of 2005 and the decreased use of MMT® in Canadian gasoline documented in Chapter 5, which began in early 2004.

Catalysts replaced under warranty on the 2001 model-year version of Model M-1 from the third quarter of 2002 through the second quarter of 2005 were subjected to visual inspection. From the start of this period through the first quarter of 2004, more than 60% of catalyst converters replaced under warranty were found to have hard reddish-brown deposits on the face of the catalyst that were physically plugging the channels of the substrate. The frequency of catalysts exhibiting plugging by reddish-brown deposits was observed to diminish over the rest of the period during which, again as documented in Chapter 5, MMT® concentrations in Canada gasoline decreased substantially. Examination of a sample of catalysts replaced under warranty in the U.S. did not reveal the presence on any catalyst of reddish-brown deposits like those observed in Canada.

The second model was the 2002 and 2003 model-year versions of Model M-2**.** Based on warranty data collected through the middle of 2005, Canadian catalyst warranty replacement rates for the 2002 model-year version of Model M-2 were approximately two times higher than those observed in the U.S**.** Many of the catalysts replaced under warranty in Canada between August 2002 and April 2004 were found through visual examination to have hard reddish-brown deposits on the face of the catalyst that were physically plugging the channels of the substrate. The average odometer reading at the time of warranty catalyst replacement was between 60,000 and 80,000 km. Again, most of the catalysts that were replaced on Canadian Model M-2 vehicles were replaced because the OBD II system MIL was illuminated and fault codes indicating a failed catalytic converter were stored in the system. Further, as with Model M-1, the observed incidence of catalyst plugging for Model M-2 decreased as MMT® use in Canadian gasoline decreased.

Manufacturer M also obtained catalyst samples from in-use 2001 model-year versions of its Model M-1. Most of these vehicles were randomly selected from the fleet of such vehicles registered in the province of Ontario, although vehicles that had a history of operation under severe conditions were excluded. Sixty-three vehicles were selected using odometer readings as an additional criterion. The odometer readings of the vehicles from which the catalysts were removed ranged from about 21,000 to 115,000 km. Visual inspection of the catalysts indicates the presence of varying degrees of reddish-brown deposits on the face of the converter that were plugging some portion of the catalyst channels. Using flow measurements, the degree of plugging of each Canadian catalyst was determined. The bulk of the catalysts were found to exhibit plugging of between 1% and 15%, with the maximum amount of plugging being about 80%. U.S. catalysts replaced under warranty, in contrast, showed substrate cracking in some cases but did not show plugging, except for those catalysts collected in the one area of the U.S. where most MMT® use has been reported.

Laboratory Studies – Manufacturer M has performed laboratory studies analyzing the deposits found on in-use catalytic converters from in-use Canadian vehicles. These analyses include particle-induced X-ray emission (PIXE) analysis to determine the elemental composition of the deposits and X-ray diffraction to determine the atomic structure of materials present in the deposits. Data from these analyses confirm that the deposits contain high concentrations of manganese present in the form of Mn_3O_4.

Vehicle Emissions Testing – Manufacturer M conducted three studies of the emissions impact associated with manganese oxide plugging of advanced catalytic converters. The first of these studies involved emissions testing using six catalytic converters obtained from in-use Model M-1 Canadian vehicles. Five of these catalysts were replaced under warranty (due to MIL illumination) and the sixth was obtained from a randomly selected in-use Model M-1 vehicle operating in Canada. The vehicles from which the catalysts were obtained had accumulated between about 56,000 and 131,000 km of operation in Canada. The six catalysts were sequentially installed on a single test vehicle and FTP emission testing was performed. Emissions, particularly of NOx, were much higher with the five warranty replacement catalysts than with the sixth catalyst. Further, relative to the observed emissions of a random sample of in-use Model M-1 vehicles in the U.S. with similar odometer readings, HC and NOx emissions from the tests with Canadian warranty replacement catalysts were 2 to 6 and 3½ to 11 times greater, respectively.

The second test program was similar but involved two larger groups of catalysts. The first group consisted of 63 catalysts randomly selected from in-use Model M-1 vehicles in Ontario. The procurement process was designed to exclude catalysts from vehicles with illuminated MILs and vehicles that were subject to atypical usage patterns. Based on flow measurements, most catalysts were observed to be plugged by 30% or less and two catalysts were found to be more than 80% plugged. Given the lack of catalysts with plugging between 30% and 80% in the first sample, a second sample of 25 catalysts was obtained from the pool of all catalysts replaced on 2001 model-year versions of Model M-1 under warranty in the province of Ontario. All of these catalysts were between 50%

and 90% plugged, based on the same flow measurements used with the first sample. The test program also included three “reference” or “baseline” catalysts, one of which was taken from a 2001 model-year Model M-1 vehicle that had accumulated about 3,000 km of operation using commercial California gasolines (referred to as the “new baseline” catalyst) and the other two representing 100,000 km of operation in the California market (referred to as “aged baseline” catalysts).

Each of the 63 catalysts from the first sample, 8 from the second sample, and the 3 baseline catalysts were installed on a single 2001 model-year Model M-1 test vehicle and emissions measurements were made over both the FTP and US06 driving cycles. All testing was performed using California Phase II certification fuel that contained no MMT®. The FTP emissions test results showed that emissions of NMHC, CO, and NOx generally began to increase once the plugging ratio exceeded about 10%; by the time the plugging ratio reached 50% or more, emissions of all three pollutants were more than double those observed with the baseline catalysts and lightly plugged (less than 10%) catalysts. The catalyst with the greatest degree of plugging also exhibited the highest emission results, which were on the order of ten times higher than those observed with the baseline catalysts. Fuel consumption was also observed to rise (and fuel economy in terms of miles per gallon decreased) as the degree of catalyst plugging became more severe. In addition, as one would expect, the magnitude of the emissions increase due to plugging relative to the new baseline catalyst was greater in the data from the US06 testing as the higher exhaust gas flow rates led to higher catalyst space velocities and greater catalyst breakthrough with the plugged catalysts**.**

The third study conducted by Manufacturer M involved a series of experiments in which emissions from seven different 2001 through 2003 model-year models produced by Manufacturer M operated on unleaded gasoline containing MMT® at the 8 mg Mn/l level were compared with emissions from clear-fueled vehicles of the same model and year. Descriptions of the vehicles and a summary of the emissions comparisons are provided in Table 11-14 and discussed in detail below. As shown, all of the vehicles were equipped with HDCC catalysts in either manifold or mid-underfloor locations.

All of the vehicles operated on MMT®-containing gasoline, and two of the vehicles operated on clear fuel (Models M-1 and M-7) were subjected to an on-road mileage accumulation program. Each of these nine vehicles accumulated about 6,000 km per week over two driving routes established on public roads, with one route being representative of city driving and the other being representative of on-highway driving, including driving in mountains. FTP emissions testing of these vehicles was conducted at various points between 6,000 and 190,000 km using clear fuel, although mileage accumulation on some vehicles operating on the MMT®-containing fuel was halted sooner because of excessive catalyst backpressure and OBD MIL illumination with storage of codes indicating catalyst failure. Emissions data for the remaining vehicles during operation on clear fuel were generated as part of the new vehicle development process. This process involved FTP emissions testing first at zero miles and then after 6,500 km of mileage accumulation. Following this testing, catalysts and oxygen sensors were removed from the test vehicles and subjected to accelerated aging using approved laboratory-based engine dynamometer procedures. The components were replaced and the vehicle was FTP emission tested after specific aging intervals that had been correlated by Manufacturer M to specific periods of on-road vehicle operation.

Model M-1 – The 2001 model-year version of Model M-1, for which high catalyst warranty rates were observed in Canada, was included in this test program. The MMT® vehicle was operated on clear fuel through 8,000 km and then operated on the MMT®-containing test fuel for another 61,000 km before driving was terminated due to high exhaust backpressure and MIL illumination with storage of a fault code related to catalyst failure. The clear-fueled vehicle underwent mileage accumulation before the MMT® vehicle. Exhaust emissions from the vehicle operated on MMT®-containing gasoline vehicle increased such that they exceeded both the 50,000-mile and 100,000-mile CA ULEV I NMOG and NOx standards to which Model M-1 was certified. As shown in Table 11-14, at the conclusion of the mileage accumulation on the MMT® vehicle its NMOG and NOx emissions were 4.5 and 10 times higher, respectively, than clear-fueled vehicle emissions at that same mileage.

Physical examination of the catalyst of the Model M-1 MMT® vehicle showed extensive plugging of catalyst cells by reddish-brown deposits. Replacement of the catalyst on the MMT® vehicle with a new catalyst reduced emission levels to below those of the clear-fueled vehicle. In addition to catalyst replacement, an effort was made to remove the manganese oxide deposits from the plugged catalyst of MMT® vehicles using ceramic beads as a grinding medium. This manual process required approximately 30 to 45 minutes to perform (excluding the time required for catalyst removal and installation).[*] Subsequent FTP emission testing showed that removal of the manganese oxides that had plugged the catalyst cells resulted in a substantial decrease in emissions, bringing emissions levels that exceeded the vehicle's certification NMOG and NOx standards down to the levels observed with the baseline catalysts.

Model M-2 – The 2003 model-year version of Model M-2 vehicles for which high catalyst warranty rates were observed was also included in this study. In this case, the MMT® vehicle was operated for only 32,000 km before MIL illumination with storage of a fault code related to catalyst failure occurred and high exhaust back pressure was observed. In this case, the MMT® vehicle operated exclusively on MMT®-containing fuel during mileage accumulation. As shown in Table 11-14, emissions of NMOG and NOx from the MMT® vehicle were 10% and 30% higher, respectively, than from the clear-fueled vehicle. Physical examination of the catalyst of the MMT® vehicle showed extensive plugging of catalyst cells by reddish-brown deposits. Replacement of the catalyst and oxygen sensors reduced NMOG and NOx emission levels to below the levels of the clear-fueled vehicle.

[*] This process is reported as being impossible to implement in a vehicle repair facility environment due to concerns regarding its effectiveness and potential adverse health impacts on technicians.

Table 11-14
Summary of Manufacturer M Testing of MMT® Effects on Emissions of Seven 2001 to 2003 Models

Model (MY)	Engine	HDCC	Catalyst Location	Standards	Odometer Reading (km)	High Backpressure	Ratio of MMT® Vehicle Emissions to Clear Vehicle @ Final Odometer		MIL ON
							NMHC	NOx	
M-1 (01)	I	Y	Manifold	ULEV I	69,000	Y	4.5	10	Y
M-2 (03)	I	Y	Mid-Underfloor	T2B5[a]	32,000	Y	1.1	1.3	Y
M-3 (03)	I	Y	Mid-Underfloor	T2B5	190,000	N	1.4	1.3	N
M-4 (03)	I	Y	Mid-Underfloor	T2B5	190,000	N	1.0	1.0	N
M-6 (03)	I	Y	Mid-Underfloor	T2B5	190,000	N	1.2	1.5	N
M-7 (03)	V	Y	Manifold	T2B5	160,000	Y	2.2	3.5	Y
M-8 (03)	V	Y	Manifold	T2B5	170,000	Y	1.5	1.7	Y

[a]Tier 2 Bin 5

Models M-3 and M-4 – Model M-3 was a 2003 model-year vehicle with an in-line engine certified to U.S. EPA Tier 2 Bin 5 emission standards. Model M-4 was a higher performance version of Model M-3 certified to the same standards. For both Model M-3 and M-4, emissions from the MMT® vehicles remained near those of clear-fueled vehicles until the 130,000 km test point. After this point, emissions from the MMT® Model M-3 vehicle increased somewhat through the 190,000 km test point, at which time the NMOG and NOx emissions were 40% and 30% higher, respectively, than those of the clear-fuel vehicle. Examination of the catalyst of the MMT® vehicle revealed reddish-brown deposits but no significant plugging of catalyst cells, and no increase in back pressure or MIL illumination was observed. The emissions of the MMT® vehicle in the Model M-4 pair remained nearly identical to those of the clear vehicle and, again, while there were reddish-brown deposits found on the catalyst of the MMT® vehicle, there was no significant plugging, increase in back pressure, or MIL illumination observed.

Unlike the other MMT® vehicles in this test program, the MMT® Model M-3 and M-4 vehicles were subjected to an evaluation of the impacts of MMT® on engine components after 25,000 km of mileage accumulation. Emissions test data from the Model M-3 vehicle obtained before and after the engine was evaluated indicate that the evaluation may have had some impact on emissions. The Model M-4 vehicle did not receive an emissions test immediately following the engine evaluation; therefore, the impact on emissions of this vehicle is not known.

Model M-6 – This was also a 2003 model-year vehicle with an in-line engine and certified to U.S. EPA Tier 2 Bin 5 emissions standards. Emissions from the MMT® vehicle remained near those of the clear-fuel vehicle until the final 190,000 km test point, at which time they were observed to be 20% higher for NMOG and 50% higher for NOx. There was also a modest increase in back pressure observed for the MMT® vehicle at the end of the mileage accumulation period. Physical examination of the catalyst of the MMT® vehicle showed moderate plugging of catalyst cells by reddish-brown deposits that were confirmed to be manganese oxides.

Model M-7 – Model M-7 was a 2003 model-year vehicle with a “V” engine configuration certified to U.S. EPA Tier 2 Bin 5 standards. As noted above, in this case a pair of test vehicles—one operating on MMT® and one operating on clear fuel—was subjected to on-road mileage accumulation. The MMT® vehicle accumulated 160,000 km before the MIL illuminated and a fault code related to catalyst failure was stored and excessive backpressure was observed. Emissions of NMOG and NOx from the MMT® vehicle were 2.2 and 3.5 times higher, respectively, than those from the clear-fuel vehicle. Physical examination of the catalyst of the MMT® vehicle showed extensive plugging of catalyst cells by reddish-brown deposits that were confirmed to be manganese oxides. Physical examination of the catalyst from the clear-fueled vehicle that was driven to 190,000 km revealed no deposits.

Model M-8 – This was another 2003 model-year vehicle with a “V” engine certified to U.S. EPA Tier 2 Bin 5 standards. As with the Model M-1 MMT® vehicle, the Model M-8 MMT® vehicle was operated for 8,000 km on clear fuel before accumulating 160,000 km on the MMT®-containing fuel. Driving was suspended at 170,000 km due to MIL illumination and storage of a fault code related to catalyst failure. High exhaust back pressure was also observed. NMOG and NOx emissions from the MMT® vehicle were 50% and 70% higher, respectively, than those of the clear fuel vehicle. Physical examination of the catalyst of the MMT® vehicle showed extensive plugging of catalyst cells by reddish-brown deposits. Replacement of the catalyst, oxygen sensors, and spark plugs reduced NMOG and NOx emission levels to below the levels of the clear fueled vehicle.

Again, the results of Manufacturer M's testing program are summarized in Table 11-14.

Manufacturer O − Manufacturer O has encountered adverse impacts resulting from the use of MMT®-containing gasoline on one model (Model O-1). The basic characteristics of this model are summarized in Table 11-15. The data demonstrating the impact of MMT® are summarized below and discussed in detail in the Report of Manufacturer O.

Table 11-15
Manufacturer O Models Demonstrated to be Adversely Impacted by MMT®

Model	Model Year	Certification	Engine	HDCC
O-1	2001	ULEV	In-Line	Yes

Laboratory Studies – Manufacturer O performed a vehicle testing program that involved in-use operation of one Model O-1 vehicle. The vehicle was operated during the period when MMT® was still being added to Canadian gasoline as a company fleet vehicle in Ontario using locally available premium unleaded gasoline known "to have MMT concentrations around the average or higher level observed in the Alliance fuel surveys for Canada." The vehicle was operated for approximately 120,000 km and visual examination of the catalyst at the end of the mileage accumulation period indicated that catalyst plugging had begun.

11.4 Given That Adverse Effects of MMT® Have Been Demonstrated on Vehicles with Advanced Emission Control Technologies and Systems, Do the Affected Vehicles Share Common Characteristics?

Based on the available evidence presented in this chapter, as well as in Chapters 7 through 10, the adverse effects of MMT® on advanced emission control technologies and systems can be divided into two main types: those associated with the formation of manganese oxide deposits in the combustion chamber, and those associated with the formation of manganese oxide deposits on the faces of catalysts in the exhaust system.

With respect to the former, effects of this type will occur in all vehicles that operate on MMT®-containing fuels regardless of the characteristics of the engine.

The mechanism by which the catalyst plugging documented above occurs has not been definitively established, but it appears that the following factors play a significant role:

1. Vehicles equipped with close-coupled catalysts or HDCC catalysts appear to be affected more frequently than vehicles with under-floor catalysts.

2. The amount of MMT®-containing fuel burned by the vehicle affects plugging, with an increase in MMT® consumption leading to a greater degree of plugging.

3. High exhaust gas and/or peak catalyst temperatures, particularly of 800º C or more, which are frequently encountered by close-coupled catalysts and HDCC catalysts, are associated with plugging.

4. As the surface area available for flow through individual catalyst cell channels decreases (or the cell density of the catalyst increases for a given wall thickness, or the thickness of the cell walls increases for a given cell density), the likelihood of plugging appears to increase.

5. Exhaust system geometry and exhaust gas flow dynamics can also, it appears, play a role in catalyst plugging. For example, sharper flow angles upstream of the catalyst have been shown to accelerate the rate at which MMT® plugging occurs.

Of the above factors, only the amount of MMT®-containing fuel burned by the vehicle is not a characteristic of the design of the emissions control system that is directly related to the ability of that system to reduce exhaust emissions. Preventing the operation of the vehicle on fuels containing MMT® requires only the elimination of MMT® from the fuel on which the vehicle operates. The use of MMT®-free unleaded gasoline has been demonstrated to be technically feasible and economically viable in North America, as well as throughout most of the world. In contrast, it has never been demonstrated that an advanced emission control system in which MMT®-caused plugging has been observed on in-use vehicles can be redesigned to eliminate that plugging and simultaneously prevent any impairment of the system's effectiveness and durability.

11.5 What is the Magnitude of the Effect of MMT®?

The magnitude of the effects of MMT® use on vehicles with advanced emission control technologies and systems will depend on a number of factors. Primary among these are ultimate increases in emissions and the failure rates for catalysts and other components that can be directly attributed to the use of MMT®.

At this point, the ultimate impacts of MMT® use on vehicle and emission system control performance cannot be definitively determined. However, what is known at this point about the consequences of the use of MMT®-containing fuels in vehicles that comply with the Tier 2/LEV II regulations is summarized below.

1. Plugging of catalysts on in-use vehicles due to manganese oxides can occur and has been documented at this point to be a substantial problem on a number of different models of in-use Canadian vehicles produced by a number of different manufacturers.

2. Vehicles with catalysts plugged by manganese oxides can have driveability problems due to excessive exhaust system backpressure. These problems can be corrected only by catalyst replacement.

3. Vehicles with catalysts plugged to a substantial degree by manganese oxides will generally experience MIL illumination and have fault codes stored indicating catalyst failure. The MIL can be extinguished and fault codes prevented from being stored only if the catalyst is replaced.

4. The plugging of catalysts by manganese oxides is most frequently observed on vehicles with advanced emissions controls systems that incorporate HDCC catalysts. Such vehicle designs are expected to become widespread as all new vehicles sold in the U.S. and Canada are required to comply with the requirements of the Tier 2/LEV II regulations.

5. Some advanced technology vehicles for which catalyst plugging due to MMT® has been demonstrated have also been shown to have, to varying degrees, increased tailpipe emissions of NMOG, CO, and NOx.

6. A slowing of the rate of increase of Canadian catalyst warranty replacement relative to the U.S. warranty rate on those models where MMT®-related plugging has been documented has been observed in direct response to the reduction in the use of MMT® in Canadian gasoline.

7. There is no demonstrated method, other than eliminating MMT® from the fuel, to ensure that an emission control system that allows a vehicle to comply with the requirements of the Tier 2/LEV II regulations will not experience catalyst plugging caused by manganese oxides and one or more of the observed problems of degraded driveability, MIL illumination, and increased emissions.

11.6 Reassessment of Impact on Emissions of the Canadian Vehicle Fleet

In light of the above factors, the potential impact of MMT® use on emissions from the Canadian vehicle fleet has been reevaluated by Air Improvement Resource, Inc. using both the data available from the Alliance-AIAM-CVMA study as well as the appropriate data related to the adverse MMT® impacts on in-use Canadian vehicles summarized above. This study, contained in Appendix E of this report, was similar to that described in Chapter 9 to evaluate the significance of the results of the Alliance-AIAM-CVMA study on in-use emissions. It examined seven scenarios for MMT® use in Canada, and it also estimated emissions for a hypothetical baseline scenario that assumed that MMT® had never been used in Canada.

The basic methodology of the Air Improvement Resource, Inc. study involved the segregation of test vehicles from the Alliance-AIAM-CVMA study and data from vehicles tested by Manufacturers D, J, and M described above into four groups intended to represent the following categories of in-use vehicles:

- Group 1: Light-duty trucks and heavy-duty vehicles certified to Tier 1 and LEV emission standards;

- Group 2: Passenger cars certified to Tier 1 emission standards;

- Group 3: Passenger cars and light-duty trucks with loaded vehicle weights of 3,750 pounds or less certified to LEV standards; and

- Group 4: Vehicles of all types certified to Tier 2 standards.

The emissions data available for vehicles operated on clear and MMT®-containing fuels were then used to develop "MMT® correction factors" that account for the impacts of MMT® on vehicle emissions as a function of mileage that were then used to adjust vehicle emission factors within the MOBILE6C emission factor model. This modified version of MOBILE6C was then used to compute adjusted emission factors reflecting the use of MMT®, which were combined with appropriate data on annual vehicle travel in Canada to yield annual inventories of gasoline vehicle emissions of VOC, CO, and NOx. Inventories were computed for calendar year 2007 to 2020 for each of the seven MMT® scenarios. The baseline scenario where MMT® was assumed to have never been used in Canada was also computed using MOBILE6C without the modifications described above.

The results of the study can be summarized as follows:

1. Using conservative assumptions that likely understate the impact of MMT® use on emissions of in-use vehicles, it was estimated that reintroduction of MMT® in 2008 in Canada at historic levels would result in increases in VOC, CO, and NOx emissions of 77%, 51%, and 12%, respectively, by 2020; and

2. Despite the phase-out of MMT® use in Canada in 2004 and 2005, the lingering adverse impacts of MMT® that have increased emissions of VOC

and CO will persist through 2020, as will modest reductions in NOx emissions.

11.7 Do MMT® Effects Vary with the Concentration of MMT® in Gasoline?

As has been reported in several studies, the amount of MMT® consumed by a vehicle appears to be one of the factors related to catalyst plugging. In general, all other things being equal, as the amount of MMT® in the fuel increases, the mileage at which plugging occurs decreases. There is no study that had determined a "safe" level of MMT® in advanced technology vehicles known to be adversely affected by MMT® use.

11.8 Would the Use of MMT® in Gasoline Affect the Introduction of Any Vehicle Combustion or Engine Technology or Emissions Control Requirement That Has Been Developed to the Point Where It Would Otherwise be Expected to be in General Use in North America?

As has been documented above, the use of MMT® in vehicles with advanced emissions control technologies and systems can adversely affect vehicle emissions, performance, and operation, as well as the emission control system. This demonstration has been made on in-use vehicles operated in Canada (which are also concurrently sold in the United States). The consequences of MMT® use observed to date include increased emissions as well as increases in consumer complaints, MIL illumination, and warranty claims. While data are not available, adverse effects such as loss of acceleration capability may also have vehicle safety consequences.

There are several key factors, outlined below, that need to be highlighted with respect to the demonstrations from the in-use laboratory provided by the Canadian experience.

1. The advanced emissions control technologies needed to achieve Tier 2 and LEV II emission levels were still being phased-in during the 2000 to 2004 period. Therefore, they were not present on many vehicle models sold during this period.

2. In the case of many manufacturers, complying with the completely phased-in requirements of the Tier 2 and LEV II regulations will require deployment of advanced emission control technology and systems on a wider range of vehicles than during the 2000 to 2004 model-year.

3. Exposure of 2000 to 2004 model-year vehicles to MMT® was limited by the gradual phase-out of MMT®, which began in early 2004.

All three of the above factors suggest that the impacts associated with MMT® use in Canada during the 2000 to 2004 period are much smaller than they would be if MMT® use had continued or resumes in Canada. Given this and the unequivocal demonstration that MMT® use is not compatible with the advanced emission control systems required for compliance with the Tier 2 emission standards, it is unclear how manufacturers could be expected to introduce vehicles equipped with these emission control systems, or those meeting similar stringent control requirements, into any market in the world where MMT® is added to unleaded gasoline.

###

12. REFERENCES

1. See http://www.nap.edu/books/030903938X/html/189.html.

2. See http://www.epa.gov/ttn/naaqs/pm/pm25_index.html.

3. Canada Gazette, Part II, Vol. 137, No. 1, January 2003.

4. California Air Resources Board, "Proposed Regulations for Low-Emission Vehicles and Clean Fuels," Staff Report and Technical Support Document, August 1990.

5. Gibbs, L.M., "Gasoline Additives, When and Why," Society of Automotive Engineers Technical Paper Series, Paper 902104, 1990.

6. Gibbs, L.M., "How Gasoline has Changed," Society of Automotive Engineers Technical Paper Series, Paper 932828, 1993.

7. Gibbs, L.M., "How Gasoline has Changed II – The Impact of Air Pollution Regulations," Society of Automotive Engineers Technical Paper Series, Paper 961950, 1996.

8. World-wide Fuel Charter, Fourth Edition, European Automobile Manufacturers Association, Alliance of Automobile Manufacturers, Engine Manufacturers Association, Japan Automobile Manufacturers Association, and Associate Members September 2006.

9. B.C. Reg. 498/95

10. Canada Gazette, Part II, Vol. 131, No. 24, pp:(needed), November 26, 1997.

11. See http://www.ec.gc.ca/energ/fuels/reports/ccme/ccme4_2_e.htm.

12. Canada Gazette, Part II, Vol. 133, No. 13, pp: 1464, June 23, 1999.

13. Federal Register, Vol. 38, No. 6., pp 1254, January 10, 1973.

14. California Air Resources Board, "Reformulated Gasoline: Proposed Phase 1 Specifications, Staff Report and Technical Support Document, August 1990.

15. Section 80.22, Title 40, Code of Federal Regulations.

16. California Air Resources Board Staff Reports 75-15-2 and 75-16-3, 1975.

17. See Section 211(f) of the Clean Air Act.

18. See http://www.chron.com/content/chronicle/business/96/04/16/mmtstory.2-0.html.

19. See Section 211(l) of the Clean Air Act.

20. See Section 211(m) of the Clean Air Act.

21. See Section 211(k) of the Clean Air Act.

22. See Subpart D, Part 80, Title 40, Code of Federal Regulations.

23. California Air Resources Board, “Proposed Regulations for California Phase 2 Reformulated Gasoline,” Staff Report and Technical Support Document, October 1991.

24. California Air Resources Board, “Proposed Regulations for Low-Emission Vehicles and Clean Fuels,” Staff Report and Technical Support Document, August 1990.

25. California Air Resources Board, “Proposed Specifications for Gasoline Certification Fuel for Motor Vehicles,” Staff Report, June 1992.

26. California Air Resources Board, “Proposed California Phase 3 Gasoline Regulations, Initial Statement of Reasons,” October 1999.

27. U.S. EPA, Staff White Paper – Study of Unique Gasoline Fuel Blends (“Boutique Fuels”), Effects on Fuel Supply and Distribution and Potential Improvements,” U.S. EPA420-P-01-004, October 2001.

28. See http://www.epa.gov/otaq/regs/fuels/boutique-list-fn.pdf.

29. Federal Register, Vol. 65, No. 28, pp: 6698, February 10, 2000.

30. U.S. EPA, “Regulatory Impact Analysis – Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emission Standards and Gasoline Sulfur Control Requirements,” EPA420-R-99-023, December 1999.

31. See http://www.crcao.com/reports/auto-oil/.

32. See http://www.aftonchemical.com/Products/index.htm.

33. Gibbs, L.M., “Gasoline Additives – When and Why,” Society of Automotive Engineers Technical Paper Series, Paper 902104, 1990.

34. Owen, K. and Coley, T., Automotive Fuels Reference Book 2nd ed., Society of Automotive Engineers, Inc., 1995, see pages 119-121 and 324.

35. Unzelman, G.H., “Manganese Gains Stature as Octane Improver for Unleaded Gasoline,” The Oil and Gas Journal, November 17, 1975, pages 49-57.

36. Bailie, J.D., “Economics of Manganese as an Antiknock in Unleaded Gasoline,” Paper AM-76-17, presented at the 1976 Annual Meeting of the National Petroleum Refiners Association, San Antonio Texas, March 30, 1976.

37. Presentation on MMT to California Air Resources Board, Ethyl Corporation, May 11, 1976.

38. Letter from E.A. Desmond, Ethyl Corporation, to J.P. DeKany, U.S. Environmental Protection Agency, August 27, 1976.

39. U.S. EPA MSAPC Advisory Circular, A/C No.26-B, January 7, 1977.

40. U.S. EPA MSAPC Advisory Circular, A/C No.26-B-1, August 12, 1977

41. State of California Air Resources Board, Resolution 77-39, July 7, 1977.

42. Memo from Michael P. Kenny, California Air Resources Board Executive Officer to California Air Resources Board Chairman, John D. Dunlap, III, February 17, 1998.

43. §211(f)(2) Clean Air Act.

44. §211(f)(3) Clean Air Act – Note that the actual ban on MMT use does not appear to have occurred until October 27, 1978, as indicated in reference 48.

45. §211(f)(4) Clean Air Act.

46. Federal Register, Vol. 59, pp 42228, August 17, 1994.

47. Federal Register, Vol. 43, pp 24742, June 7, 1978.

48. Federal Register, Vol. 43, pp 41424, September 18, 1978.

49. Federal Register, Vol. 46, pp 35180, July 7, 1981.

50. Federal Register, Vol. 46, pp 58360, December 1, 1981.

51. Federal Register, Vol. 55, pp 22947, June 5, 1990.

52. Federal Register, Vol. 55, pp 52215, December 20, 1990.

53. Federal Register, Vol. 56, pp 36811, August 1, 1991.

54. Federal Register, Vol. 57, pp 2535, January 22, 1992.

55. Federal Register, Vol. 58, pp 35950, July 2, 1993.

56. Ethyl Corp. v. E.P.A., No. 94-1505. 51 F.3d 1053 (D.C. Cir. 1995).

57. Federal Register, Vol. 60, pp 36414, July 17, 1995.

58. See http://www.epa.gov/otaq/rfg/whereyoulive.htm.

59. §211(k)((2)(D) of the Clean Air Act.

60. §80.41(h)(1) Title 40, Code of Federal Regulations.

61. Unleaded Automotive Gasoline, CGSB 3.5-2004, Canadian General Standards Board, November 1, 2004.

62. Standard for Unleaded Automotive Gasoline, 3-GP-5Ma, Canadian Government Specifications Board, December 1978.

63. Minutes from the 87th Meeting of the Petroleum Committee, Canadian Government Specifications Board, specific comments on three-way catalysts and MMT use made by committee member J. Labuda of Environment Canada, November 9, 1978.

64. Unleaded Automotive Gasoline, CAN2-3.5-M79, Canadian General Standards Board, May 1979.

65. "An Assessment of the Effect of MMT on Light-Duty Vehicle Exhaust Emissions in the Canadian Environment," Working Group under the Jurisdiction of the Gasoline and Alternative Automotive Fuels Committee, Canadian General Standards Board, April 4, 1986.

66. Methylcyclopentadienyl Manganese Tricarbonyl (MMT) Case Study, National Round Table on the Environment and the Economy, Health, Environment & the Economy Program, November 1999.

67. Manganese-Based Fuel Additives Act, 1997, Chapter 11; in force June 24, 1997.

68. Dispute Regarding the Manganese-based Fuel Additives Act, submission by the Government of Alberta to the Agreement on Internal Trade, December 1, 1997.

69. Report of the Article 1704 Panel Concerning a Dispute Between Alberta And Canada Regarding the Manganese-Based Fuel Additives Act, File No. 97/98 - 15 - MMT - P058, The Agreement on Internal Trade, June 12, 1998.

70. "On-Road Vehicle and Engine Emission Regulations," Canada Gazette, Part II, Part 2, Volume 137, Issue 1, January 1, 2003.

71. Summer and Winter AAMA and Alliance North American Fuel Surveys of Motor Gasoline: Winter 1994 through Winter 2007.

72. Canadian Petroleum Products Institute, "2004 Environmental And Safety Performance Report," available at http://www.ec.gc.ca/ceparegistry/participation/archives/default.cfm?intyear=2004

73. "Cleaner Cars, the History and Technology of Emission Control Since the 1960s," J.R. Mondt, Society of Automotive Engineers, 2000.

74. "Catalytic Air Pollution Control, Commercial Technology," R.M. Heck and R.J. Farrauto, Van Nordstrand Reinhold, 1995.

75. "Internal Combustion Engine Fundamentals," Chapter 11, J.B. Heywood, McGraw-Hill, 1998.

76. "Tier 2/LEV II Emission Control Technologies for Light-Duty Gasoline Vehicles," Manufacturers of Emission Controls Association, August 2003.

77. Faggan, J.E., et al, "An Evaluation of Manganese as an Antiknock in Unleaded Gasoline," Society of Automotive Engineers Technical Paper Series, Paper No. 750925, 1975.

78. Lenane, D.L., "MMT - A Further Evaluation," Society of Automotive Engineers Technical Paper Series, Paper No. 770656, 1977.

79. Lenane, D.L., "Effect of MMT on Emissions from Production Cars," Society of Automotive Engineers Technical Paper Series, Paper No. 780003, 1978.

80. Hughmark, G.A., and Sobel, B.A., "A Statistical Analysis of the Effect of MMT Concentration on Hydrocarbon Emissions," Society of Automotive Engineers Technical Paper Series, Paper No. 800393, 1980.

81. Benson, J.D., "Manganese Fuel Additive (MMT) Can Cause Vehicle Problems," Society of Automotive Engineers Technical Paper Series, Paper No. 770655, 1977.

82. Faix, L.J., "A Study of the Effects of Manganese Fuel Additive On Automotive Emissions," Society of Automotive Engineers Technical Paper Series, Paper No. 780002, 1978.

83. Furey, R. L., and Summers J.C., "How MMT Causes Plugging of Monolithic Converters," Society of Automotive Engineers Technical Paper Series, Paper No. 780004, 1978.

84. Lichtenstein, I.E., and Mundy, J.P., "MMT Plugging of Oxidation Catalysts on Ceramic and Metal Supports During Engine Dyno Studies of Catalyst Durability," Society of Automotive Engineers Technical Paper Series, Paper No. 780005, 1978.

85. Wotring, W.T., et al., "50,000 Mile Vehicle Road Test of Three-Way and NOx Reduction Catalyst Systems," Society of Automotive Engineers, Technical Paper Series, Paper No. 780608, 1978.

86. Benson, J.D, et al., "Results of Coordinating Research Council MMT Field Test Program," Society of Automotive Engineers Technical Paper Series, Paper No. 790706, 1979.

87. Moran, J. B., "The Environmental Implications of Manganese as an Alternate Antiknock," Society of Automotive Engineers Technical Paper Series, Paper No. 750926, 1975.

88. Wallace, J.S., and Garbe, R.J., "Effect of MMT on Exhaust Emissions," Society of Automotive Engineers, Technical Paper Series, Paper No. 790707, 1979.

89. Gibbs, R. et al., "Emissions from In-Use Catalyst Vehicles," Society of Automotive Engineers Technical Paper Series, Paper No. 770064, 1977.

90. Cheng, S.S., "Catalytic Converter Plugging in MMT-Fueled Vehicles," GM Research Report, R&D – 9814, June 2004.

91. Williamson, et al., "Effects of Fuel Additive MMT on Contaminant Retention and Catalyst Performance," Society of Automotive Engineers Technical Paper Series, Paper No. 821193, 1982.

92. Petroleum Association for the Conservation of the Canadian Environment Comments Regarding Proposed 1986 Light-Duty Automotive Emission Standards, April 1983.

93. Lenane, D.L., "Effect of a Fuel Additive On Emission Control Systems," Society of Automotive Engineers, Technical Paper Series, Paper No. 902097, 1990.

94. Aradi, A.A., "The Physical and Chemical Effect of Manganese Oxides on Automobile Catalytic Converters," Society of Automotive Engineers, Technical Paper Series, Paper No. 940747, 1994.

95. Roos, J.W., et al., "A Systems Approach to Improved Exhaust Catalyst Durability: The Role of the MMT Fuel Additive," Society of Automotive Engineers, Technical Paper Series, Paper No. 2000-01-1880, 2000.

96. Memorandum from SAI to Ethyl Corporation, May 2, 1994.

97. Roos, J.W., et al., "The Effect of Manganese Oxides On OBD-II Catalytic Converter Monitoring," Society of Automotive Engineers, Technical Paper Series, Paper No. 942056, 1994.

98. Roos, J.W., "Evaluation of On-Board Diagnostic Systems and the Impact of Gasoline Containing MMT," Society of Automotive Engineers, Technical Paper Series, Paper No. 972849, 1997.

99. Roos, J.W., et al, "Reformulating Gasoline for Lower Emissions Using the Fuel Additive MMT," Society of Automotive Engineers Technical Paper Series, Paper No. 2002-01-2893, 2002.

100. Hurley, R.G., et al., "Characterization of Automotive Catalysts Exposed to the Fuel Additive MMT," Society of Automotive Engineers, Technical Paper Series, Paper No. 890582, 1989.

101. Chrysler Corporation Technical Response to Environmental Protection Agency Regarding Ethyl Corporation Fuel Additive Waiver for MMT, June 1990.

102. Hammerle, R.H., et al., "Particulate Emissions from Current Model Vehicles Using Gasoline with Methylcyclopentadienyl Manganese Tricarbonyl," Society of Automotive Engineers Technical Paper Series, Paper No. 912436, 1991.

103. Hurley, R.G., et al., "The Effect on Emissions and Emission Component Durability by the Fuel Additive Methylcyclopentadienyl Manganese Tricarbonyl (MMT)," Society of Automotive Engineers, Technical Paper Series, Paper No. 912437, 1991.

104. Hurley, R.G., et al., "The Effect on of Mileage on Emissions and Emission Component Durability by the Fuel Additive Methylcyclopentadienyl Manganese Tricarbonyl (MMT)," Society of Automotive Engineers, Technical Paper Series, Paper No. 920730, 1992.

105. Hubbard, C.P., et al, "The Effect of MMT on the OBD-II Catalyst Efficiency Monitor," Society of Automotive Engineers, Technical Paper Series, Paper No. 932855, 1993.

106. Duncan, J., and Braddock, J.N., "Combustor Study of the Deactivation of a Three-Way Catalyst by Lead and Manganese," Society of Automotive Engineers, Technical Paper Series, Paper No. 841408, 1984.

107. Lenane, D.L., “Effect of a Fuel Additive On Emission Control Systems,” Society of Automotive Engineers, Technical Paper Series, Paper No. 902097, 1990.

108. Alliance MMT Program Part 1 Report – July 29, 2002: See http://autoalliance.org/archives/mmt3.pdf, http://autoalliance.org/archives/ mmt4.pdf, http://autoalliance.org/archives/mmt5.pdf, and http://autoalliance.org/archives/ mmt6.pdf.

109. Alliance MMT Program Part 2 Report – July 29, 2002: See http://autoalliance.org/archives/mmt8.pdf, http://autoalliance.org/archives/ mmt9.pdf, http://autoalliance.org/archives/mmt10.pdf, http://autoalliance.org/archives/mmt11.pdf, and http://autoalliance.org/archives/mmt12.pdf.

110. Maxwell, R., “Review and Assessment of the AAMA/AIAM Test Program Protocol for Investigation of the Effect of MMT Fuel Additive on Vehicle Emissions Levels and Onboard Diagnostics System Performance,” REM-MMT 96-01, October 1996. (Appendix 4 of the Part 1 report contained in reference 108).

111. Letter dated March 22, 1996, from Newton Perry of Ethyl Corporation to Jim Steiger of the American Automobile Manufacturers Association.

112. Letter from James P. Steiger of the American Automobile Manufacturers Association to Newton Perry of Ethyl Corporation dated June 21, 1996.

113. “A Critical Analysis of the Alliance of Automobile Manufacturers’ MMT Study: Separating Fact from Fiction,” Ethyl Corporation, July 2003.

114. Roos, J.W., et al, “A Peer-Reviewed Critical Analysis of SAE Paper 2002-01-2894 ‘The Impact of MMT Gasoline Additive on Exhaust Emissions and Fuel Economy of Low Emission Vehicles (LEV)’,” Society of Automotive Engineers Technical Paper Series, Paper No. 2002-01-2903, 2002.

115. MacKay, J. and Benson, J., “The North American Automobile Manufacturers’ MMT Study: A Response to Issues Raised,” 2005.

116. Cunningham, L.J., et al, “AAM/AIAM Fleet Test Program: Analysis and Comments,” Society of Automotive Engineers Technical Paper Series, Paper No. 2003-01-3287, 2003.

117. California Air Resources Board, Proposed Regulations for Low-Emission Vehicles and Clean Fuels, Staff Report, August 13, 1990.

118. Benson, J.D., and Dana, G., “The Impact of MMT Gasoline Additive on Exhaust Emissions and Fuel Economy of Low Emission Vehicles (LEV),” Society of Automotive Engineers Technical Paper Series, Paper No. 2002-01-2894, 2002.

119. Whitney, K.A., "Characterization of Particulate Exhaust Emissions from Light-Duty Vehicles," Southwest Research Institute Report No. SwRI 03.05578, July 2004.

120. Carlson, T.R., and Austin, T.C., "Evaluation of New Driving Cycles," Sierra Research Report No. SR94-09-03, September 1994.

121. McCabe, R.W., et al, "Effects of MMT Fuel Additive on Emission System Components: Comparison of Clear- and MMT-fueled Escort Vehicles from the Alliance Study," Society of Automotive Engineers Technical Paper Series, Paper No. 2004-01-1084, 2004.

122. Boone, W.P., et al, "Effect of MMT Fuel Additive on Emission System Components: Detailed Parts Analysis from Clear- and MMT-Fueled Escort Vehicles from the Alliance Study," Society of Automotive Engineers Technical Paper Series, Paper No. 2005-01-1108, 2005.

123. Personal Communication between James Lyons and Robert McCabe, January 2005.

124. "Effects of MMT in Gasoline on Emissions from On-Road Motor Vehicles in Canada," Air Improvement Resource, Inc., November 11, 2002.

125. Cunningham, L.J., et al, "Assessing High-Cell Density Catalyst Durability with MMT Fuel Additive in Severe Driving Conditions," Society of Automotive Engineers Technical Paper Series, Paper No. 2005-01-3840, 2005.

126. Richter, H., "Influence of Ash-Forming Gasoline Additives Such as MMT on Exhaust Emissions and Performance Characteristics of PC-Engines," Undated.

127. Shimizu, C., and Ohtaka, Y., "Parametric Analysis of Catalytic Converter Plugging Caused by Manganese-Based Gasoline Additives," Society of Automotive Engineers Technical Paper Series, Paper No. 2007-01-1070, 2007.

128. Roos, J.W., et al, "The Interaction of MMT Combustion Products with the Exhaust Catalyst Face," Society of Automotive Engineers Technical Paper Series, Paper No. 2007-01-1078, 2007.

129. Schindler, K., "Impact of MMT on Vehicle Emission Performance," presented at the Asian Vehicle Emission Control Conference, 2004, April 27-29, Beijing, China.

130. "NAAMSA Experience Relation to the Addition of MMT to Unleaded Petrol in South Africa," National Association of Automobile Manufacturers and Assemblers of South Africa, August 2003.

131. Roos, J.W., et al., "A Survey of American and Canadian Consumer Experience – The Performance of Late Model Year Vehicles Operating on Gasoline With and Without the Gasoline Fuel Additive MMT," Society of Automotive Engineers Technical Paper Series, Paper No. 2006-01-3405, 2006.

132. Meffert, M.W., et al., "Evaluation of Factors Affecting Vehicle Emission Compliance Using Regional Inspection and Maintenance Program Data," Society of Automotive Engineers Technical Paper Series, Paper No. 2006-01-3406, 2006.

133. See http://www.epa.gov/oms/recall.htm.

134. See http://www.ec.gc.ca/ceparegistry/participation/archives/default.cfm?intyear=2004

135. "The Impact of Gasoline Fuel Sulfur on Catalytic Emission Control Systems," Manufacturers of Emission Controls Association, September 1998.

136. California Air Resources Board, "Staff Report, Initial Statement of Reasons, Proposed Amendments to California Exhaust and Evaporative Emission Standards for Test Procedures for Passenger Cars, Light-Duty Trucks and Medium-Duty Vehicles 'LEV II' and Proposed Amendments to California Motor Vehicle Certification, Assembly-Line and In-Use Test Requirements 'CAP 2000,'" September 1998.

137. Yamamoto, S., et al., "In-line Hydrocarbon (HC) Adsorber System for Reducing Cold-Start Emissions," Society of Automotive Engineers, Technical Paper Series, Paper No. 2000-01-0892, 2000.

138. Tamura, Y., et al., "Development of Advanced Emission-Control Technologies for Gasoline Direct-Injection Engines," Society of Automotive Engineers, Technical Paper Series, Paper No. 2001-01-0254, 2001.

139. See http://www.epa.gov/otaq/regs/toxics/420f07017.htm

The information presented in Appendices A through C was developed during the period from 2004 to 2005 and does not reflect modifications or new regulations made since that time.

Appendix A

Canadian Federal and British Columbia Motor Vehicle Exhaust Emission Standards For Passenger Cars and Light-Duty Trucks 1971 and Later Model Years

Canadian Federal Standards

As in the U.S., Canada has been imposing federal emission standards for over three decades. Except for a 12-year period covering the 1975 thru 1987 model years, and a brief period for the 1996-1997 model years, Canada generally has imposed (or implemented through Memoranda of Understanding with the Canadian auto manufacturing industry) the same federal standards as applied federally in the U.S. Following the U.S. pattern, Canadian standards have become progressively more stringent over time.

I. 1971 - 1974 Model Years

For the 1971 - 1974 model years, Canada controlled emissions nationally from new light-duty vehicles and light-duty trucks through regulations adopted by the Ministry of Transport (Transport Canada) under the Motor Vehicle Safety Act. These early standards were based on the EPA standards governing similar vehicles in the U.S. The standards were as follows:

1971 - 1974 Model Years (g/mi)[a]			
Model Year	**HC**	**CO**	**NOx**
1971	2.2	23	---
1972	3.4	39	---
1973-1974	3.4	39	3.00

[a] 7-Mode test method used for 1971 model year; CVS-72 method used for 1972-74 model years.

II. 1975 - 1987 Model Years

For this period, Canada imposed its own light-duty vehicle and light-duty truck (<6,000 lbs GVWR) emission standards, which were less stringent than comparable U.S. standards. These regulations were embodied in Section 1103 of the Motor Vehicle Safety Regulations.

1975 - 1987 Model Years (g/mi, CVS-75 Test)		
HC	**CO**	**NOx**
2	25	3.1

These standards were set at a level that allowed manufacturers the option of certifying with or without catalytic converters.

III. 1988 - 1993 Model Years ("Tier 0")

For the 1988 thru 1993 model years, by means of amendments to Section 1103 adopted in 1986, Canada re-aligned its standards with U.S. EPA "Tier 0" standards, shown below (LDV standards were 50,000 mile durability basis; LDT standards were 120,000 mile durability basis). Light-duty truck applicability was also extended to vehicles >3750 lbs LVWR and <8500 lbs GVWR.

1988 - 1993 Model Years ("Tier 0") (g/mi, CVS-75 Test)								
Model Years	**HC**		**CO**		**NOx**		**PM[a]**	
	LDV	**LDT**	**LDV**	**LDT**	**LDV**	**LDT[b]**	**LDV**	**LDT[b]**
1988-93	0.41	0.80	3.4	10	1.00	1.20	0.20	0.26

[a] PM standards apply to Diesel only.
[b] For LDTs over 3,750 lbs LVW, NOx standard was 1.7 g/mi.

Virtually all vehicles certified to these standards used catalytic converters.

IV. 1994 - 1995 Model Years (Partial Implementation of U.S. "Tier 1" Standards)

For the 1994-95 model years, Canada did not adopt more stringent emissions regulations. Instead, in February 1992 Transport Canada entered into a Memorandum of Understanding (MOU) with the Canadian automobile manufacturers under which auto manufacturers agreed to implement U.S. EPA Tier 1 standards for gasoline-fueled 1994 and 1995 model year light duty vehicles (passenger cars) and light-duty trucks <8500 lbs GVWR. Rather than applying the Tier 1 phase-in schedule applicable under EPA regulations, under the MOU Canadian vehicles were harmonized with U.S standards on a "product" basis, i.e., if a vehicle model manufactured for sale in the U.S. was designed to meet Tier 1 standards, then the same model would be offered for sale in Canada. The practical result was that Tier 1-compliant vehicles were phased-in in Canada, but at a rate different from that in the U.S. due to the different model mix in Canada. The U.S. EPA Tier 1 standards, in g/mi based on the CVS-75 test procedure, are shown below.

Tier 1 LDV (PC) Standards						
Fuel	**Durability Basis**	**THC**	**NMHC**	**CO**	**NOx**	**PM**
Gasoline	50K	0.41	0.25	3.4	0.4	0.08
	100K	---	0.31	4.2	0.6	0.10
Diesel	50K	0.41	0.25	3.4	1.0	0.08
	100K	---	0.31	4.2	1.25	0.10

Tier 1 LDT Standards							
Fuel	**Weight Category**	**Durability Basis**	**THC**	**NMHC**	**CO**	**NOx**	**PM**
Gasoline	LDT1	50K	---	0.25	3.4	0.4	0.08
		100K	0.80	0.31	4.2	0.6	0.10
	LDT2	50K	---	0.32	4.4	0.7	0.08
		100K	0.80	0.40	5.5	0.97	0.10
	LDT3	50K	---	0.32	4.4	0.7	---
		100K	0.80	0.46	6.4	0.98	0.10
	LDT4	50K	---	0.39	5.0	1.1	---
		100K	0.80	0.56	7.3	1.53	0.12
Diesel	LDT1	50K	---	0.25	3.4	1.0	0.08
		100K	0.80	0.31	4.2	1.25	0.10
	LDT2	50K	---	0.32	4.4	---	0.08
		100K	0.80	0.40	5.5	0.97	0.10
	LDT3	50K	---	0.32	4.4	0.7	---
		120K	0.80	0.46	6.4	0.98	0.10
	LDT4	50K	---	0.39	5.0	1.1	---
		120K	0.80	0.56	7.3	1.53	0.12

V. 1996-1997 Model Years

The 1992 MOU was not extended beyond the 1994-95 model years, nor did Transport Canada revise its regulations. As a result, the requirements for 1996-1997 model year light-duty vehicles and light trucks reverted back to those applicable during the 1988 to 1993 model years.

VI. 1998-2000 Model Years (Full Implementation of U.S. "Tier 1" Standards)

In June of 1997, Transport Canada revised its regulations to uniformly apply U.S. EPA Tier 1 standards to all 1998 and later model year light-duty vehicles (passenger cars) and light-duty trucks < 8500 lbs GVWR. The standards are shown in section IV above.

Tier 1 vehicles were also subject to Supplemental Federal Test Procedure (SFTP) requirements, which were standards to control emissions during aggressive driving (SF06 Test Procedure) and while the air conditioning system is operating (SC03 Test Procedure). In order to coordinate with the implementation of the NLEV program in the U.S., the SFTP requirements were delayed one year and did not take effect until the 2001 model year. The applicable SFTP standards were as follows:

Supplemental Federal Test Procedures (g/mi)

Vehicle Type	5 yrs/50,000-mi Durability Basis				10 yrs/100,000-mi Durability Basis			
	Composite NMHC+NOx	A/C Test CO	USO6 CO	Composite CO	Composite NMHC+NOx	A/C Test CO	US06 CO	Composite CO
LDV[e]	0.65[b]	3.0[a]	9.0	3.4	0.91[c]	3.7[a]	11.1	4.2
LDT1[e]	0.65[b]	3.0[a]	9.0	3.4	0.91[c]	3.7[a]	11.1	4.2
LDT2[a]	1.02	3.9	11.6	4.4	1.37	4.9	14.6	5.5
LDT3[a]	1.02	3.9	11.6	4.4	1.44[d]	5.6[d]	16.9[d]	6.4[d]
LDT4[a]	1.49	4.4	13.2	5.0	2.09[d]	6.4[d]	19.3[d]	7.3[d]

[a] Gasoline vehicles only.
[b] 1.48 g/mi for Diesel vehicles.
[c] 2.07 g/mi for Diesel vehicles.
[d] Standards apply at useful life of 11 yrs/120,000 mi.
[e] Gasoline and Diesel vehicles only.

Tier 1 vehicles were also subject to the following additional standards:

- Cold CO (gasoline vehicles only): CO emissions not to exceed 10.0 g/mi at 20º F for LDVs, LDT1s, and LDT2s, and 12.5 g/mi for LDT3s and LDT4s at 50,000 mi.

- Idle CO (gasoline, methanol, CNG, and LPG LDTs): CO emissions not to exceed 0.50% of total exhaust gas at 120,000 mi.

- Certification Short Test (gasoline vehicles only): Emissions not to exceed 100 ppm HC or 0.50% of total exhaust gas at idle and 2500 rpm at 4K mi.

VII. 2001 - 2003 Model Years ("NLEV" Standards)

The Tier 1 exhaust emission standards for 1998 and later model year light-duty vehicles and light trucks in the Transport Canada regulations were not revised for the 2001-2003 model years, and remained in place as the official regulatory standards. However, pursuant to a June 2001 Memorandum of Understanding between the Canadian government and Canadian automotive manufacturers, the latter voluntarily certified their vehicles to more stringent National Low Emission Vehicle (NLEV) standards that were mandatory in designated eastern states in the U.S. for the 1999-2000 model years to address higher ozone levels in that area and then applied nationally in the U.S. for the 2001-2003 model years. The NLEV standards, shown below, were similar to the LEV I standards in effect in California over this period.

In addition, NLEV vehicles had to meet Tier 1 standards at high altitude, and special 50º F emission standards at 4,000 miles (except Diesel, CNG, or hybrid vehicles). Gasoline fueled NLEVs had to meet certification short-test standards: not to exceed 100 ppm HC or 0.50% exhaust gas CO at idle and 2500 rpm at 4,000 miles. Highway NOx could not exceed 1.33 times the applicable FTP NOx certification standard. The full useful life for the THC standards LDT1s and LDT2s was set at 11 yrs/120,000 miles. Various exceptions and special requirements were applied to alternative-fuel and flex-fuel vehicles. Special provisions applied to small-volume manufacturers.

NLEV Exhaust Emission Standards (FTP-75, g/mi)

Vehicle Type	Emission Category	5 yrs/50,000-mi Useful Life						
		THC	**NMHC**	**NMOG**	**CO**	**NOx**	**PM**	**HCHO**
LDV	TLEV	0.41	---	0.125	3.4	0.4	0.08	0.015
	LEV	0.41	---	0.075	3.4	0.2	0.08	0.015
	ULEV	0.41	---	0.040	1.7	0.2	0.08	0.008
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
LDT1	TLEV	---	---	0.125	3.4	0.4	0.08	0.015
	LEV	---	---	0.075	3.4	0.2	0.08	0.015
	ULEV	---	---	0.040	1.7	0.2	0.08	0.008
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
LDT2	TLEV	---	---	0.160	4.4	0.7	0.08	0.018
	LEV	---	---	0.100	4.4	0.4	0.08	0.018
	ULEV	---	---	0.050	2.2	0.4	0.08	0.009
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000

NLEV Exhaust Emission Standards (FTP-75, g/mi)								
Vehicle Type	**Emission Category**	**10 yrs/100,000-mi Useful Life**						
		THC	**NMHC**	**NMOG**	**CO**	**NOx**	**PM**	**HCHO**
LDV	TLEV	---	---	0.156	4.2	0.6	0.08	0.018
	LEV	---	---	0.090	4.2	0.3	0.08	0.018
	ULEV	---	---	0.055	2.1	0.3	0.04	0.011
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
LDT1	TLEV	0.80	---	0.156	4.2	0.6	0.08	0.018
	LEV	0.80	---	0.090	4.2	0.3	0.08	0.018
	ULEV	0.80	---	0.055	2.1	0.3	0.04	0.011
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
LDT2	TLEV	0.80	---	0.200	5.5	0.9	0.10	0.023
	LEV	0.80	---	0.130	5.5	0.5	0.10	0.023
	ULEV	0.80	---	0.070	2.8	0.5	0.05	0.013
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000

Under the MOU, Canada did not enforce the NLEV fleet average NMOG standards that applied in the U.S. Instead, manufacturers harmonized on a “product” basis, i.e., if a vehicle model manufactured for sale in the U.S. was designed to meet U.S. fleet average standards, then the same model would be offered for sale in Canada. The U.S. NLEV fleet average NMOG standards are shown below for informational purposes:

NLEV Fleet Average NMOG Standards (g/mi)	
Vehicle Type	**2001-2003 Model Years**
LDV and LDT1	0.075
LDT2	0.100

Similarly, the NLEV supplemental federal test procedures governing emissions on the more aggressive US06 test procedure and the SC03 test procedure for driving with the A/C system in operation were implemented on a “product” harmonization basis under the MOU, rather than in strict accordance with the phase-in schedule that applied in the U.S. The U.S. SFTP standards are shown below for informational purposes:

NLEV SFTP Standards (g/mi)								
Durability Period	Test	Pollutant	LDV (PC)		LDT1		LDT2	
			Tier1/ TLEV	LEV/ ULEV	Tier1/ TLEV	LEV/ ULEV	Tier1/ TLEV[a]	LEV/ ULEV
4,000 mi	US06	NMHC+ NOx	---	0.14	---	0.14	---	0.25
		CO	---	8.0	---	8.0	---	10.5
	A/C	NMHC+ NOx	---	0.20	---	0.20	---	0.27
		CO	---	2.7	---	2.7	---	3.5
5 yrs/ 50,000 mi	Com-posite	NMHC+ NOx	0.65[b]	---	0.65[b]	---	1.02	---
	A/C	CO	3.0c	---	3.0c	---	3.9	---
	US06	CO	9.0	---	9.0	---	11.6	---
	Com-posite	CO	3.4	---	3.4	---	4.4	---
10 yrs/ 100,000 mi	Com-posite	NMHC+ NOx	0.91[d]	---	0.91[d]	---	1.37	---
	A/C	CO	3.7c	---	3.7c	---	4.9	---
	US06	CO	11.1	---	11.1	---	14.6	---
	Com-posite	CO	4.2	---	4.2	---	5.5	---

[a] Except Diesel vehicles.
[b] 1.48 g/mi for Diesel vehicles.
[c] Not applicable to Diesel vehicles.
[d] 2.07 g/mi for Diesel vehicles.

VIII. 2004 And Later Model Years ("Tier 2" Standards)

A. Exhaust Emission Standards

In 1999, the Canadian government passed the Canadian Environmental Protection Act (CEPA). Among other things, CEPA transferred authority over regulation of motor vehicle emissions from Transport Canada to Environment Canada. After a period of debate to determine whether complete harmonization with the U.S. program was still in the best interests of Canada, the government decided to continue its policy of harmonization, and in 2002 Environment Canada adopted the U.S. EPA Tier 2 standards. This action had the effect, in Canada as in the U.S., of making larger passenger vehicles up to 10,000 lbs GVWR subject to the same standards as smaller passenger cars and light-duty trucks.

The EPA Tier 2 standards for 2004 and later apply to PCs, LDTs up to 8,500 lbs GVWR, and MDPVs up to 10,000 lbs. The LDT category is broken down into the same four weight categories as for the Tier 1 program, with LDT1 and LDT2 together comprising the light light-duty truck (LLDT) category up through 6,000 lbs GVWR, and LDT3 and LDT4 together comprising the heavy light-duty truck (HLDT) category 6001-8,500 lbs GVWR. Except where noted, the same standards apply regardless of the fuel used. The standards include eight permanent certification levels or "bins" and a fleet average NOx standard of 0.07 g/mi. Three temporary certification bins (9, 10, and an MDPV bin) are available as transition bins in the early years of the program, and expire after the 2006 model year (2008 model year for HLDTs). The Tier 2 standards are set forth in the following table:

Tier 2 Exhaust Emission Standards (CVS-75 Test, g/mi)

Bin	50,000-mi Durability Basis					120,000-mi Durability Basis				
	NMOG	CO	NOx	PM	HCHO	NMOG	CO	NOx[g]	PM	HCHO
Temporary Bins										
MDPV[a]	0.195	5.0	0.6	---	0.022	0.280	7.3	0.9	0.12	0.032
10[b,c,d,f]	0.125 (0.160)	3.4 (4.4)	0.4	---	0.015 (0.018)	0.156 (0.230)	4.2 (6.4)	0.6	0.08	0.018 (0.027)
9[b,c,e]	0.075 (0.140)	3.4	0.2	---	0.015	0.090 (0.180)	4.2	0.3	0.06	0.018
Permanent Bins										
8[c]	0.100 (0.125)	3.4	0.14	---	0.015	0.125 (0.156)	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	---	0.015	0.090	4.2	0.15	0.02	0.018
6	0.075	3.4	0.08	---	0.015	0.090	4.2	0.10	0.01	0.018
5	0.075	3.4	0.05	---	0.015	0.090	4.2	0.07	0.01	0.018
4	---	---	---	---	---	0.070	2.1	0.04	0.01	0.011
3	---	---	---	---	---	0.055	2.1	0.03	0.01	0.011
2	---	---	---	---	---	0.010	2.1	0.02	0.01	0.004
1	---	---	---	---	---	0.000	0.0	0.00	0.00	0.000

[a] Expires after 2008 model year.
[b] Bin deleted at end of 2006 model year (2008 model year for HLDTs).
[c] Higher NMOG, CO, and HCOH values apply only to HLDTs and expire after 2008.
[d] Optional temporary NMOG standards of 0.195 g/mi (50,000 mi) and 0.280 g/mi (120,000 mi) apply only to qualifying LDT4s and MDPVs.
[e] Optional temporary NMOG standards of 0.100 (50,000 mi) and 0.130 g/mi (120,000 mi) apply only to qualifying LDT2s.
[f] 50,000 mi standards optional for Diesels certified to Bin 10.
[g] Manufacturer's fleet of Tier 2 vehicles must comply with an average of 0.07 g/mi.

The fleet average NOx standard is a particularly important feature of these standards, as it determines how many vehicles in each of the applicable bins may be produced in a given model year.

The U.S. EPA Tier 2 regulations contain a 25/50/75/100% phase-in schedule for PCs and LLDTs over the 2004/05/06/07 and later model years, and 50/100% for HLDTs and MDPVs over the 2008/09 and later model years. All Tier 2 vehicles produced in compliance with the phase-in schedule must meet the 0.07 g/mi NOx fleet average requirement. In place of the EPA phase-in schedule, Environment Canada adopted the following fleet average NOx phase-in requirements applicable to two separate categories (LDVs + LLDTs and HLDTs + MDPVs) of a manufacturer's entire fleet beginning in the 2004 model year:

Canadian Fleet Average NOx Phase-in Requirements (g/mi)						
Model Year	**2004**	**2005**	**2006**	**2007**	**2008**	**2009 & Later**
LDVs & LLDTs	0.25	0.19	0.13	0.07	0.07	0.07
HLDTs & MDPVs	0.53	0.43	0.33	0.20	0.14	

Environment Canada considers its fleet average NOx phase-in requirements to be equivalent to the U.S. EPA phase-in schedule.

B. Tier 2 Supplemental Federal Test Procedures

2004 and later model-year LDVs (PCs) and LDTs fueled by gasoline or Diesel are subject to Supplemental Federal Test Procedure (SFTP) standards during more aggressive driving (US06 test procedure) and while the A/C system is operating (SC03 test procedure). The SFTP standards do not apply to alternative-fueled LDVs and LDTs, flex-fueled LDVs and LDTs when operating on alternative fuel, or MDPVs. The following two tables show the applicable 4000 mi and full useful life standards:

4000 mi SFTP Standards For Tier 2 and Interim Non-Tier 2 LDVs and LDTs (g/mi)				
	US06		SC03	
Vehicle Type	**NMHC+NOx**	**CO**	**NMHC+NOx**	**CO**
LDV/LDT1	0.14	8.0	0.20	2.7
LDT2	0.25	10.5	0.27	3.5
LDT3	0.4	10.5	0.31	3.5
LDT4	0.6	11.8	0.44	4.0

Full Useful Life SFTP Standards (g/mi)				
Vehicle Type	**NMHC+NOx (weighted)[a,c]**	**CO[b,c]**		
		US06	**SC03**	**Weighted**
LDV/LDT1	0.91 (0.65)	11.1 (9.0)	3.7 (3.0)	4.2 (3.4)
LDT2	1.37 (1.02)	14.6 (11.6)	4.9 (3.9)	5.5 (4.4)
LDT3	1.44	16.9	5.6	6.4
LDT4	2.09	19.3	6.4	7.3

[a] Weighting formula for NMHC+NOx and optional weighting for CO is 0.35*(FTP)+0.28*(US06)+0.37*(SC03).
[b] CO standards are stand-alone for US06 and SC03 with option for a weighted standard.
[c] Intermediate-life standards are shown in parentheses for Diesel LDV/LLDTs opting to calculate intermediate-life SFTP standards in lieu of 4,000-mi SFTP standards.

If a manufacturer uses the weighted CO standard, the applicable full useful life SFTP standards for NMHC+NOx, PM, and CO must be calculated using the following formula:

$$\text{SFTP Std} = \text{SFTP Std}_1\text{-}[0.35*(\text{FTP Std}_1\text{-Current FTP Std})]$$

The standard values for SFTP Std_1 are those in the above table. The standard values for FTP Std_1 are those in the following table:

Tier 1 Full Useful Life FTP Standards (g/mi)				
Vehicle Type	**NMHC[a]**	**NOx[a]**	**CO[a]**	**PM**
LDV/LDT1	0.31 (0.25)	0.6 (0.4)	4.2 (3.4)	0.10
LDT2	0.40 (0.32)	0.97 (0.7)	5.5 (4.4)	0.10
LDT3	0.46	0.98	6.4	0.10
LDT4	0.56	1.53	7.3	0.12

[a] Intermediate-life standards are shown in parentheses for Diesel LDV/LLDTs opting to calculate intermediate-life SFTP standards.

In addition, there are optional SFTP standards for gasoline-, Diesel-, and flex-fueled interim non-Tier 2 LDV and LLDTs certified to Bin 10 Tier 2 standards, and for gasoline-, Diesel-, and flex-fueled LDT3s and LDT4s.

C. In-Use Standards

The following in-use standards apply to 2004-2008 model year LDVs/LLDTs and to HLDTs/MDPVs through the 2010 model years, using commercially available fuels. These standards do not apply to certification, and are the first time that Canada has imposed in-use standards applicable to vehicles driven by the public.

In-Use Certification Standards (g/mi)[b]					
Certification Bin No.	**Durability Period (mi)**	**NOx In-Use**	**NOx Certification[a]**	**NMOG In-use**	**NMOG Certification[a]**
5	50,000	0.07	0.05	---	0.075
	120,000	0.10	0.07	---	0.090
4	120,000	0.06	0.04	---	0.070
3	120,000	0.05	0.03	0.09	0.055
2	120,000	0.03	0.02	0.02	0.010

[a] Shown for reference only.
[b] Separate standards apply for Diesel vehicles certified to Bin 10 standards.

Following the model years noted above, the Tier 2 standards to which a vehicle is certified become the applicable in-use standards.

D. Other Standards

Tier 2 vehicles are subject to the following additional exhaust emission standards:

- Cold CO Standards (applicable only to gasoline-fueled LDV/LDTs and MDPVs): 10.0 g/mi at 20º F for LDVs and LDT1s; 12.5 g/mi for LDT2s, LDT3s, and MDPVs (other than interim non-Tier 2 MDPVs).

- Certification Short Standards (applicable to gasoline-fueled Otto-cycle LDV/LDTs and MDPVs): HC 100 ppm (as hexane) for certification and SEA testing and 200 ppm (hexane) for in-use testing; CO 0.5% for certification and SEA testing and 1.2% for in-use testing.

- Highway NOx Standards (except for MDPVs): Maximum NOx on federal Highway Fuel Economy Test cannot exceed 1.33 times the FTP NOx to which the vehicle is certified.

- On-Board Diagnostic Requirements: Canadian vehicles must comply with U.S. Federal OBD requirements

- Evaporative and Refueling Emission Standards: Canadian vehicles must comply with U.S. Federal requirements.

British Columbia
Motor Vehicle Emission Regulations

The Canadian province of British Columbia (BC) adopted a Motor Vehicle Emission Reduction Regulation in December 1995. The regulation imposed the following requirements on passenger cars and light-duty trucks up to 6,000 lbs GVW:

- For 1998-2000 MY vehicles, compliance with U.S. federal Tier 1 emission standards but with non-mandatory fleet average NMOG standards (compliance with these standards could generate NMOG credits for later use).

- For 2001 and later MY vehicles, compliance with California's LEV I emission regulations, excluding California's zero-emission vehicle (ZEV) requirements, and loosely based on the California NMOG requirements. Under this approach, BC imposed the following fleet average NMOG limits:

BC Fleet Average NMOG Standards (g/mi)				
Vehicle Category	**1998-99[a]**	**2000[a]**	**2001 thru 2004**	**2005 & Later**
Cars & LDTs up to 3750 lbs GVW	0.250	0.125	0.075	0.070
LDTs 3751-5750 lbs GVW	0.320	0.160	0.100	0.098
[a] 1998 thru 2000 NMOG standards were voluntary.				

- For 1998 and later MY vehicles, "sales targets" were set to encourage (but not require) the introduction of cleaner technology vehicles such as ultra low emission vehicles (ULEVs), hybrid vehicles (HEVs), and ZEVs, with the goal of having such vehicles account for 10% of new vehicles sold by the 2003 model year.

The BC regulation was repealed in December 2002, after the Canadian federal government negotiated a Memorandum of Understanding with the Canadian automotive industry in June 2001 under which new vehicles sold in Canada beginning with the 2001 model year would meet U.S. federal NLEV standards (equivalent to the California LEV I standards), and after the federal government indicated an intent to enforce the U.S. EPA's more stringent Tier 2 standards in Canada beginning with the 2004 model year.

Appendix B

California

1966 and Later Model Year
Light- and Medium-Duty Vehicle
Exhaust Emission Standards
and OBD Requirements

California Standards

I. Passenger Car Exhaust Standards 1966-2003

A passenger car is any vehicle designed primarily for transportation of persons and having a design capacity of 12 persons or less. [13 CCR 1900(b)(12)]

A. 1966-79 MY Gasoline Passenger Cars [13 CCR 1955.1, 1959.5; pre-1975 standards no longer in CARB regulations]

Manufacturers certifying new vehicles to the following standards had to demonstrate compliance at 50,000 miles. All standards are expressed in grams per mile (g/mi) unless otherwise noted.

1966-79 MY Gasoline Passenger Cars					
Year	**Displacement**	**HC**	**CO**	**NOx**	**Notes**
1966-67	All	275 ppm	1.5%	---	7 mode test
1968-69	50-100 CID	410 ppm	2.3%	---	“
	101-140 CID	350 ppm	2.0%	---	“
	Over 140 CID	275 ppm	1.5%	---	“
1970	All	2.2	23	---	“
1971	“	2.2	23	4.0	“
1972	“	1.5	23	3.0	“
	“	3.2	39	3.2	CVS-72
1973	“	3.2	39	3.0	“
1974	“	3.2	39	2.0	“
1975-76	“	0.9	9.0	2.0	CVS-75
1977-79	“	0.41	9.0	1.5	“

B. 1980-92 MY Gasoline and Diesel Passenger Cars [13 CCR 1960, 1960.1(a), (b), (c), (d), (e)(1)]

1. Primary Standards

Manufacturers certifying new vehicles to the following standards had to demonstrate compliance at 50,000 miles. In 1981 and 1982, manufacturers had the choice of certifying new vehicles to Option 1 or Option 2 listed below. In 1989, manufacturers had to certify no more than 50% of their vehicles to the 0.7 g/mi NOx option. In 1990-93, manufacturers had to certify no more than 10% of the previous year's production to the 0.7 g/mi NOx standard. Those vehicles certified to the optional 0.7 g/mi NOx standard were subject to a 7-year/75,000-mile recall for selected emission control parts.

1980-92 MY Gasoline and Diesel Passenger Cars					
Year	**Hydrocarbons (g/mi)**		**CO (g/mi)**	**NOx (g/mi)**	**Notes**
	Non-Methane	**Total**			
1980	0.39	0.41	9.0	1.0	
1981-82	---	0.41	3.4	1.0	
	0.39	0.41	7.0	0.7	Optional
1983-88	0.39	0.41	7.0	0.4	
	0.39	0.41	7.0	0.7	Optional
1989-92	0.39	0.41	7.0	0.4	
	0.39	0.41	7.0	0.7	Optional

2. Optional 100,000-Mile Gasoline and Diesel PC Standards

Manufacturers had the option of certifying new vehicles to the following 100,000-mile standards. Manufacturers needed to demonstrate compliance with both the 50,000- and 100,000-mile standards for hydrocarbons and carbon monoxide and a 100,000-mile NOx standard. For the 1989 and later model years, only Diesel light-duty trucks could certify to these standards. When applicable, manufacturers could certify vehicles to either non-methane or total hydrocarbon standards.

Optional 100,000-Mile Gasoline and Diesel PC Standards					
Year	**Mileage**	**Hydrocarbons (g/mi)**		**CO (g/mi)**	**NOx (g/mi)**
		Non-Methane	**Total**		
1980	100K	0.39	0.41	9.0	1.5
	100K	0.46	---	10.6	1.5
1981	100K	0.39	0.41	3.4	1.5
	100K	0.46	---	4.0	1.5
1982-83	100K	0.39	0.41	7.0	1.5
	100K	0.46	---	8.3	1.5
1984-88	100K	0.39	0.41	7.0	1.0
	100K	0.46	---	8.3	1.0
1989-92	100K	0.46	---	8.3	1.0

C. 1993-2003 MY Gasoline, Diesel and Methanol Passenger Cars

1. Phase-in, Primary and Tier 1 Standards [13 CCR 1960.1(f)(1) and (2)]

Manufacturers had to certify a minimum of 40% of their 1993 and 80% of their 1994 passenger cars to specified primary standards, with the remainder certifying to phase-in standards, as shown below. Beginning in 1995 all passenger cars had to meet "Tier 1" standards. Alternatively, manufacturers could voluntarily certify to more stringent low emission vehicle (LEV I) standards, which first became available in the 1992 model year. 1993 vehicles certified to the 0.7 g/m NOx standard were subject to a 7 year/75,000-mile recall for selected emission control parts. Manufacturers choosing to certify Diesel passenger cars to the optional standards had to demonstrate compliance at 100,000 miles. For methanol-fueled vehicles, including flexible-fueled vehicles, NMHC means organic material hydrocarbon equivalent (OMHCE). Beginning in model year 1994, manufacturers were also required to meet a fleet average non-methane organic gas (NMOG) requirement.

1993-2003 MY Gasoline, Diesel and Methanol Passenger Cars					
Year	**Mileage**	**NMHC (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**	**Notes**
1993-94 Primary	50,000	0.25	3.4	0.4	
	50,000	0.25	3.4	0.7	1993 Option Only
	100,000	0.31	4.2	---	
1993-94 Phase-in	50,000	0.39	7.0	0.4	
	50,000	0.39	7.0	0.7	Optional
	100,000	0.46	8.3	1.0	Diesel Option
1995-2003 ("Tier 1")	50,000	0.25	3.4	0.4	
	100,000	0.31	4.2	0.6[a]	
	100,000	0.31	4.2	1.0	Diesel-only Option
[a] 0.6 for 1996 and later MYs					

2. Low-Emission Vehicle Standards (LEV I) [13 CCR 1960.1(g)(1)]

1992 thru 2003 model year low-emission vehicles operating on any fuel could certify to the following LEV 1 exhaust emission standards. These emission standards were set to further compliance with the fleet average NMOG requirements that began with the 1994 model year (see below). The emissions of alternate fueled vehicles could be adjusted to account for the lower reactivity of the NMOG emissions. Note that flexible-fuel and dual-fuel vehicles were certified to separate standards based on use of gasoline.

Low-Emission Vehicle Standards (LEV I)			
50,000-Mile Standards	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**
Low-Emission Vehicles			
Transitional Low-Emission Vehicle (TLEV)	0.125	3.4	0.4
Low-Emission Vehicle (LEV)	0.075	3.4	0.2
Ultra Low-Emission Vehicle (ULEV)	0.040	1.7	0.2
Zero Emission Vehicle (ZEV)	Zero	Zero	Zero
Gasoline Standards For Flexible and Dual-Fuel Low-Emission Vehicles			
Transitional Low-Emission Vehicle (TLEV)	0.25	3.4	0.4
Low-Emission Vehicle (LEV)	0.125	3.4	0.2
Ultra Low-Emission Vehicle (ULEV)	0.075	1.7	0.2

Low-Emission Vehicle Standards (LEV I)			
100,000-Mile Standards	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**
Low-Emission Vehicles			
Transitional Low-Emission Vehicle (TLEV)	0.156	4.2	0.6
Low-Emission Vehicle (LEV)	0.090	4.2	0.3
Ultra Low-Emission Vehicle (ULEV)	0.055	2.1	0.3
Zero Emission Vehicle (ZEV)	Zero	Zero	Zero
Gasoline Standards For Flexible and Dual-Fuel Low-Emission Vehicles			
Transitional Low-Emission Vehicle (TLEV)	0.31	4.2	0.6
Low-Emission Vehicle (LEV)	0.156	4.2	0.3
Ultra Low-Emission Vehicle (ULEV)	0.090	2.1	0.3

3. Fleet Average NMOG And ZEV Requirements [13 CCR 1960.1(g)(2)]

The number of vehicles that had to be certified to the LEV I exhaust emission standards was dictated by a manufacturer's fleet average NMOG emissions, which for the 1994-2003 MYs could not exceed the levels in the following table. The fleet average requirements applied to the manufacturer's combined fleet of passenger cards and light-duty trucks (0-3750 lbs.). Compliance with the fleet average requirements was met by averaging the NMHC or NMOG standards from the number of PCs and LDTs certified to the primary, phase-in, and Tier 1 standards with the number of vehicles certified to the low-emission vehicle categories. In order to receive credit for the lower NMOG of a low-emission vehicle category, a vehicle had to meet the CO and NOx standards for the category to which it was certifying. NMOG emissions include oxygenated and non-oxygenated hydrocarbons. Beginning in 1998, a minimum percentage of each manufacturer's combined sales of passenger cars and light-duty trucks (0-3750 lbs) was required to be zero-emission vehicles; however, the ZEV percentage requirements were never enforced due to subsequent regulatory changes, postponements, and litigation. See Section IV for the revised ZEV requirements that are currently in effect.

Fleet Average NMOG And ZEV Requirements		
Year	**Fleet Average NMOG (g/mi)** [a]	**% of ZEVs Required**
1994	0.250	---
1995	0.231	---
1996	0.225	---
1997	0.202	---
1998	0.157	2
1999	0.113	2
2000	0.073	2
2001	0.070	5
2002	0.068	5
2003	0.062	10
[a] Combined with LDTs 0-3750 lbs		

4. Intermediate In-Use Compliance Standards [13 CCR 1960.1(g)(1), fn6]

When tested for in-use emissions, LEV I passenger cars were subject to somewhat less stringent standards, designated as Intermediate In-use Compliance Standards, for a limited number of model years, as shown below (g/mi).

Intermediate In-Use Compliance Standards									
Durability Basis	**TLEVs**		**LEVs**			**ULEVs**			
	MY	**NMOG**	**MY**	**NMOG**	**NOx**	**MY**	**NMOG**	**CO**	**NOx**
50,000	Thru 1995	0.188	Thru 1999	0.100	0.3	Thru 1998	0.058	2.6	0.3
						99-02	0.055	2.1	0.3
100,000	N/A	N/A	1999	0.125	0.4	99-02	0.075	3.4	0.4

The standards above also apply to dual- and bi-fuel cars operating on a fuel other than gasoline; separate less stringent in-use NMOG standards (50,000 mi durability basis) apply during operation on gasoline.

II. Light-Duty Truck Exhaust Standards – 1966-2003

Prior to the 2000 MY, a light-duty truck was any motor vehicle rated at 6,000 pounds gross vehicle weight or less designed primarily for purposes of transportation of property, was a derivative of such vehicle, or was available with special features enabling off-street or off-highway operation and use. Beginning with the 2000 MY, the upper weight limit in the definition was revised to 8,500 lbs GVW (to include SUVs and lighter-duty full-size pickup trucks). [13 CCR 1900(b)(8)]

A. 1966-79 Gasoline Light-Duty Truck Standards [13 CCR 1955.5, 1959.5; pre-1975 standards no longer in CARB regulations]

Manufacturers certifying new vehicles to the following standards had to demonstrate compliance at 50,000 miles. For 1979 vehicles the standards are dependent on equivalent inertia weight.

1966-79 Gasoline Light-Duty Truck Standards					
Year	**Displacement or Vehicle Weight**	**HC**	**CO**	**NOx**	**Notes**
1966-67	All	275 ppm	1.5 %	---	7 mode test
1968-69	50-100 CID	410 ppm	2.3 %	---	"
	101-140 CID	350 ppm	2.0 %	---	"
	Over 140 CID	275 ppm	1.5 %	---	"
From the 1970 model year all emission are measured in grams per mile (g/mi).					
1970	All	2.2	23	---	"
1971	"	2.2	23	4.0	"
1972	"	1.5	23	3.0	"
	"	3.2	39	3.2	CVS-72
1973	"	3.2	39	3.0	"
1974	"	3.2	39	2.0	"
1975	"	2.0	20	2.0	CVS-75
1976-78	"	0.9	17	2.0	"
1979	0-3999	0.41	9.0	1.5	"
	0-3999 4WD	0.41	9.0	2.0	
	4000-5999	0.5	9.0	2.0	

B. 1980-92 Gasoline and Diesel Light-Duty Trucks Standards [13 CCR 1960, 1960.1(a), (b), (c), (d), (e)(1)]

1. Primary Standards

Manufacturers certifying new vehicles to the following standards had to demonstrate compliance at 50,000 miles. For 1979-87 vehicles the standards were dependent on equivalent inertia weight, and for 1988-92 vehicles the standards were based on loaded vehicle weight. Manufacturers had to certify a minimum of 50% of their 1989 and 85% of their 1990-92 vehicles to the primary 0.4 g/mi NOx standard. Those vehicles certified to the optional 1.0 g/m NOx standard were subject to a 7-year/75,000-mile recall for selected emission control parts.

1980-92 Gasoline and Diesel Light-Duty Trucks Standards						
		Hydrocarbons (g/mi)		**CO**	**NOx**	
Year	**Weight (lbs)**	**Non-Methane**	**Total**	**(g/mi)**	**(g/mi)**	**Notes**
1980	0-3999	0.39	0.41	9.0	1.5	
	0-3999 4wd	0.39	0.41	9.0	2.0	
	4000-5999	0.50	0.50	9.0	-	
1981-82	0-3999	0.39	0.41	9.0	1.0	
	4000-5999	0.50	0.50	9.0	1.5	
1983-87	0-3999	0.39	0.41	9.0	0.4	
		0.39	0.41	9.0	1.0	Optional
	4000-5999	0.50	0.50	9.0	1.0	
1988	0-3750	0.39	0.41	9.0	0.4	
		0.39	0.41	9.0	1.0	Optional
	3751-5750	0.50	0.50	9.0	1.0	
1989	0-3750	0.39	0.41	9.0	0.4	
		0.39	0.41	9.0	1.0	Optional
	3751-5750	0.50	0.50	9.0	1.0	
1990-92	0-3750	0.39	0.41	9.0	0.4	
		0.39	0.41	9.0	0.7	Optional
	3751-5750	0.50	0.50	9.0	1.0	

2. Optional 100,000-Mile Gasoline and Diesel Light-Duty Truck Standards

Manufacturers had the option of certifying new 1980-92 MY vehicles to the following 50,000/100,000-mile standards. Manufacturers had to demonstrate compliance with both the 50,000- and 100,000-mile standards for hydrocarbons and carbon monoxide and a

100,000 mile NOx standard. For 1989 and later model years, only Diesel light-duty trucks could certify to these standards. Where applicable, manufacturers could certify vehicles to either non-methane or total hydrocarbon standards. For 1979-87 vehicles, the standards were dependent on equivalent inertia weight; for 1988-92 vehicles, the standards were based on loaded vehicle weight.

Optional 100,000-Mile Gasoline and Diesel Light-Duty Truck Standards						
Year	**Weight (lbs)**	**Mileage**	**Hydrocarbons (g/mi)**		**CO (g/mi)**	**NOx (g/mi)**
			Non-Methane	**Total**		
1981-83	0-3999	100,000	0.39	0.41	9.0	1.5
		100,000	0.46	---	10.6	1.5
	4000-5999	100,000	0.50	0.50	9.0	2.0
1984-87	0-3999	100,000	0.39	0.41	9.0	1.0
		100,000	0.46	---	10.6	1.0
	4000-5999	100,000	0.50	0.50	9.0	1.5
1988	0-3750	100,000	0.39	0.41	9.0	1.0
		100,000	0.46	---	10.6	1.0
	3751-5750	100,000	0.50	0.50	9.0	1.5
1989-92	0-3750	100,000	0.46	---	10.6	1.0
	3751-5750	100,000	0.50	0.50	9.0	1.5

C. 1993-2003 Gasoline, Diesel, and Methanol Light-Duty Truck Standards

1. Primary, Phase-in and Tier 1 Standards [13 CCR 1960.1(f)(1) and (2)]

Manufacturers had to certify a minimum of 40% of their 1993 and 80% of their 1994 LDTs to specified primary standards, with the remainder certifying to phase-in standards, as shown below. Beginning in 1995 all LDTs had to meet "Tier 1" standards, also shown below. Alternatively, manufacturers could voluntarily certify to more stringent low emission vehicle (LEV I) standards, which first became available in the 1992 model year. 1993 vehicles certified to the 0.7 g/m NOx standard were subject to a 7 year/75,000-mile recall for selected emission control parts. Manufacturers choosing to certify Diesel LDTs to the Tier 1 standards had to demonstrate compliance at 100,000 miles. For methanol-fueled vehicles, including flexible-fueled vehicles, NMHC means organic material hydrocarbon equivalent (OMHCE). Beginning in model-year 1994, manufacturers were also required to meet a fleet average NMOG requirement.

Primary, Phase-in and Tier 1 Standards					
Year	**Weight (lbs)**	**Mileage**	**NMHC**	**CO**	**NOx**
1993-94 Primary	0-3750	50,000	0.25	3.4	0.4
		50,000[a]	0.25	3.4	0.7
		100,000	0.31	4.2	---
		100,000[b]	0.31	4.2	1.0
	3751-5750	50,000	0.32	4.4	1.0
		100,000	0.40	5.5	---
		100,000[b]	0.40	5.5	1.5
1993-94 Phase-in	0-3750	50,000	0.39	9.0	0.4
		50,000[a]	0.39	9.0	0.7
		100,000	0.46	10.6	1.0
	3751-5750	50,000	0.50	9.0	1.0
		100,000	0.50	9.0	1.5
1995-2003 Tier 1	0-3750	50,000	0.25	3.4	0.4
		100,000	0.31	4.2	---
		100,000[b]	0.31	4.2	1.0
	3751-5750	50,000	0.32	4.4	0.7
		100,000	0.40	5.5	---
		100,000[b]	0.40	5.5	1.5

[a] Optional
[b] Diesel optional

2. Low-Emission Vehicle Standards For Light-Duty Trucks (LEV I) [13 CCR 1960.1(g)(1)]

Low-emission LDTs were vehicles operating on any fuel that met the following exhaust emission standards. These emission standards were used to compute the fleet average NMOG (see below). The emissions of alternate fueled vehicles could be adjusted to account for the lower reactivity of the NMOG emissions. Flexible-fuel and dual-fuel vehicles had to certify to separate standards based on use of gasoline.

Low-Emission Vehicle Standards For Light-Duty Trucks (LEV I)			
(0-3750 lbs) 50,000-mile standards	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**
Low-Emission Vehicle Standards			
Transitional Low-Emission Vehicle (TLEV)	0.125	3.4	0.4
Low-Emission Vehicle (LEV)	0.075	3.4	0.2
Ultra Low-Emission Vehicle (ULEV)	0.040	1.7	0.2
Zero Emission Vehicle (ZEV)	Zero	Zero	Zero
Gasoline Standards for Flexible and Dual-Fuel Low-Emission Vehicles			
Transitional Low-Emission Vehicle (TLEV)	0.25	3.4	0.4
Low-Emission Vehicle (LEV)	0.125	3.4	0.2
Ultra Low-Emission Vehicle (ULEV)	0.075	1.7	0.2

Low-Emission Vehicle Standards For Light-Duty Trucks (LEV I)			
(0-3750 lbs) 100,000-mile standards	**NMOG (g/mi)**	**CO (g/mi**	**NOx (g/mi)**
Low-Emission Vehicle Standards			
Transitional Low-Emission Vehicle (TLEV)	0.156	4.2	0.6
Low-Emission Vehicle (LEV)	0.090	4.2	0.3
Ultra Low-Emission Vehicle (ULEV)	0.055	2.1	0.3
Zero Emission Vehicle (ZEV)	Zero	Zero	Zero
Gasoline Standards for Flexible and Dual-Fuel Low-Emission Vehicles			
Transitional Low-Emission Vehicle (TLEV)	0.31	4.2	0.6
Low-Emission Vehicle (LEV)	0.156	4.2	0.3
Ultra Low-Emission Vehicle (ULEV)	0.090	2.1	0.3

Low-Emission Vehicle Standards For Light-Duty Trucks (LEV I)			
(3751-5750 lbs) 50,000-mile standards	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**
Low-Emission Vehicle Standards			
Transitional Low-Emission Vehicle (TLEV)	0.160	4.4	0.7
Low-Emission Vehicle (LEV)	0.100	4.4	0.4
Ultra Low-Emission Vehicle (ULEV)	0.050	2.2	0.4
Zero Emission Vehicle (ZEV)	Zero	Zero	Zero
Gasoline Standards for Flexible and Dual-Fuel Low-Emission Vehicles			
Transitional Low-Emission Vehicle (TLEV)	0.32	4.4	0.7
Low-Emission Vehicle (LEV)	0.160	4.4	0.4
Ultra Low-Emission Vehicle (ULEV)	0.100	2.2	0.4

Low-Emission Vehicle Standards For Light-Duty Trucks (LEV I)			
(3751-5750 lbs) 100,000-mile standards	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**
Low-Emission Vehicle Standards			
Transitional Low-Emission Vehicle (TLEV)	0.200	5.5	0.9
Low-Emission Vehicle (LEV)	0.130	5.5	0.5
Ultra Low-Emission Vehicle (ULEV)	0.070	2.8	0.5
Zero Emission Vehicle (ZEV)	Zero	Zero	Zero
Gasoline Standards for Flexible and Dual-Fuel Low-Emission Vehicles			
Transitional Low-Emission Vehicle (TLEV)	0.40	5.5	0.9
Low-Emission Vehicle (LEV)	0.200	5.5	0.5
Ultra Low-Emission Vehicle (ULEV)	0.130	2.8	0.5

3. Fleet Average NMOG Requirements

The number of LDTs that had to be certified to the LEV I exhaust emission standards was dictated by a manufacturer's fleet average NMOG emissions, which for the 1994-2003 MYs could not exceed the levels in the following table. For LDTs 0-3750 lbs, compliance with the fleet average requirements was met by averaging the NMHC or NMOG standards from the number of such vehicles (combined with the number of passenger cars) certified to the primary, phase-in or Tier 1 standards with vehicles certified to the low-emission vehicle categories. Separate fleet average standards applied to the 3751-5750 lbs LDT category. In order to receive credit for the lower NMOG of a low-emission vehicle category, a vehicle had to meet the CO and NOx standard for the category to which it was certifying. NMOG emissions include oxygenated and non-oxygenated hydrocarbons. Beginning in 1998, a minimum percentage of each manufacturer's passenger car and LDT combined sales was required to be zero-emission vehicles; however, due to regulatory postponements, changes, and litigation, the ZEV requirements were never enforced. The ZEV requirements are described in Section IV below.

Fleet Average NMOG Requirements			
Year	**0-3750 lbs (g/m)[a]**	**3751-5750 lbs (g/m)**	**% ZEVs required (0-3750 lbs only)[a]**
1994	0.250	0.320	---
1995	0.231	0.295	---
1996	0.225	0.287	---
1997	0.202	0.260	---
1998	0.157	0.205	2
1999	0.113	0.150	2
2000	0.073	0.099	2
2001	0.070	0.098	5
2002	0.068	0.095	5
2003 and Later	0.062	0.093	10

[a] LDT and PC sales combined

4. Intermediate In-Use Compliance Standards [13 CCR 1960.1(g)(1), fn6]

When tested for in-use emissions, LEV I light-duty trucks 0-3750 lbs LVW were subject to the same less stringent standards as passenger cars, designated as Intermediate In-use Compliance Standards, for a limited number of model years, as shown below (g/mi).

Intermediate In-Use Compliance Standards									
Durability Basis	**TLEVs**		**LEVs**			**ULEVs**			
	MY	**NMOG**	**MY**	**NMOG**	**NOx**	**MY**	**NMOG**	**CO**	**NOx**
50,000	Thru 1995	0.188	Thru 1999	0.100	0.3	Thru 1998	0.058	2.6	0.3
						99-02	0.055	2.1	0.3
100,000	N/A	N/A	1999	0.125	0.4	99-02	0.075	3.4	0.4

The Intermediate In-use Compliance Standards for LEV I light-duty trucks 3751-5750 lbs LVW were as follows:

Intermediate In-Use Compliance Standards									
Durability Basis	TLEVs		LEVs			ULEVs			
	MY	NMOG	MY	NMOG	NOx	MY	NMOG	CO	NOx
50,000	Thru 1995	0.238	Thru 1998	0.128	0.5	Thru 1998	0.075	3.3	0.5
			1999	0.130	0.5	99-02	0.070	2.8	0.5
100,000	N/A	N/A	1999	0.160	0.7	99-02	0.100	4.4	0.7

For dual- and bi-fuel light trucks in both weight categories, the in-use standards shown above apply when the vehicle is operated on a fuel other than gasoline; separate, less stringent in-use NMOG standards apply (50,000 mi durability basis) during operation on gasoline.

III. Medium-Duty Vehicle Exhaust Standards 1978-2003

Prior to 1995, a medium-duty vehicle was defined as any heavy-duty vehicle having a manufacturer's GVWR of 8,500 lbs or less. Manufacturers could elect to certify pre-1995 vehicles up to 10,000 pounds GVW as medium-duty vehicles.

There are currently four categories of vehicles that are medium-duty vehicles:

1. Any pre-1995 HD vehicle having a manufacturer's gross vehicle weight rating (GVWR) of 8,500 pounds or less;
2. Any 1992 thru 2006 HD vehicle with a manufacturer's GVWR of 14,000 lbs or less that is certified to LEV, ULEV, or SULEV standards in 13 CCR 1960.1(h)(2);
3. Any 1995 thru 2003 HD vehicle with a manufacturer's GVWR of 14,000 lbs or less that is certified to the standards in 13 CCR 1960.1(h)(1); and
4. Any 2000 and later HD vehicle with a manufacturer's GVWR between 8,501 and 14,000 lbs certified to LEV, ULEV, SULEV, or ZEV standards in 13 CCR 1961(a)(1) or 1962. [13 CCR 1900(b)(8)]

A. 1978-94 Gasoline and Diesel Medium-Duty Vehicles [13CCR 1959, 1959.5, 1960, 1960.1(a), (b), (c), (d) and (e)(1)]

Manufacturers certifying new vehicles to the following standards had to demonstrate compliance at 50,000 miles. For medium-duty vehicles before 1978, see the heavy-duty vehicle standards. For 1981-87 vehicles, the standards were dependent on equivalent inertia weight; for 1988-94 vehicles, the standards were based on loaded vehicle weight.

1983-88 NOx standards were based on a production average. 1983-88 medium-duty vehicles that certified to the 1.0 g/mi NOx standard were subject to a minimum 7-year/75,000-mile recall for selected emission control parts. Manufacturers could certify 50% of their 1989 and 85% of their 1990-93 medium-duty vehicles (0-3750 lbs LVW) to the primary 0.4 g/mi NOx standard.

1. Primary Standards

1978-94 Gasoline and Diesel Medium-Duty Vehicles Primary Standards						
Year	**Weight (lbs)**	**Hydrocarbons (g/mi)**		**CO (g/mi)**	**NOx (g/mi)**	**Notes**
		Non-Methane	**Total**			
1978-79	All	0.90	---	17	2.3	
1980	All	0.90	0.9	17	2.3	
1981-82	0-3999	0.39	0.41	9.0	1.0	
	4000-5999	0.50	0.50	9.0	1.5	
	6000-8500	0.60	0.60	9.0	2.0	
1983-87	0-3999	0.39	0.41	9.0	0.4	
		0.39	0.41	9.0	1.0	Optional
	4000-5999	0.50	0.50	9.0	1.0	
	6000-8500	0.60	0.60	9.0	1.5	
1988	0-3750	0.39	0.41	9.0	0.4	
		0.39	0.41	9.0	1.0	Optional
	3751-5750	0.50	0.50	9.0	1.0	
	5751-8750	0.60	0.60	9.0	1.5	
1989	0-3750	0.39	0.41	9.0	0.4	Primary
		0.39	0.41	9.0	1.0	Optional
	3751-5750	0.50	0.50	9.0	1.0	
	5751-8750	0.60	0.60	9.0	1.5	
1990-94	0-3750	0.39	0.41	9.0	0.4	Primary
		0.39	0.41	9.0	0.7	Optional
	3751-5750	0.50	0.50	9.0	1.0	
	5751-8750	0.60	0.60	9.0	1.5	

2. Optional 100,000-Mile Medium-Duty Vehicle Standards

Manufacturers could choose to certify medium-duty vehicles to the following optional emission standards. Manufacturers had to demonstrate compliance with both the 50,000-

and 100,000-mile standards. When applicable, manufacturers could certify vehicles to either non-methane or total hydrocarbon standards. For 1979-87, vehicles the standards were dependent on equivalent inertia weight; for 1988-92 vehicles, the standards were based on loaded vehicle weight. 1989 and later standards were not applicable to methanol medium-duty vehicles.

1981-94 Gasoline and Diesel Medium-Duty Vehicles
Optional 100,000-Mile Medium-Duty Vehicle Standards

Year	Weight (lbs)	Mileage	Hydrocarbons (g/mi)		CO (g/mi)	NOx (g/mi)
			Non-Methane	Total		
1981-82	0-3999	100,000	0.39	0.41	9.0	1.5
		100,000	0.46	---	10.6	1.5
	4000-5999	100,000	0.50	0.50	9.0	2.0
	Over 5999	100,000	0.60	0.60	9.0	2.3
1983	0-3999	100,000	0.39	0.41	9.0	1.5
		100,000	0.46	---	10.6	1.5
	4000-5999	100,000	0.50	0.50	9.0	2.0
	Over 5999	100,000	0.60	0.60	9.0	2.0
1984-87	0-3999	100,000	0.39	0.41	9.0	1.0
		100,000	0.46	---	10.6	1.0
	4000-5999	100,000	0.50	0.50	9.0	1.5
	Over 5999	100,000	0.60	0.60	9.0	2.0
1988	0-3750	100,000	0.39	0.41	9.0	1.0
		100,000	0.46	0.41	10.6	1.0
	3751-5750	100,000	0.50	0.50	9.0	1.0
	Over 5750	100,000	0.60	0.60	9.0	2.0
1989-94	0-3750	100,000	0.46	---	10.6	1.0
	3751-5750	100,000	0.50	0.50	9.0	1.5
	Over 5750	100,000	0.60	0.60	9.0	2.0

B. 1995-2003 Gasoline, Diesel, and Methanol Medium-Duty Vehicle Standards

1. “Tier 1” (Non-LEV) Standards [13 CCR 1960.1(h)(1)]

Manufacturers certifying new vehicles to the following standards had to demonstrate compliance to the 50,000- and 120,000-mile standards. Standards were based on loaded vehicle weight (LVW). The particulate standards were for Diesel medium-duty vehicles.

The following standards were further modified by more stringent medium-duty low-emission vehicle phase-in standards. For the 1995 model year only, manufacturers could certify a maximum of 50% of their vehicles to the applicable 1994 model-year standards and test procedures. For methanol-fueled vehicles, including flexible-fueled vehicles, NMHC means organic material hydrocarbon equivalent (OMHCE).

1995-2003 Gasoline, Diesel, and Methanol Medium-Duty Vehicle "Tier 1" (Non-LEV) Standards					
Weight (lbs)	**Mileage**	**NMHC (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**
0-3750	50,000	0.25	3.4	0.4	---
	120,000	0.36	5.0	0.55	0.08
3751-5750	50,000	0.32	4.4	0.7	---
	120,000	0.46	6.4	0.98	0.10
5751-8500	50,000	0.39	5.0	1.1	---
	120,000	0.56	7.3	1.53	0.12
8501-10,000	50,000	0.46	5.5	1.3	---
	120,000	0.66	8.1	1.81	0.12
10,001-14,000	50,000	0.60	7.0	2.0	---
	120,000	0.86	10.3	2.77	0.12

2. Medium-Duty Low-Emission Vehicle Requirements (LEV I) [13 CCR 1960.1(h)(2) fn10]

Beginning in 1998, a minimum percentage of all medium-duty vehicles were required to be certified as low-emission vehicles, per the table below. (The phase-in requirements for 2001 and later MDVs are described in the LEV II program, below.)

Medium-Duty Low-Emission Vehicle Requirements		
Year	**LEV %**	**ULEV %**
1998	25	2
1999	50	2
2000	75	2

Manufacturers who sold LEVs, ULEVs, and ZEVs prior to 1998 were eligible to earn credits. Credits could be earned beginning in the 1992 model year by meeting the LEV or ULEV standards. Credits earned could be applied to the production requirements starting in the 1998 model year.

3. Low-Emission and Ultra-Low-Emission Medium-Duty Vehicle Standards (LEV I) [13 CCR 1960.1(h)(2)]

To certify as a low-emission vehicle (LEV) or ultra-low-emission vehicle (ULEV) with the Air Resources Board, the exhaust emissions from new 1992 thru 2006 alternate fueled medium-duty vehicles could not exceed the following standards. The emissions of alternate fueled vehicles could be adjusted to account for the lower reactivity of the NMOG emissions. Flexible-fuel and dual-fuel vehicles also had to certify to the gasoline standards.

Low-Emission and Ultra-Low-Emission Medium-Duty Vehicles LEV Category					
Weight (lbs)	**Mileage**	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**
0-3750	50,000	0.125	3.4	0.4	---
	120,000	0.180	5.0	0.6	0.08
3751-5750	50,000	0.160	4.4	0.4	---
	120,000	0.230	6.4	0.6	0.10
5751-8500	50,000	0.195	5.0	0.6	---
	120,000	0.280	7.3	0.9	0.12
8501-10,000	50,000	0.230	5.5	0.7	---
	120,000	0.330	8.1	1.0	0.12
10,001-14,000	50,000	0.300	7.0	1.0	---
	120,000	0.430	10.3	1.5	0.12

Low-Emission and Ultra-Low-Emission Medium-Duty Vehicles ULEV Category					
Weight (lbs)	Mileage	NMOG (g/mi)	CO (g/mi)	NOx (g/mi)	PM (g/mi)
0-3750	50,000	0.075	1.7	0.2	---
	120,000	0.107	2.5	0.3	0.04
3751-5750	50,000	0.100	4.4	0.4	---
	120,000	0.143	6.4	0.6	0.05
5751-8,500	50,000	0.117	5.0	0.6	---
	120,000	0.167	7.3	0.9	0.06
8,501-10,000	50,000	0.138	5.5	0.7	---
	120,000	0.197	8.1	1.0	0.06
10,001-14,000	50,000	0.180	7.0	1.0	---
	120,000	0.257	10.3	1.5	0.06

4. Intermediate In-Use Compliance Standards [13 CCR 1960.1(h)(2), fn 9]

When tested for in-use emissions, LEV I medium-duty vehicles were subject to less stringent standards, designated as Intermediate In-use Compliance Standards, for a limited number of model years, as shown below (g/mi).

Intermediate In-Use Compliance Standards										
Vehicle Type	MY	Dura-bility	3751-5750		5751-8500		8501-10,000		10,001-14,000	
			NMOG	NOx	NMOG	NOx	NMOG	NOx	NMOG	NOx
LEV	Thru 1997	50K	0.238	0.7	0.293	1.1	0.345	1.3	0.450	2.0
	98-99		0.238	0.6	0.293	0.9	0.345	1.0	0.450	1.5
	2000		---	0.6	---	0.9	---	1.0	---	1.5
	2000	120K	---	0.8	---	1.2	---	1.3	---	2.0
ULEV	Thru 2000	50K	0.128	0.6	0.156	0.9	0.184	1.0	0.240	1.5
	2000	120K	0.160	0.8	0.195	1.2	0.230	1.3	0.300	2.0
	01-02	50K	0.128	---	0.156	---	0.184	---	0.240	---
	01-02	120K	0.160	---	0.195	---	0.230	---	0.300	---
SULEV	Thru 2002	50K	0.072	0.3	0.084	0.45	0.100	0.5	0.130	0.7
	2002	120K	0.100	0.4	0.117	0.6	0.138	0.65	0.180	1.0
Note: Dashed line indicates that certification standards apply.										

The standards above apply to flex-fuel and bi-fuel MDVs when operating on a fuel other than gasoline; when operated on gasoline separate less stringent NMOG standards (50,000 mi durability basis) apply to such vehicles.

5. Gasoline Standards for Flexible and Dual-Fueled Low-Emission Vehicles [13 CCR 1960.1(h)(2), fn4]

Gasoline Standards for Flexible and Dual-Fueled Low-Emission Vehicles LEV Category					
Weight (lbs)	**Mileage**	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**
0-3750	50,000	0.25	3.4	0.4	---
	120,000	0.36	5.0	0.6	0.08
3751-5750	50,000	0.32	4.4	0.4	---
	120,000	0.46	6.4	0.6	0.10
5751-8500	50,000	0.39	5.0	0.6	---
	120,000	0.56	7.3	0.9	0.12
8501-10,000	50,000	0.46	5.5	0.7	---
	120,000	0.66	8.1	1.0	0.12
10,001-14,000	50,000	0.60	7.0	1.0	---
	120,000	0.86	10.3	1.5	0.12

Gasoline Standards for Flexible and Dual-Fueled Low-Emission Vehicles ULEV Category					
Weight (lbs) 1968 - 1993 MY Federal Emission Standards	**Mileage**	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**	**PM (g/mi)**
0-3750	50,000	0.125	1.7	0.2	---
	120,000	0.180	2.5	0.3	0.04
3751-5750	50,000	0.160	4.4	0.4	---
	120,000	0.230	6.4	0.6	0.05
5751-8500	50,000	0.195	5.0	0.6	---
	120,000	0.280	7.3	0.9	0.06
8501-10,000	50,000	0.230	5.5	0.7	---
	120,000	0.330	8.1	1.0	0.06
10,001-14,000	50,000	0.300	7.0	1.0	---
	120,000	0.430	10.3	1.5	0.06

6. Incomplete Medium-Duty Vehicles or Diesel Engine Standards [1960.1(h)(2) fn 8, 1958.6(g) and (h)]

Manufacturers have the option of certifying these vehicles to specified HD standards and test procedures. A manufacturer may choose either a set of non-LEV standards for 1995 thru 2003 models or LEV/ULEV standards (see below).

IV. Passenger Car, Light-Duty Truck, and Medium-Duty Vehicle Exhaust Standards — 2004 and Later (LEV II and ZEV Programs)

In 2001-02, CARB updated and revised its LEV and ZEV programs by adopting more stringent fleet average NMOG standards and low-emission vehicle standards, by including small pickups and SUVs up to 8500 lbs GVW in the light-duty truck category, and by setting a new ZEV implementation schedule beginning at 10% in 2005 and rising to 16% in 2018 and later. Caveat: These are complex programs, with many details not covered here. Users of this publication are advised to review the regulatory requirements directly in 13 CCR sections 1961 and 1962.

A. LEV II Exhaust Emission Standards [13 CCR 1961]

1. Certification Standards

The "LEV II" exhaust standards in the following table apply to passenger cars, LDTs, MDVs operating on gasoline or Diesel fuel, and to fuel flexible, bi-fuel, and dual-fuel vehicles of the same types when operating on gaseous or alcohol fuel. PCs and LDTs are tested at their loaded vehicle weight; MDVs are tested at their adjusted loaded vehicle weight. Measured NMOG emissions for vehicles certified on a gaseous fuel other than conventional gasoline (including pre-2004 reformulated gasoline) must apply specified reactivity adjustment factors. There are less stringent standards for small-volume manufacturers.

LEV II Exhaust Emission Standards Certification Standards							
Vehicle Type	**Durability Basis (mi)**	**Vehicle Category**	**NMOG (g/mi)**	**CO (g/mi)**	**NOx (g/mi)**	**HCHO (mg/mi)**	**PM (g/mi)**
PCs & LDTs < 8500 lbs GVW	50,000	LEV	0.075	3.4	0.05	15	N/A
		LEV Opt. 1	0.075	3.4	0.07	15	N/A
		ULEV	0.040	1.7	0.05	8	N/A
	120,000	LEV	0.090	4.2	0.07	18	0.01
		LEV Opt. 1	0.090	4.2	0.10	18	0.01
		ULEV	0.055	2.1	0.07	11	0.01
		SULEV	0.010	1.0	0.02	4	0.01
	150,000 (Optional)	LEV	0.090	4.2	0.07	18	0.01
		LEV Opt. 1	0.090	4.2	0.10	18	0.01
		ULEV	0.055	2.1	0.07	11	0.01
		SULEV	0.010	1.0	0.02	4	0.01
MDVs 8501-10,000 lbs GVW	120,000	LEV	0.195	6.4	0.2	32	0.12
		ULEV	0.143	6.4	0.2	16	0.06
		SULEV	0.100	3.2	0.1	8	0.06
	150,000 (Optional)	LEV	0.195	6.4	0.2	32	0.12
		ULEV	0.143	6.4	0.2	16	0.06
		SULEV	0.100	3.2	0.1	8	0.06
MDVs 10,001-14,000 lbs GVW	120,000	LEV	0.230	7.3	0.4	40	0.12
		ULEV	0.167	7.3	0.4	21	0.06
		SULEV	0.117	3.7	0.2	10	0.06
	150,000 (Optional)	LEV	0.230	7.3	0.4	40	0.12
		ULEV	0.167	7.3	0.4	21	0.06
		SULEV	0.117	3.7	0.2	10	0.06

2. Phase-in Schedules

The LEV II standards are phased in according to the following schedules, except that there are separate schedules for small-volume and independent, small-volume manufacturers:

i. Schedule For PCs and LDTs

Schedule For PCs and LDTs	
Model Year	**PC/LDT1/LDT2 (%)**
2004	25
2005	50
2006	75
2007 and Later	100

ii. Schedule For Non-LEV II MDVs

Schedule For Non-LEV II MDVs					
Model Year	**MDVs Certified To LEV I MDV Standards (%)**		**MDVs Certified To Optional HD Standards (%)**		
	LEV	**ULEV**	**Tier 1**	**LEV**	**ULEV**
2001	80	20	100	0	0
2002	70	30	0	100	0
2003	60	40	0	100	0
2004 and Later	40	60	0	0	100

iii. Schedule For LEV II MDVs

The following schedule applies, except for MDVs optionally certified to HDV standards (which must all meet the HDV standards beginning in 2005):

Schedule For LEV II MDVs	
Model Year	**Requirement**
2004	1 Test Group/Year
2005	“
2006	“
2007 and Later	100%

B. Fleet Average NMOG Requirements

1. Fleet Average Standards

Each manufacturer of PCs and LDT1s produced and delivered for sale in California must meet fleet average NMOG exhaust mass emission standards, as shown below.

Model Year	**Fleet Average NMOG (g/mi) (50,000 mi durability basis)**	
	All PCs; LDTs 0-3750 lbs LVW	**LDTs 3751 lbs LVW-8500 lbs GVW**
2004	0.053	0.085
2005	0.049	0.076
2006	0.046	0.062
2007	0.043	0.055
2008	0.040	0.050
2009	0.038	0.047
2010 and later	0.035	0.043

2. Applicable NMOG Values

The NMOG values to be used in calculating fleet average NMOG depend on the vehicle model year, the vehicle emission category and weight, and the standards to which the vehicle is certified, as specified in the following table. NMOG values for HEVs are separately specified in the regulation.

Applicable NMOG Values			
Model Year/ Vehicle Type	**Emission Category**	**Emission Standard Value**	
		All PCs; LDTs 0-3750 lbs LVW	**LDTs 3751-5750 lbs LVW**
2001 & Later "Federal" Vehicles	All	Fed. std. to which vehicle is certified	Fed. std. to which vehicle is certified
2001-2003 Tier 1	Tier 1	0.25	0.32
2001-2006 LEV I	TLEVs	0.125	0.160
	LEVs	0.075	0.100
	ULEVs	0.040	0.050
		All PCs; LDTs 0-3750 lbs LVW	**LDTs lbs LVW 3750-8500 lbs GVW**
2004 & Later LEV II Vehicles	LEVs	0.75	0.075
	ULEVs	0.040	0.040
	SULEVs	0.01	0.01
2004 & Later Cert. to LEV II 150,000 mi Standards	LEVs	0.06	0.06
	ULEVs	0.03	0.03
	SULEVs	0.0085	0.0085

C. Intermediate In-Use Compliance Standards

When tested for in-use emissions, LEV II vehicles are subject to less stringent standards, designated as Intermediate In-use Compliance Standards, for a limited number of model years, as shown below (g/mi). For vehicles certified prior to the 2007 MY, the standards apply for the first two years the vehicle is certified to the new standard. For SULEVs certified prior to the 2004 MY, the standards apply through the 2006 MY.

Intermediate In-Use Compliance Standards				
Vehicle Type	**Durability Basis (mi)**	**PCs and LDTs**		**MDVs 8500-10,000 lbs GVWR**
		NMOG	**NOx**	**NOx**
LEV/ULEV	50K	N/A	0.07	N/A
	120K	N/A	0.10	0.3
	150K	N/A	0.10	0.3
LEV, Opt. 1	50K	N/A	0.10	N/A
	120K	N/A	0.14	N/A
	150K	N/A	0.14	N/A
SULEV	120K	0.020	0.03	0.15
	150K	0.020	0.03	0.15

D. ZEV Program [13 CCR 1962]

1. ZEV Percentage Requirements

Beginning with the 2005 MY, the table below sets forth the minimum fraction of a manufacturer's total production of PCs and LDT1s that are "produced and delivered" to California (based on three-year rolling average production volumes) that must be ZEVs (or the equivalent in ZEV credits).

ZEV Percentage Requirements	
Model Year	**Minimum ZEV Percentage**
2005 thru 2008	10
2009-2011	11
2012 thru 2014	12
2015 thru 2017	14
2018 and Later	16

2. Phase-in of LDT2s

LDT2s must be included in a manufacturer's California sales base, against which the ZEV percentages in the table above are applied, according to the following schedule:

Phase-in of LDT2s	
Model Year	**Percentage**
2007	17
2008	34
2009	51
2010	68
2011	85
2012 and Later	100

3. Large Volume Manufacturer (LVM) Primary Requirements

Large Volume Manufacturer (LVM) Primary Requirements			
Model Years	**Credits from ZEVs**	**Credits from ZEVs or AT PZEVs**	**Credits from PZEVs**
2005 thru 2008	20% (minimum)	20% (minimum)	Remainder (can include 03-04 PZEVs up to 6% of 97-01 PC and LDT1 production for 05 and 06 MYs)
2008 and Later	Remainder	50% (maximum)	Cannot exceed 6% of CA PC, LDT1, and LDT2 production

Pre-2005 MY vehicles voluntarily certified as ZEVs can be counted fully toward meeting ZEV requirements. Intermediate-volume manufacturers (IVMs) may meet their ZEV requirements with up to 100% PZEVs or credits from such vehicles.

4. Large-Volume Manufacturer (LVM) Alternative Requirements

i. Minimum ZEV Percentage

A LVM may elect annually to comply with the ZEV regulation by meeting the following alternative requirements (provided that switching to the alternative requirements is allowed only if the manufacturer previously met all requirements of the primary approach). The alternative approach sunsets after the 2017 model year. The "place in service requirement" includes documentation of registration with the California DMV.

Minimum ZEV Percentage		
Model Years	**Minimum ZEV Percentage (produce, deliver for sale, and place in service)**	**Types of ZEVs or ZEV Credits**
2005 thru 2008	1.09	Up to one-half Type I or Type II, w/ 20 Type I = 1 Type III and 10 Type II = 1 Type III, and 33 yrs extended svc 97-03 ZEVs = 1 Type III ZEV
2009 thru 2011	Calculated (see following table)	"
2012 thru 2014	"	Up to one-half Type I or Type II, w/ 10 Type I = 1 Type III and 5 Type II = 1 Type III
2015 thru 2017	"	"

ii. Calculation of Minimum ZEV Percentage (2009-2012 MYs)

This calculation is the “target number” of credits for each time period divided by the applicable model year ZEV obligation of all LVMs for the same period, as follows:

Calculation of Minimum ZEV Percentage					
Time Period (MYs)	**Target No. of Type III ZEVs**	**Credits Per Vehicle**	**Target No. of Credits**	**Combined MY ZEV Obligation**	**Alternative Path Percentage**
2009 thru 2004	2,500	4	10,000	A	(10,000/A)x100
2012 thru 2114	25,000	3	75,000	B	(75,000/B)x100
2015 thru 2017	50,000	3	150,000	C	(150,000/C)x100

iii. Minimum Fraction That Must Be ZEVs

In addition, the manufacturer must produce ZEVs and other types of vehicles in the following fractions:

Minimum Fraction That Must Be ZEVs		
Model Years	**Minimum % of ZEVs and AT PZEVs (or credits from such vehicles)**	**Maximum % PZEVs**
2005 thru 2008	40	Remainder
2009 thru 2017	Remainder	6% of mfr’s PC, LDT1, and LDT2 California production volume

5. Allowances, Multipliers, & Credits

i. PZEV Allowances

The ZEV regulation contains extensive provisions, summarized in the table below, that assign additional allowances (i.e., credits) for PZEVs. Consult the regulation for details.

PZEV Allowances	
Vehicle Type/MY	**Available Allowances**
PZEV (meets SULEV exhaust stds, has zero evap. emissions, 150K mi OBD II system, 150K mi emissions warranty)	Baseline Allowance = 0.2 ZEV credit. All allowances cannot give a PZEV credit greater than a Type II ZEV and are subject to cap of 3.0 for 2012 and later MYs
	Zero Emission VMT Allowance up to 2.25 (includes HEVs w/ off-vehicle charging capability)
	Advanced ZEV Componentry Allowance (e.g., high pressure gaseous or H_2 fuel (max. allow. = 0.2) or "qualifying" HEV drive system (allow. dep. on type of HEV))
	Low Fuel-Cycle Emissions Allowance up to 0.3 if emissions are less than 0.1 g/mi

ii. ZEV Credit Multipliers – 1996-2002 MYs

ZEV Credit Multipliers – 1996-2002 MYs	
Vehicle Type/MY	**Available Multipliers**
ZEVs 1996-2000 MYs (use "combined" credits)	1996-98 ZEVs - credit multiplier of 2 or 3 dep. if specified vehicle range and battery specific energy criteria are met (eligible for both multipliers)
	1999-2000 ZEVs - same as for 1996-98 MY ZEVs, except not eligible for both multipliers
ZEVs 2001-2002 MYs (use "combined" credits)	4.0 "phase-in" multiplier if placed in service prior to 9/3/03; see 2003 and later MY if placed in service after that date
	Multiplier from 1 to 10, based on urban all-electric range, w/ extra credit for fast refueling (full or 60-mile range)

iii. ZEV Credit Multipliers - 2003 MY and Later

2003 and later MY ZEVs earn credit multipliers from 0.15 to 40 depending on the ZEV-type and model year. Model year is determined based on the year a vehicle is "placed in service," up to June 30 after the end of the model year. There are five "tiers" of ZEVs: NEV (no minimum all-electric range), Type O (<50 mi. all-electric range), Type I (50-100 mi all-electric range), Type II (> 100 mi all-electric range), and Type III (fuel cell EV with > 100 mi all-electric range and fast refueling (>95% refueling in < 10 min.)).

ZEV Credit Multipliers - 2003 MY and Later					
Model Year	**NEV**	**Type 0**	**Type I**	**Type II**	**Type III**
2003	1.25	1.5	8	12	40
2004	0.625	"	8	12	"
2005	0.625	"	8	12	"
2006	0.15	"	7	10	"
2007	"	"	7	10	"
2008	"	"	7	10	"
2009	"	1	2	3	4
2010	"	1	2	3	4
2011	"	1	2	3	4
2012 +	"	1	2	3	3

In addition, 2004 thru 2011 MY ZEVs earn a 1.25 multiplier if they are sold to a motorist or leased for three or more years to a motorist with an option to purchase or re-lease for two years or more, and a Type II ZEV (fuel cell vehicle) that is placed in service in a "Section 177 State" (a state that has adopted California's ZEV regulation under sec. 177 of the federal Clean Air Act) can be counted toward compliance with both the California ZEV regulation and the other state's regulation.

6. Extended Service Multiplier

Each 1997 thru 2003 MY PZEV and ZEV (other than a NEV) with ≥ 10 mi zero emission range earns an additional credit for each full year it is registered for operation on California roads beyond its first three years of service, through the 2011 calendar year. The credit is 0.1 times the ZEV credit otherwise earned by the vehicle, including multipliers for additional years in service prior to April 24, 2003, and 0.2 times the ZEV credit for each additional year in service after that date.

7. Advanced Technology Demonstration Programs

A vehicle, other than a NEV, can earn ZEV credits even though it is not "delivered for sale" if it is placed in an advanced technology demonstration program relating to safety, infrastructure, fuel specifications or public education (if approved by the Executive Officer) and if the vehicle is "situated in California" more than 50 percent of the first year.

8. ZEV Credits for Transportation Systems

A 2001 thru 2011 MY ZEV (other than a NEV), AT PZEV, or PZEV can earn extra credits if it is placed in an "innovative" transportation system and the Executive Officer determines it demonstrates the application of shared use, intelligent technologies or linkage to transit operations, as shown below:

ZEV Credits for Transportation Systems			
Vehicle Type	**Credit Cap (Max. Fraction of Mfr's ZEV Obligation)**	**Shared Use, Intelligence**	**Linkage to Transit**
PZEV	1/50th	2	1
AT PZEV	1/20th	4	2
ZEV	1/10th	6	3

V. Cold Temperature Standards [13 CCR 1960.1(p), 1961(a)(5)]

1996 and later PCs, LDTs, and MDVs under 8500 lbs GVWR must comply with the standards listed below when tested in accordance with applicable EPA test procedures at a nominal temperature of 20° F. Diesel, NG, hybrid, and zero-emission vehicles are exempt from these requirements.

Cold Temperature Standards			
Vehicle Type	**LVW (lbs)**	**Durability Basis (mi)**	**CO (g/mi)**
PC	All	50,000	10.0
LDT	0-3750	"	10.0
LDT	3751-5750	"	12.5
MDV	0-3750	"	10.0
MDV	3750-8500	"	12.5

VI. Supplemental Federal Test Procedure Exhaust Standards

CARB has adopted EPA's Supplemental Federal Test Procedures (SFTP) to measure emissions during aggressive/microtransient driving over the US06 driving cycle, and for driving with the vehicle air conditioning system operating.

A. SFTP Standards For 2001 & Later PCs and LDTs Other Than LEVs, ULEVs, and ZEVs [13 CCR 1960.1(q), 1961(a)(7)]

SFTP Standards For 2001 & Later PCs and LDTs Other Than LEVs, ULEVs, and ZEVs							
Vehicle Type	**LVW (lbs)**	**Durability Basis (mi)**	**Fuel Type**	**NMHC+NOx (Composite)**	**A/C Test (g/mi)**	**USO6 Test (g/mi)**	**Composite Option (g/mi)**
PC	All	50,000	Gas	0.65	3.0	9.0	3.4
			Diesel	1.48	N/a	9.0	3.4
		100,000	Gas	0.91	3.7	11.1	4.2
			Diesel	2.07	N/a	11.1	4.2
LDT	0-3750	50,000	Gas	0.65	3.0	9.0	3.4
			Diesel	1.48	N/a	9.0	3.4
		100,000	Gas	0.91	3.7	11.1	4.2
			Diesel	2.07	N/a	11.1	4.2
LDT	3751-5750	50,000	Gas	1.02	3.9	11.6	4.4
			Diesel	N/a	N/a	N/a	N/a
		100,000	Gas	1.37	4.9	14.6	5.5
			Diesel	N/a	N/a	N/a	N/a

A four-year phase-in schedule applies to these standards: 25/50/85/100% in 2001/2002/2003/2004 and later, respectively. Small-volume manufacturers must be fully compliant in 2004 and later.

B. SFTP Standards For 2001 & Later PC and LDT LEVs, ULEVs, and SULEVs, and 2003 & Later Medium-Duty LEVs, ULEVs, and SULEVs [13 CCR 1960.1(r)]

SFTP Standards For 2001 & Later PC and LDT LEVs, ULEVs, and SULEVs, and 2003 & Later Medium-Duty LEVs, ULEVs, and SULEVs					
		USO6 Test		**A/C Test**	
Vehicle Type	**LVW (lbs)**	**NMHC+NOx (g/mi)**	**CO (g/mi)**	**NMHC+NOx (g/mi)**	**CO (g/mi)**
PC	All	0.14	8.0	0.20	2.7
LDT	0-3750	0.14	8.0	0.20	2.7
LDT	3751-5750	0.25	10.5	0.27	3.5
MDV	3751-5750	0.40	10.5	0.31	3.5
MDV	5751-8500	0.60	11.8	0.44	4.0

A five-year phase-in schedule applies to these standards for PCs and LDTs: 25/50/85/100% in 2001/2002/2003/2004 and later, respectively. A three-year schedule applies for MDVs: 25/50/100% in 2003/2004/2005 and later, respectively.

VII. Optional Standards for 1995 Thru 2003 Incomplete MDVs and Diesel Engines Used in MDVs [13 CCR 1956.8(g)]

In lieu of meeting CARB's primary standards for MDVs (see above), manufacturers of 1995 thru 2003 model year incomplete MDVs and Diesel engines used in MDVs could optionally meet the following exhaust emission standards (g/bhp-hr).

Optional Standards for 1995 Thru 2003 Incomplete MDVs and Diesel Engines Used in MDVs			
Model Year	**CO**	**NMHC+NOx**	**PM**
1995 thru 2003	14.4	3.9	0.10

For methanol-fueled engines, NMHC means OMHCE. The PM standard applied only to Diesel engines and vehicles. A manufacturer could certify up to 50% of its 1995 MY production to 1994 MDV standards.

VIII. Optional Exhaust Standards for 1992 Thru 2004 Otto-Cycle Engines Used in Incomplete Medium-Duty Low-Emission Vehicles, and 1992 and Later Diesel Engines used in Medium-Duty Low-Emission Vehicles [13 CCR 1956.8(g)]

In lieu of meeting CARB's primary standards for MDVs (see above), manufacturers of 1992 thru 2004 Otto-cycle engines used in incomplete medium-duty low-emission vehicles and 1992 and later Diesel engines used in medium-duty, low-emission vehicles could optionally meet the exhaust emission standards shown in the table below.

For ethanol-fueled vehicles, NMHC means OMHCE. The PM standards applied only to Diesel engines and vehicles. Manufacturers meeting standards for the LEV category and 1992-2003 ULEV engines were deemed to meet the standards described above in section VI. Under Option A for 2004 and later ULEVs, NMHC emissions could not exceed 0.5 g/bhp-hr. Manufacturers could use emissions averaging to meet the optional ULEV NMHC+NOx and PM standards for 2004 and later Diesel engines. CARB's Averaging, Banking, and Trading (ABT) program also applied to many of the NMHC+NOx and PM standards, as noted in the table. For 2007 and later engines, optional alternative standards applied for early NOx and PM compliant engines.

Optional Exhaust Standards for 1992 Thru 2004 Otto-Cycle Engines Used in Incomplete Medium-Duty Low-Emission Vehicles, and 1992 and Later Diesel Engines used in Medium-Duty Low-Emission Vehicles

Model Year	Vehicle Category	CO	NMHC + NOx	NMHC	NOx	HCHO	PM
1992-2001[a]	LEV	14.4	3.5[c]	N/A	N/A	0.050	0.10[c]
2002-2003[a]	LEV	"	3.0[c]	"	"	"	0.10[c]
1992-2003[a]	ULEV	"	2.5[c]	"	"	"	0.10[c]
2004 & Later	ULEV Opt. A	"	2.5[b,c]	"	"	"	0.10[b,c]
2004 & Later	ULEV Opt. B	"	2.4[b,c]	"	"	"	0.10[b,c]
2007 & Later	ULEV	15.5	N/A	0.14	0.2	"	0.01
1992 & Later	SULEV	7.2	2.0[c]	N/A	N/A	0.025	0.05[c]
2007 & Later	SULEV	7.7	N/A	0.07	0.1	0.025	0.005

[a] Manufacturers meeting these standards were deemed to satisfy the Supplemental Federal Test Procedure Exhaust Standards described in Section VI.
[b] Diesel engines could use emissions averaging to meet these standards.
[c] CARB's Averaging, Banking, and Trading (ABT) program applied.

IX. Miscellaneous Exhaust Standards

A. Highway NOx Emissions Standards

Since 1979, CARB has imposed a limit on NOx emissions to assure that emissions are controlled while vehicles are driven at higher cruise speeds. Emissions are measured on the federal highway fuel economy driving cycle. The limit is expressed as a fraction of the principal NOx certification standard.

Highway NOx Emissions Standards			
Model Year	**PCs**	**LDTs**	**MDVs**
1979-1981	1.33	2.00	2.00
1992 and later	1.33	1.33	2.00[a]
[a] 2.0 for 2004 and later MYs			

B. 1993 and Later Formaldehyde Standards [13 CCR 1960.1(e)(2)]

Manufacturers of methanol- and flexible-fueled passenger cars, light-duty trucks, and medium-duty vehicles must comply with the following formaldehyde standards at 50,000 miles. The standards are in milligrams per mile.

1993 and Later Formaldehyde Standards		
Vehicle Type	**Vehicle Weight (GVWR)**	**Formaldehyde (mg/mi)**
Passenger cars	All	15
LDTs	0-3750	15
MDVs	3751-5750	18
MDVs	5751-8750	22
	8751-10,000	28
	10,001-14000	36

C. Low-Emission Vehicle Formaldehyde Exhaust Emission Standards [13 CCR 1960.1(e)(3)]

To be certified by CARB as a low-emission vehicle, 1992 thru 2006 model-year passenger cars, light-duty trucks, and medium-duty vehicles must also meet the following formaldehyde standards. The standards are in milligrams per mile.

Low-Emission Vehicle Formaldehyde Exhaust Emission Standards				
Vehicle Type	**Vehicle Weight (GVWR)**	**Mileage (miles)**	**Category**	**Formaldehyde (mg/mi)**
PC and LDT	All 0-3750	50,000	TLEV LEV ULEV	15 15 8
		100,000	TLEV LEV ULEV	18 18 11
LDT	3751-5750	50,000	TLEV LEV ULEV	18 18 9
		100,000	TLEV LEV ULEV	23 23 13
MDV	0-3750	50,000	LEV ULEV	15 8
		120,000	LEV ULEV	22 12
	3751-5750	50,000	LEV ULEV SULEV	18 9 4
		120,000	LEV ULEV SULEV	27 13 6
	5751-8500	50,000	LEV ULEV SULEV	22 11 6
		120,000	LEV ULEV SULEV	32 16 8
	8501-10,000	50,000	LEV ULEV SULEV	28 14 7
		120,000	LEV ULEV SULEV	40 21 10
	10,001-14,000	50,000	LEV ULEV SULEV	36 18 9
		120,000	LEV ULEV SULEV	52 26 13

D. 1982-2003 Diesel Particulate Matter Standards [13 CCR 1960.1]

1982-2003 Diesel passenger cars and light-duty trucks were subject to the following 50,000-mile particulate exhaust standards, except that Diesel vehicles were subject to the particulate standards at 100,000 miles for the low-emission vehicle categories. Medium-duty vehicle particulate standards vary according to the test weight classification and low-emission vehicle category of the vehicle. For further information, see the medium-duty vehicle section.

1982-2003 Diesel Particulate Matter Standards			
Year	**Category**	**Subcategory**	**PM (g/mi)**
1982-84	PCs & LDTs	N/A	0.6
1985	PCs & LDTs	N/A	0.4
1986-1988	PCs & LDTs	N/A	0.2
1989-1992	PCs & LDTs	N/A	0.08
1992-2003	PCs & LDTs 0-3750 lbs LVW	TLEV LEV ULEV	0.08 0.08 0.04
	PCs & LDTs 3751-5750 lbs LVW	TLEV LEV ULEV	0.10 0.10 0.05

X. <u>On-Board Diagnostic (OBD) System Requirements</u>

CARB's OBD regulation began as brief, generalized instructions for vehicles to self-monitor for proper function of several specified emission control systems and components that provided output to or received input from the vehicle computer. It has now evolved to a complex and very specific set of design and performance requirements covering a long list of emission control devices and systems, accompanied by a detailed enforcement regulation intended to assure proper in-use operation of all monitors.

A. OBD I – 1988 - 1993 Model Years [13 CCR 1968]

OBD I – 1988 - 1993 Model Years	
Date of Action	**Action Taken**
April 1985	Adoption of original OBD I requirements, phased in over the 1988-91 model years, for gasoline-fueled passenger cars and light trucks with 3-way catalysts and feedback control. Required functional monitoring and reporting faults relating to the on-board processor, EGR and fuel metering, and any “computer-sensed emission related component” (e.g., ignition system, temperature and throttle position sensors, oxygen sensors).

B. OBD II – 1994 - 2003 Model Years [13 CCR 1968.1]

OBD II – 1994 - 2003 Model Years	
Date of Action	**Action Taken**
September 1989	Adoption of expanded OBD II requirements for gasoline and alternate fuel passenger cars, light-duty trucks, and medium-duty vehicles to include functional and “performance-based”* monitoring of catalyst, misfire, evaporative purge, oxygen sensor, secondary air, EGR flow rate, closed-loop fuel control, I/M readiness, sensor performance, A/C system leakage, and comprehensive component (input/output) monitoring. Other requirements included tampering deterrence, fuel system monitoring, “comprehensive” sensor condition monitoring, standardized fault codes, “freeze-frame” documentation of system conditions when a malfunction occurs, and standardized specifications for tools used to download information. Phased in over 1994-96 model years.
September 1991	Extensive revisions to address coordination with pending EPA regulation, technical feasibility, false MILs, and lead time. Included relaxed catalyst monitoring requirements; elimination of need to illuminate MIL for catalyst, misfire, and evaporative malfunctions on 1994-95 model year vehicles; and relaxed criteria for vehicle recalls. Addition of leak detection requirement for 0.040” large evaporative leaks. Included Diesel vehicles beginning with 1996 model year.

* “Performance-based” refers to malfunction criteria based on applicable emissions standards, e.g., requiring a catalyst malfunction to be recorded if emissions exceed 1.5 times the applicable HC certification standard.

OBD II – 1994 - 2003 Model Years	
Date of Action	**Action Taken**
July 1993	Adopted revisions to allow compliance exemptions and deficiency waivers for 1994 model year, and up to two waivers for the 1995 model year (with minor fines applicable to more than two waivers), in response to petition by Ford.
December 1994	Imposed more stringent requirements for catalyst, misfire and comprehensive component monitoring. Added new requirement to monitor for evaporative system small (0.020”) leaks. Adopted various phase-in schedules for new requirements. Extended deficiency waiver provisions to include 1996-1999 model years.
December 1996	Adopted changes to provide additional flexibility and lead time for catalyst and misfire monitoring. Added new monitoring requirements for thermostat and PCV valves. Extended availability of deficiency waivers through 2004 and later model years.

C. OBD II – 2004 and Later Model Years [13 CCR 1968.2, 1968.5]

OBD II – 2004 and Later Model Years	
Date of Action	**Action Taken**
April 2002	Major revisions imposing more stringent requirements for 2004 and later model years, including catalyst NOx, misfire, oxygen sensor, and air injection monitoring. Imposed new “full vehicle life” system durability requirement. Added new requirements for monitoring of cold start and variable valve technology. Added new requirements for Diesel vehicles. Added a new, separate enforcement regulation requiring in-use testing and recall even if no emissions increase is associated with a monitoring defect.

Appendix C

U.S. Federal Exhaust Emission Standards
For 1968 and Later Model Year
Light- and Medium-Duty Vehicles and Trucks

U.S. Federal Standards

I. Pre-1969 – 1993 Model Year Light-Duty Vehicles (Passenger Cars) and Light-Duty Trucks

For the 1963-67 model years, the only federal requirement was a closed crankcase. Exhaust standards first began to apply in the 1968 model year and are shown below (in g/mi unless otherwise indicated). Different standards applied to small volume manufacturers and vehicles fueled with other than gasoline or Diesel. For the 1968 - 1981 model years, LDTs were split into two weight categories: “light light-duty” 0-3750 lbs LVW and “heavy light-duty” 3751-6000 lbs LVW; for 1982 and later model years, the upper limit to the heavy light-duty category was set at 8,500 lbs GVWR (6,000 lbs curb weight). LDT standards applied to both categories unless otherwise indicated. Generally, the useful life period for both LDVs and LDTs was 5 yrs/50,000 miles thru the 1989 model year, with LDTs changing to 11 yrs/120,000 miles for 1990 and later.

1968 - 1993 MY Federal Emission Standards

Model Year	Test		HC		CO		NOx		PM[a]	
	LDV	LDT	LDV	LDT	LDV	LDT	LDV	LDT	LDV	LDT
1968-69	7-Mode		410 ppm		2.3%		N/A		N/A	
1970-71	“		2.2		23		“		“	
1972	CVS-72		3.4		39		“		“	
1973-74	“		“		“		3.00		“	
1975-76	CVS-75		1.5	2	15	20	3.10		“	
1977-78	“		“	“	“	“	2.00	3.10	“	
1979	“		“	1.7	“	18	“	2.30	“	
1980	“		0.41	“	7	“	“	“	“	
1981	“		“	“	3.4	“	1.0	“	“	
1982-83	“		“	“	“	10	“	“	0.60	
1984-86	“		“	0.80	“	“	“	“	“	
	“		“	“	“	“	“	“	.20	.26[c]
1988-89	“		“	“	“	“	“	1.2[b]	“	“[c]
1990	“		“	“	“	“	“	“	“	“[c]
1991-93	“		“	“	“	“	“	“	“	“[c]

Notes:
[a] PM standards apply to only Diesel.
[b] 1.7 g/mi for LDTs over 3750 lbs LVW.
[c] 0.45 g/mi for LDTs over 3750 LVW.

II. 1994 - 2003 Model Year Light-Duty Vehicles (Passenger Cars) and Light-Duty Trucks (Tier 1)

The federal Tier 1 exhaust standards applied to passenger cars (PCs) and four weight categories of light-duty trucks (LDTs) up to 8,500 lbs GVWR. PCs and two categories of LDTs were phased in 40/80/100% over the 1994/95/96 model years. The two LDT weight categories were LDT1 (0-3750 lbs LVW) and LDT2 (3751-5750 lbs LVW). The other two weight categories, LDT3 (3751-5750 lbs ALVW) and LDT4 (>5750 lbs ALVW), were phased in 50/100% in 1996/97 and later. The 1991-93 model year standards above ("Tier 0" standards) applied to non-phased-in vehicles. Different standards generally applied for methanol-, NG-, and LPG-fueled vehicles. The Tier 1 standards for gasoline- and Diesel-fueled vehicles, in g/mi based on the CVS-75 test procedure, are shown below.

A. LDV (PC) Standards

Tier 1 LDV (PC) Standards

Fuel	Durability Basis	THC	NMHC	CO	NOx	PM
Gasoline	50K	0.41	0.25	3.4	0.4	0.08
	100K	---	0.31	4.2	0.6	0.10
Diesel	50K	0.41	0.25	3.4	1.0	0.08
	100K	---	0.31	4.2	1.25	0.10

B. LDT Standards

Tier 1 LDT Standards

Fuel	Weight Category	Durability Basis	THC	NMHC	CO	NOx	PM
Gasoline	LDT1	50K	---	0.25	3.4	0.4	0.08
		100K	0.80	0.31	4.2	0.6	0.10
	LDT2	50K	---	0.32	4.4	0.7	0.08
		100K	0.80	0.40	5.5	0.97	0.10
	LDT3	50K	---	0.32	4.4	0.7	---
		100K	0.80	0.46	6.4	0.98	0.10
	LDT4	50K	---	0.39	5.0	1.1	---
		100K	0.80	0.56	7.3	1.53	0.12

Tier 1 LDT Standards							
Fuel	**Weight Category**	**Durability Basis**	**THC**	**NMHC**	**CO**	**NOx**	**PM**
Diesel	LDT1	50K	---	0.25	3.4	1.0	0.08
		100K	0.80	0.31	4.2	1.25	0.10
	LDT2	50K	---	0.32	4.4	---	0.08
		100K	0.80	0.40	5.5	0.97	0.10
	LDT3	50K	---	0.32	4.4	0.7	---
		120K	0.80	0.46	6.4	0.98	0.10
	LDT4	50K	---	0.39	5.0	1.1	---
		120K	0.80	0.56	7.3	1.53	0.12

C. Supplemental Federal Test Procedures

Tier 1 vehicles were subject to Supplemental Federal Test Procedures (SFTPs) and standards to control emissions during aggressive driving (SF06 Test Procedure) and while the air conditioning system is operating (SC03 Test Procedure). The SFTPs were phased in for LDVs (PCs), LDT1s, and LDT2s 40/80/100% in 2000/01/02 and later. The phase-in schedule for LDT3s and LDT4s was 40/80% in 2002/03. The applicable standards were as follows:

SFTP (g/mi)								
	5 yrs/50,000-mi Durability Basis				**10 yrs/100,000-mi Durability Basis**			
Vehicle Type	**Composite NMHC+NOx**	**A/C Test CO**	**USO6 CO**	**Composite CO**	**Composite NMHC+NOx**	**A/C Test CO**	**US06 CO**	**Composite CO**
LDV[e]	0.65[b]	3.0[a]	9.0	3.4	0.91[c]	3.7[a]	11.1	4.2
LDT1[e]	0.65[b]	3.0[a]	9.0	3.4	0.91[c]	3.7[a]	11.1	4.2
LDT2[a]	1.02	3.9	11.6	4.4	1.37	4.9	14.6	5.5
LDT3[a]	1.02	3.9	11.6	4.4	1.44[d]	5.6[d]	16.9[d]	6.4[d]
LDT4[a]	1.49	4.4	13.2	5.0	2.09[d]	6.4[d]	19.3[d]	7.3[d]

Notes:
[a] Gasoline vehicles only.
[b] 1.48 g/mi for Diesel vehicles.
[c] 2.07 g/mi for Diesel vehicles.
[d] Standards apply at useful life of 11 yrs/120,000 mi.
[e] Gasoline and Diesel vehicles only.

D. Other Standards

Tier 1 vehicles were subject to the following additional standards:

- Cold CO (gasoline vehicles only): At 20°F, CO emissions not to exceed 10.0 g/mi for LDVs, LDT1s, and LDT2s, and 12.5 g/mi for LDT3s and LDT4s at 50,000 mi.

- Idle CO (gasoline, methanol, CNG, and LPG LDTs): CO emissions not to exceed 0.50% of total exhaust gas at 120,000 mi.

- Certification Short Test (gasoline vehicles only): Emissions not to exceed 100 ppm HC or 0.50% of total exhaust gas at idle and 2500 rpm at 4K mi.

III. National Low-Emission Vehicle (NLEV) Program

The NLEV program applied to LDVs, LDT1s, and LDT2s only. For the 1999 through 2003 model years, its purpose was to impose emission standards (generally equivalent to the CARB LEV I standards) that were more stringent than EPA's Tier 1 standards before federal Tier 2 standards became effective with the 2004 model year. The NLEV program applied first in 12 northeastern states affected by ozone transport, plus the District of Columbia, in 1999–2000, then applied nationally beginning in 2001. Twenty-three manufacturers chose to participate in the program.

A. NLEV Exhaust Emission Standards

NLEV Exhaust Emission Standards (FTP-75, g/mi)								
Vehicle Type	**Emission Category**	**5 yrs/50,000-mi Useful Life**						
		THC	**NMHC**	**NMOG**	**CO**	**NOx**	**PM**	**HCHO**
LDV	TLEV	0.41	---	0.125	3.4	0.4	0.08	0.015
	LEV	0.41	---	0.075	3.4	0.2	0.08	0.015
	ULEV	0.41	---	0.040	1.7	0.2	0.08	0.008
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
LDT1	TLEV	---	---	0.125	3.4	0.4	0.08	0.015
	LEV	---	---	0.075	3.4	0.2	0.08	0.015
	ULEV	---	---	0.040	1.7	0.2	0.08	0.008
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
LDT2	TLEV	---	---	0.160	4.4	0.7	0.08	0.018
	LEV	---	---	0.100	4.4	0.4	0.08	0.018
	ULEV	---	---	0.050	2.2	0.4	0.08	0.009
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
Vehicle Type	**Emission Category**	**10 yrs/100,000-mi Useful Life**						
		THC	**NMHC**	**NMOG**	**CO**	**NOx**	**PM**	**HCHO**
LDV	TLEV	---	---	0.156	4.2	0.6	0.08	0.018
	LEV	---	---	0.090	4.2	0.3	0.08	0.018
	ULEV	---	---	0.055	2.1	0.3	0.04	0.011
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
LDT1	TLEV	0.80	---	0.156	4.2	0.6	0.08	0.018
	LEV	0.80	---	0.090	4.2	0.3	0.08	0.018
	ULEV	0.80	---	0.055	2.1	0.3	0.04	0.011
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000
LDT2	TLEV	0.80	---	0.200	5.5	0.9	0.10	0.023
	LEV	0.80	---	0.130	5.5	0.5	0.10	0.023
	ULEV	0.80	---	0.070	2.8	0.5	0.05	0.013
	ZEV	0.00	0.00	0.000	0.0	0.0	0.00	0.000

NLEV vehicles had to meet Tier 1 standards at high altitude, and special 50º F emission standards at 4,000 miles (except Diesel, CNG, or hybrid vehicles). Special interim in-use standards applied to 1999 LEVs and 1999–2002 ULEVs. Gasoline NLEVs had to meet certification short-test standards: not to exceed 100 ppm HC or 0.50% exhaust gas CO at idle and 2500 rpm at 4,000 miles. Highway NOx could not exceed 1.33 times the applicable FTP NOx certification standard. The full useful life for the THC standard for LDT1s and LDT2s was set at 11 yrs/120,000 miles. Various exceptions and special requirements applied to alternative-fuel and flex-fuel vehicles. Special provisions applied to small-volume manufacturers.

B. Fleet Average NMOG Standards

Manufacturers could select the applicable emission category for certification of their vehicles as long as they met the following fleet average NMOG standards:

NLEV Fleet Average NMOG Standards (g/mi)		
Vehicle Type	**1999-2000 Model Years**	**2001-2003 Model Years**
LDV and LDT1	0.148	0.075
LDT2	0.190	0.100

C. Supplemental Federal Test Procedures

Gasoline and Diesel NLEV vehicles were also subject to SFTP standards governing emissions on the more aggressive US06 test procedure and the SC03 test procedure for driving with the A/C system in operation. These standards were phased in (all vehicle categories) according to the following schedule: 25/50/85% in 2001/02/03, with small-volume manufacturers exempt until the last year of the phase-in.

NLEV SFTP Standards (g/mi)								
			LDV (PC)		LDT1		LDT2	
Durability Period	Test	Pollutant	Tier1/ TLEV	LEV/ ULEV	Tier1/ TLEV	LEV/ ULEV	Tier1/ TLEV[a]	LEV/ ULEV
4,000 mi	US06	NMHC+ NOx	---	0.14	---	0.14	---	0.25
		CO	---	8.0	---	8.0	---	10.5
	A/C	NMHC+ NOx	---	0.20	---	0.20	---	0.27
		CO	---	2.7	---	2.7	---	3.5
5 yrs/ 50,000 mi	Com-posite	NMHC+ NOx	0.65[b]	---	0.65[b]	---	1.02	---
	A/C	CO	3.0[c]	---	3.0[c]	---	3.9	---
	US06	CO	9.0	---	9.0	---	11.6	---
	Com-posite	CO	3.4	---	3.4	---	4.4	---
10 yrs/ 100,000 mi	Com-posite	NMHC+ NOx	0.91[d]	---	0.91[d]	---	1.37	---
	A/C	CO	3.7[c]	---	3.7[c]	---	4.9	---
	US06	CO	11.1	---	11.1	---	14.6	---
	Com-posite	CO	4.2	---	4.2	---	5.5	---

Notes:
[a] Except Diesel vehicles.
[b] 1.48 g/mi for Diesel vehicles.
[c] Not applicable to Diesel vehicles.
[d] 2.07 g/mi for Diesel vehicles.

IV. 2004 and Later Model Year Light-Duty Vehicles (Passenger Cars), Light-Duty Trucks, and Medium-Duty Passenger Vehicles (Tier 2)

A. Exhaust Emission Standards

The federal Tier 2 standards for 2004 and later apply to passenger cars (PCs), light-duty trucks (LDTs) up to 8,500 lbs GVWR, and medium-duty passenger vehicles (MDPVs) up to 10,000 lbs. The LDT category is broken down into the same four weight categories as for the Tier 1 program, with LDT1 and LDT2 together comprising the light light-duty truck (LLDT) category up through 6,000 lbs GVWR, and LDT3 and LDT4 together comprising the heavy light-duty truck (HLDT) category of 6,001-8,500 lbs GVWR. Except where noted, the same standards apply regardless of the fuel used. The standards include eight permanent certification levels or "bins" and a fleet average NOx standard of 0.07 g/mi for each manufacturer. Three temporary certification bins (9, 10, and an MDPV bin) are available as transition bins in the early years of the program, and expire after the 2006 model year (2008 model year for HLDTs). The Tier 2 standards and the Tier 2 phase-in schedule are set forth in the following tables:

Tier 2 Exhaust Emission Standards (CVS-75 Test, g/mi)

Bin	50,000-mi Durability Basis					120,000-mi Durability Basis				
	NMOG	CO	NOx	PM	HCHO	NMOG	CO	NOx[g]	PM	HCHO
Temporary Bins										
MDPV[a]	0.195	5.0	.6	---	0.022	0.280	7.3	0.9	0.12	0.032
10[b,c,d,f]	0.125 (0.160)	3.4 (4.4)	0.4	---	0.015 (0.018)	0.156 (0.230)	4.2 (6.4)	0.6	0.08	0.018 (0.027)
9[b,c,e]	0.075 (0.140)	3.4	0.2	---	0.015	0.090 (0.180)	4.2	0.3	0.06	0.018
Permanent Bins										
8[c]	0.100 (0.125)	3.4	0.14	---	0.015	0.125 (0.156)	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	---	0.015	0.090	4.2	0.15	0.02	0.018
6	0.075	3.4	0.08	---	0.015	0.090	4.2	0.10	0.01	0.018
5	0.075	3.4	0.05	---	0.015	0.090	4.2	0.07	0.01	0.018
4	---	---	---	---	---	0.070	2.1	0.04	0.01	0.011
3	---	---	---	---	---	0.055	2.1	0.03	0.01	0.011
2	---	---	---	---	---	0.010	2.1	0.02	0.01	0.004
1	---	---	---	---	---	0.000	0.0	0.00	0.00	0.000

Notes:
[a] Expires after 2008 model year.
[b] Bin deleted at end of 2006 model year (2008 model year for HLDTs).
[c] Higher NMOG, CO, and HCOH values apply only to HLDTs and expire after 2008.
[d] Optional temporary NMOG standards of 0.195 g/mi (50,000 mi) and 0.280 g/mi (120,000 mi) applies to qualifying LDT4s and MDPVs only.
[e] Optional temporary NMOG standards of 0.100 (50,000 mi) and 0.130 g/mi (120,000 mi) applies to qualifying LDT2s only.
[f] 50,000 mi standards optional for Diesels certified to Bin 10.
[g] Manufacturer's fleet must average 0.07 g/mi.

Tier 2 Phase-In Schedule		
Vehicle Category	**Percentages**	**Years**
PCs, LLDTs	25/50/75/100	2004/05/06/07 and later
HLDTs, MDPVs	50/100	2008/09 and later

During the phase-in period, PCs and LLDTs not certified to Tier 2 standards must meet an interim average NOx standard of 0.30 g/mi (equivalent to NLEV standards for LDVs). During 2004-08, HLDTs and MDPVs not certified to Tier 2 standards must phase into an interim program with an average NOx standard of 0.20 g/mi, with those not covered by the phase-in meeting NOx caps of 0.60 g/mi for HLDTs and 0.90 g/mi for MDPVs.

B. Supplemental Federal Test Procedures

2004 and later model year LDVs (PCs) and LDTs fueled by gasoline or Diesel are subject to Supplemental Federal Test Procedure (SFTP) standards. The SFTP standards do not apply to alternative-fueled LDVs and LDTs, flex-fueled LDVs and LDTs when operating on alternative fuel, or MDPVs. The following two tables show the applicable 4000 mi and full useful life standards:

4000 mi SFTP Standards For Tier 2 and Interim Non-Tier 2 LDVs and LDTs (g/mi)				
	US06		**SC03**	
Vehicle Type	**NMHC+NOx**	**CO**	**NMHC+NOx**	**CO**
LDV/LDT1	0.14	8.0	0.20	2.7
LDT2	0.25	10.5	0.27	3.5
LDT3	0.4	10.5	0.31	3.5
LDT4	0.6	11.8	0.44	4.0

Tier 1 Full Useful Life SFTP Standards (g/mi)				
Vehicle Type	**NMHC+NOx (weighted)[a,c]**	**CO[b,c]**		
		US06	**SC03**	**Weighted**
LDV/LDT1	0.91 (0.65)	11.1 (9.0)	3.7 (3.0)	4.2 (3.4)
LDT2	1.37 (1.02)	14.6 (11.6)	4.9 (3.9)	5.5 (4.4)
LDT3	1.44	16.9	5.6	6.4
LDT4	2.09	19.3	6.4	7.3

Notes:
[a] Weighting formula for NMHC+NOx and optional weighting for CO is 0.35*(FTP)+0.28*(US06)+0.37*(SC03).
[b] CO standards are standalone for US06 and SC03 with option for a weighted standard.
[c] Intermediate life standards are shown in parentheses for Diesel LDV/LLDTs opting to calculate intermediate life SFTP standards in lieu of 4,000 mi SFTP standards.

If a manufacturer uses the weighted CO standard, then the applicable full useful life SFTP standards for NMHC+NOx, PM, and CO must be calculated using the following fomula:

$$\text{SFTP Std} = \text{SFTP Std}_1 - [0.35*(\text{FTP Std}_1 - \text{Current FTP Std})]$$

The standard values for SFTP Std_1 are those in the above table. The standard values for FTP Std_1 are those in the following table:

Tier 1 Full Useful Life FTP Standards (g/mi)				
Vehicle Type	**NMHC[a]**	**NOx[a]**	**CO[a]**	**PM**
LDV/LDT1	0.31 (0.25)	0.6 (0.4)	4.2 (3.4)	0.10
LDT2	0.40 (0.32)	0.97 (0.7)	5.5 (4.4)	0.10
LDT3	0.46	0.98	6.4	0.10
LDT4	0.56	1.53	7.3	0.12

Notes:
[a] Intermediate life standards are shown in parentheses for Diesel LDV/LLDTs opting to calculate intermediate life SFTP standards.

In addition, there are optional SFTP standards for gasoline, Diesel, and flex-fueled interim non-Tier 2 LDV and LLDTs certified to Bin 10 Tier 2 standards, and for gasoline, Diesel, and flex-fueled LDT3s and LDT4s.

C. In-Use Standards

The following in-use standards apply to LDVs/LLDTs through the 2008 model years and to HLDTs/MDPVs through the 2010 model years. These standards do not apply to certification or SEA testing.

In-Use Certification Standards (g/mi)[b]					
Certification Bin No.	**Durability Period (mi)**	**NOx In-Use**	**NOx Certification[a]**	**NMOG In-use**	**NMOG Certification[a]**
5	50,000	0.07	0.05	---	0.075
	120,000	0.10	0.07	---	0.090
4	120,000	0.06	0.04	---	0.070
3	120,000	0.05	0.03	0.09	0.055
2	120,000	0.03	0.02	0.02	0.010

Notes:
[a] Shown for reference only.
[b] Separate standards apply for Diesel vehicles certified to Bin 10 standards.

D. Other Standards

Tier 2 vehicles are subject to the following additional exhaust emission standards:

- Cold CO Standards (applicable only to gasoline-fueled LDV/LDTs and MDPVs): At 20°F, 10.0 g/mi for LDVs and LDT1s; 12.5 g/mi for LDT2s, LDT3s, and MDPVs (other than interim non-Tier 2 MDPVs).

- Certification Short Standards (applicable to gasoline-fueled Otto-cycle LDV/LDTs and MDPVs): HC 100 ppm (as hexane) for certification and SEA testing and 200 ppm (hexane) for in-use testing; CO 0.5% for certification and SEA testing and 1.2% for in-use testing.

- Highway NOx Standards (except for MDPVs): Maximum NOx on federal Highway Fuel Economy Test cannot exceed 1.33 times the FTP NOx to which the vehicle is certified.

Appendix D

Manufacturer Reports

Best Viewed in Color

Manufacturer A

Use and Experience with High Density Close Coupled (HDCC) Catalyst Systems in the Canadian Market with Exposure to MMT®

Manufacturer A Information

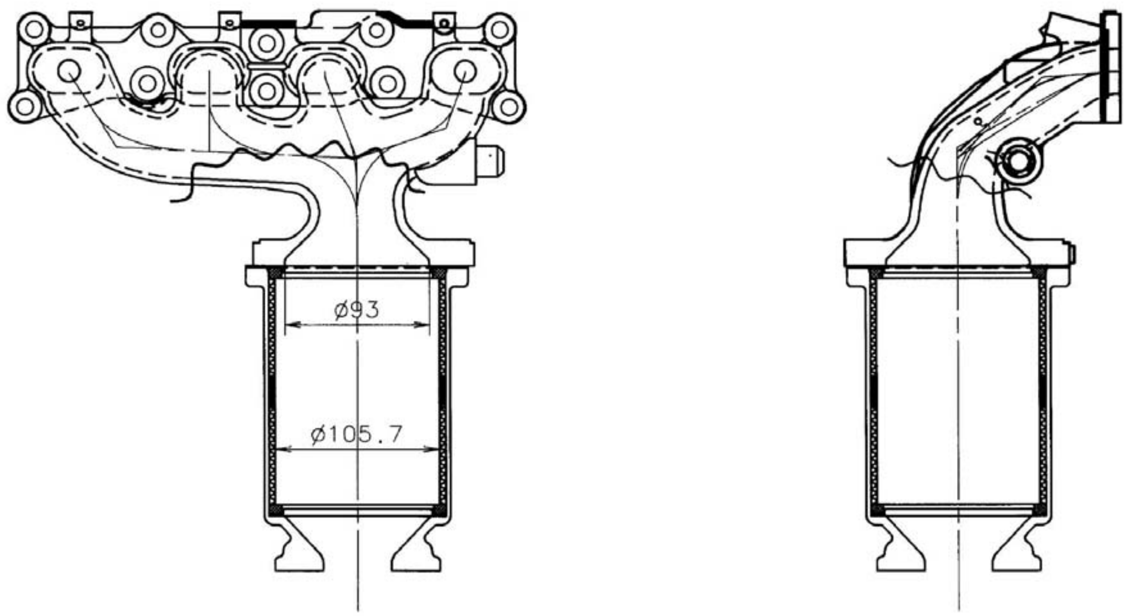
High Density Close Coupled (HDCC) Catalysts Used Prior to MY2004:

- Manufacturer A introduced an HDCC catalyst vehicle in MY 2002 in both the US and Canada. It was an ~2 liter I4 engine with a single 600 cpsi (4 mil wall thickness) ceramic close coupled catalyst.
    - This was certified to NLEV-ULEV standards and was not designed for Tier 2 Bin 5 requirements.
        - To comply with T2B5 it needed significant modification such as grade-up of the catalyst and/or A/F control change to reduce NOx.
        - "A/F control change" means to use the feedback system controlled by the rear O2 sensor. The optimum catalyst efficiency would be achieved by controlling the fuel trim bias calculated based on the rear O2 signal, even if the rich or lean shift of the front O2 sensor occurred.
    - Description of the catalyst system follows:
        - 600 cpsi w/4 mill wall thickness
        - Close coupled at exit plane of the exhaust manifold (distance from the closes exhaust port to the catalyst face was 200 mm)
        - Ratio of catalyst volume to engine displacement was 1290 cc (catalyst) / 1991 cc (engine displacement) = .65
        - Diameter of inlet pipe: 93 mm; diameter of monolith: 105.7 mm
        - Flow angle at the catalyst face: Flow is turned ahead of the catalyst face so as to make flow at the face perpendicular.
        - Time for light-off on the FTP: "It takes about 30 – 40 seconds for 50% efficiency and 60 – 70 seconds for 90% efficiency."
        - Figure 1 provides a diagram of catalyst configuration.

Best Viewed in Color

Figure 1

Diagram of Catalyst Configuration



- A second HDCC model was added in MY 2003, again both in the US and Canada. It was a ~3 liter V6 engine with a single 600 cpsi (4 mil wall-thickness) close coupled catalyst. Additional description is not included for this case as this model year 2003 vehicle was too new to have accumulated enough mileage while MMT remained in the Canadian fuel to give a meaningful indication of whether the product would have been sensitive to MMT related problems.

Experience w/MMT Plugging:

- Manufacturer A did not know of any plugging with its MY2002 HDCC application. No special analysis of warranty data was performed to try to see if there might have been beginning signs of an abnormality in catalyst repair trends. No random inspection of in-use vehicles were conducted to look for signs of the beginning of a build up of deposits. Even as a MY2002 vehicle, few vehicles from this relatively low sales volume fleet would have had enough exposure to fuel containing MMT to have been expected to show any significant trends.

Additionally, as discussed above, this system was not designed for Tier 2 Bin 5 compliance so it was not considered worthwhile to try to perform any extraordinary analysis or testing of this vehicle regarding response to MMT.

- Manufacturer A had previously experienced some plugging on a 1999 model year model certified to Tier 1 standards. Three plugged catalysts from a model which used a close coupled 400 cpsi catalyst were identified.
  - All three were returned for analysis from the dealers.
  - They were discovered as a result of consumer complaint/warranty repairs.
  - No chemical analyses of the deposits were conducted but deposits had the typical orange/reddish color of manganese oxide deposits.
  - The catalysts are no longer available so additional follow up analyses or testing cannot be done.

Future Technology Plans:

- Manufacturer A has been using and expects to continue into the foreseeable future to use close coupled 600 to 900 cpsi catalysts as the predominant approach to complying with tier 2 bin 5 (and lower bins) and SULEV standards.
- Manufacturer A believes use of 600 and higher cpsi catalysts are the most reasonable way to comply with the stringent standard from the viewpoint of cost, durability, and reliability.
- One exception was identified that involves use of a high density underfloor catalyst for a model certified to Tier 2 Bin 5 standards. Some additional models may continue to use underfloor catalyst but only when being certified to bins higher than Bin 5. For the one T2B5 exception, packaging and other vehicle constraints prohibits the use of a close coupled design. This in turn results in the need to incorporate additional less than desirable design measures including:
  - Accelerated warm-up system (high idle rpm and ignition retard)
  - Reduced heat capacity of the exhaust manifold
  - Optimized exhaust gas flow (i.e., the shape of the exhaust manifold is optimized so that the heat from the exhaust gas is expanded thoroughly)

Emission Testing and Mechanism Analysis:

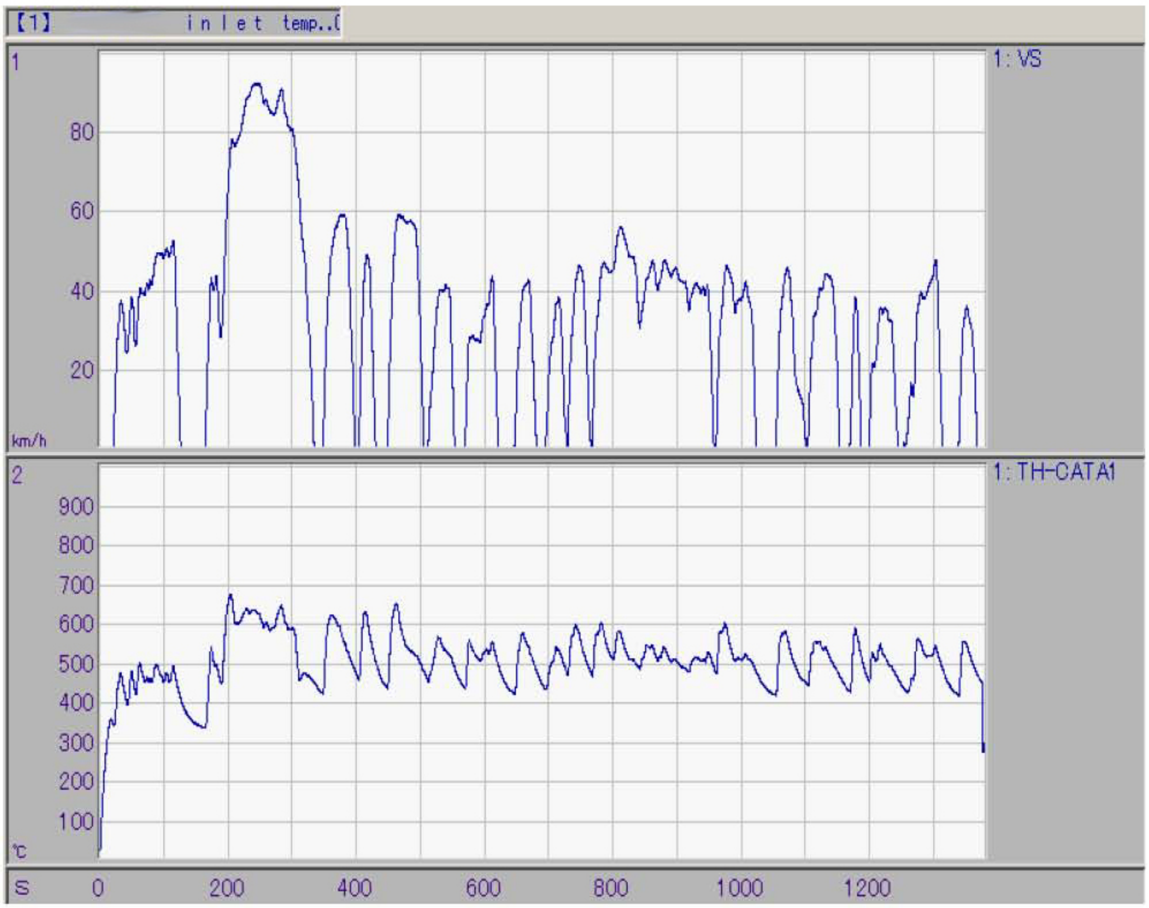
- Figures 2 and 3 provide temperature information for the MY2002 HDCC product tested on the US06 and FTP test cycles. This includes inlet temperatures for the FTP and both brick temperature (measured 1.5 inches behind the catalyst face) and inlet temperatures for the US06 cycle.

- Based on comparison of this temperature information with several other industry cases where plugging had been observed it appears that this vehicle runs at a somewhat lower temperature. This does not mean it might not have eventually exhibited plugged had this MY2002 vehicle been exposed to fuel containing MMT for longer mileage accumulation period before MMT was removed.

- The above product was not certified to Tier 2 Bin 5 or more stringent standards. Design changes to allow for compliance at this level would directionally increase temperature.

Figure 2

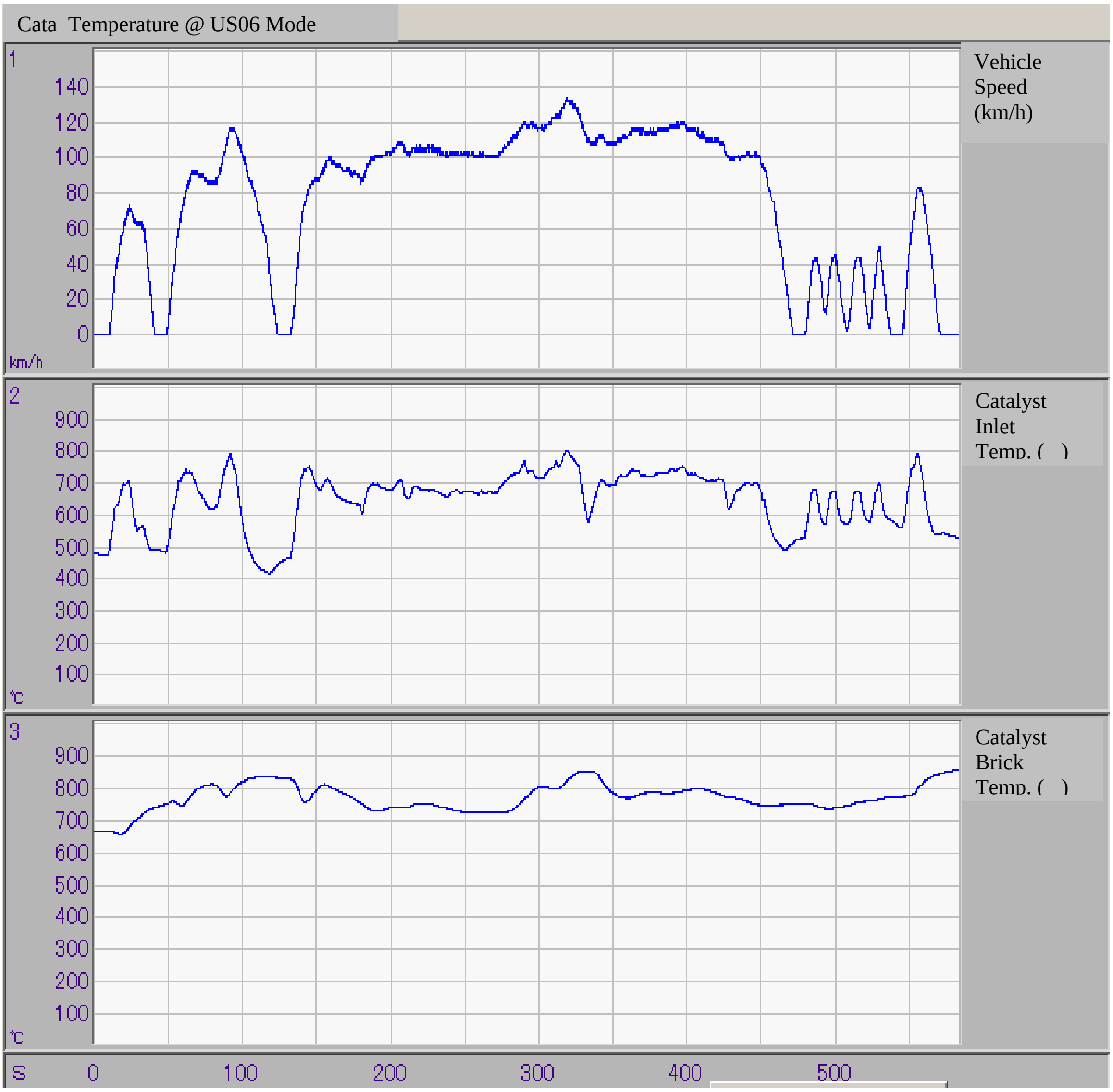
FTP - Inlet Catalyst Temperature (degrees C)



Best Viewed in Color

Figure 3

US06 - Both Inlet and Brick Temperature (degrees C)
(Brick temperature was measured 1.5 inches behind face)



Summary Statement by Manufacturer A

Market experience with our one and only vehicle model using an HDCC system before MMT was removed from Canadian fuel did not last long enough (before MMT was removed) to allow definitive conclusions about the sensitivity of this model to MMT related catalyst plugging. Additionally, this vehicle was not optimized for T2B5 compliance. Catalyst temperatures have increased on vehicles that have been optimized for T2B5 compliance and could go even higher in the future as we further optimize for both low emissions and maximum fuel economy. Fortunately our newer T2B5 compliant technology products have not been exposed to fuel containing MMT. However, we are concerned that if MMT were to be put back into the fuel that a number of our products would experience catalyst plugging problems similar to what other manufacturers experienced with products introduced earlier and which contained catalyst design, location, and operating temperature characteristics similar to our more recent products.

Best Viewed in Color

Manufacturer C

Use and Experience with High Density Close Coupled (HDCC) Catalyst Systems in the Canadian Market with Exposure to MMT®

Manufacturer "C" Information

High Density Close Coupled (HDCC) Catalysts Used Prior to MY2004:

Manufacturer C sold three basic models prior to MY2004 that used HDCC catalyst systems.

1. Model "C-1" was a *passenger vehicle* with a 4 cylinder engine. It began using a HDCC 600 cpsi catalyst beginning in MY2000.

    - In MY2000 there was only a single 600 cpsi front catalyst; the vehicle was certified to the Tier 1 standard.
    - In MY2001, the 600 cpsi front catalyst was retained, but a second downstream 400 cpsi catalyst was added; this was certified to the LEV standard.
    - In MY2002, both the close coupled front catalyst and the downstream catalyst were changed to 900 cpsi; this was certified to the ULEV standard. The catalyst configuration did not change through MY2004; however the model was certified to Tier 2 Bin 5 in MY 2004.
    - Model C-1 was first certified to SFTP standards in MY2002.
    - Design details:
        - Ratio of close coupled catalyst volume to engine displacement:
            - 2001 MY: 0.54
            - 2001 MY (R/C*): 0.39

              *R/C refers to running change - this catalyst was changed and vehicle was recertified during the model year.
            - 2002-2004 MY: 0.37
        - Ratio of catalyst face surface to engine displacement (UNITS are cm^2 for catalyst surface area divided by cm^3 for engine volume = 1/cm)
            - 2001 MY: 0.03
            - 2001 MY (R/C) 0.032
            - 2002-2004 MY: 0.038
        - The front catalyst was mounted to the exhaust manifold. The distance from exhaust ports to front face was approximately 230mm on average for 4 cylinders.
        - The exhaust flow was designed to be perpendicular to the catalyst face.
        - The front catalyst substrate was ceramic with 4 MIL wall thickness.
        - Manifold material was "SUS."

2. Model "C-2" was a *passenger vehicle* with a V6 engine. It began using a HDCC 600 cpsi catalyst in MY2001.
    - In MY2001, this vehicle used two 600 cpsi ceramic front catalysts, one on each side of the V-engine followed by a single 400 cpsi catalyst downstream; this was certified to the LEV standard.
    - In MY2002, the front catalyst arrangement was changed to a 900+600(M) configuration (i.e., one bank had a 900 cpsi ceramic catalyst and the other a 600 cpsi metallic catalyst); this was certified to the LEV standard through MY2003.
    - In MY2004, the same system configuration used in 2002 and 2003 was certified to Tier 2 Bin 5 standards.
    - Model C-2 was first certified to SFTP standards in MY2000.
    - Design details:
        - Ratio of close coupled catalyst volume to engine displacement:
            - 2001 MY: 0.5
            - 2002-2004 MY: 0.4
        - Ratio of catalyst face surface to engine displacement (UNITS are cm^2 divided by cm^3 for engine volume = 1/cm)
            - 2001 MY: 0.041
            - 2002-2004 MY: 0.041
        - The catalyst was mounted to the exhaust manifold.
        - Manifold material was cast iron.
        - Exhaust flow was designed to be perpendicular to the catalyst face.
        - Wall thicknesses for the various front catalysts were:
            - 4 MIL for 600 cpsi ceramic catalysts.
            - 30µm for 600 cpsi metallic catalysts.
            - 2 MIL for 900 cpsi ceramic catalysts.

3. Model "C-3" was an *SUV* with a V6 engine. It began using its first HDCC in MY 2002.
    - It used two 900 cpsi front catalysts, one on each side of the V-engine followed by a 400 cpsi catalyst for the downstream (under floor) catalyst.
    - Model C-3 was certified to the LEV standard in both 2002 and 2003. In MY 2004, it was certified to Tier 2 Bin 5.
    - Model C-3 was first certified to SFTP standards in MY2004.
    - Design details:
        - The front catalyst was mounted to the exhaust manifold.
        - Ratio of close coupled catalyst volume to engine displacement:
            - 2002 MY: 0.57
            - 2003-2004 MY: 0.42
        - Ratio of catalyst face surface to engine displacement (UNITS are cm^2 divided by cm^3 for engine volume = 1/cm)
            - 2002 MY: 0.039
            - 2003-2004 MY: 0.047
        - Manifold material was cast iron.

- Exhaust flow was designed to be perpendicular to the catalyst face.
- The front catalyst was a 900 cpsi ceramic catalyst with a wall thickness of 2 MIL.

Experience w/MMT Plugging:

- Manufacturer C has experienced catalyst plugging with all three cases described above. Warranty claims associated with ALL catalyst problems were observed to be higher in Canada than in the USA.
- The hypothesis that the consistently higher percentage of warranty claims in Canada compared to the USA was due to MMT was verified by inspecting a sample of warranty return catalysts.
- Sample pictures of plugged catalysts removed from Canadian vehicles are included in Attachment 1a through 1e. [NOTE: These pictures are mostly from model C-1 because this is what was available. The purpose was to illustrate what a plugged catalyst looks like. No pictures were available for model C-2 and few pictures were available for model C-3. However, data was collected regarding all three models even though pictures were not taken.]
- Manufacturer C also experienced MMT related plugging with catalysts in China. Attachment 2 is an example picture of a partially plugged catalyst from China. This was a 900 cpsi catalyst removed from an SUV having the same engine as model C-1.
- When inspecting a sample of warranty return catalysts, the percentage of the face area that was plugged was recorded. These results were plotted vs. mileage accumulated for each catalyst. This plot is provided as Attachment 3. The percentage of area plugged was based upon visual inspection. The percentage recorded was the estimate of the fraction of the total surface area covered with deposits.
- Warranty rate information showed that the total catalyst replacement rate in Canada substantially exceeded the comparable rate in the USA. Since MMT was not used in the USA (except in one very isolated region in the "four corners" area of Utah, Colorado, New Mexico, and Arizona), the US catalyst replacement rate can be viewed as a "baseline" rate representing normal catalyst repair rates for the models in question. The higher Canadian rate would then be attributable at least in part if not totally to MMT contamination which would not have been observed in the USA. Because of the highly sensitive nature of the "confidential" warranty rate information, these rates are not included in this report. However, the ratios of the Canadian total catalyst warranty replacement rate divided by the comparable US rate for the various models appears in Attachment 4. This gives an indication how much higher the Canadian rate was.
    - These ratios were based on warranty experience as of the summer of 2004. This was approximately the time when MMT was being voluntarily removed from most Canadian fuel.

- Warranty rates were computed two different ways.
  1. One was a simple percentage computed as total number of warranty claims divided by total sales for the model year.
  2. The second was a Weible analysis that statistically projected the warranty rate to 100,000 km based upon the actual warranty performance to date. This projection assumed no removal of MMT. This outcome never had a chance to come to pass since MMT was voluntarily removed by most Canadian refiners during 2004.
- The table in attachment 4 provides the Canadian divided by USA ratio for each of the analysis methods for models C-1, C-2, and C-3 for model years 2001 and 2002.

- Because the above warranty analysis was performed on a cumulative basis at a single point in time rather than on a trend basis, this analysis did not give a picture of how things changed with time once MMT was removed from most of the fuel in Canada. To provide a view of the change resulting from MMT removal, Manufacturer C analyzed warranty incidents involving replacement of catalysts due to MMT plugging. Attachment 5 provides a histogram of number of incidents per month over an extended time period. The vertical scale is blinded to protect confidential information. But the shape of the distribution clearly shows a reduction in monthly repair incidents after the time that MMT was removed from most Canadian fuel.

Future Technology Plans:

- All of Manufacturer C's future vehicles designed for compliance with Tier 2 Bin 5 (or lower) standards will use HDCC catalyst designs.

  - To comply with strict regulation, such as Tier 2, emission systems require not only warm up purification performance but also warm up performance.
  - To implement quick activation under cold situations, close coupled catalysts have been adopted, which are favorable to increasing the BED temperature. In addition to improve warm-up performance, thin-walled substrates are used which have a low heat mass and high density substrate which has a larger geometric surface area. At the same time, these measures also improve purification performance.
  - Although increasing the use of precious metal is a possible solution to obtain a high purification ratio; it is not enough to reduce cold emissions. Also, electric heated catalysts could be adopted to reduce cold emissions, but this would increase costs, decrease durability and reduce fuel economy performance. For these reasons, high CPSI catalysts are the choice technology.

Emission Testing and Mechanism Analysis:

- Attachment 6 illustrates and explains further a test which shows that the CO conversion rate of a plugged catalyst can be restored from near 50% to about 95% by removing MMT deposits. However, this MMT removal process would not be usable as a "field" repair technique. [NOTE: CO data was used because it correlates to the OBD which shows in-use failure. NOx data was not available from this test.]

- Attachment 7 presents results of emissions testing performed using an approximately 90% plugged catalyst the was removed from a Canadian vehicle. The catalyst was tested on a slave test vehicle (i.e., the whole Canadian vehicle was not retrieved). Emissions exceeded the standards for each HC, CO and NOx. **Emissions for each pollutant were roughly 3 times the USA MMT free baseline at the comparable mileage.**

- Attachment 8 presents results of an XRD analysis of plugged catalysts. Mn_30_4 was the main component of deposits..

- Particle size distribution was also analyzed before and after calcination at various temperatures (400, 650, and 900^{o}C). This shows an increase in particle size distribution with temperature. See Attachment 9.

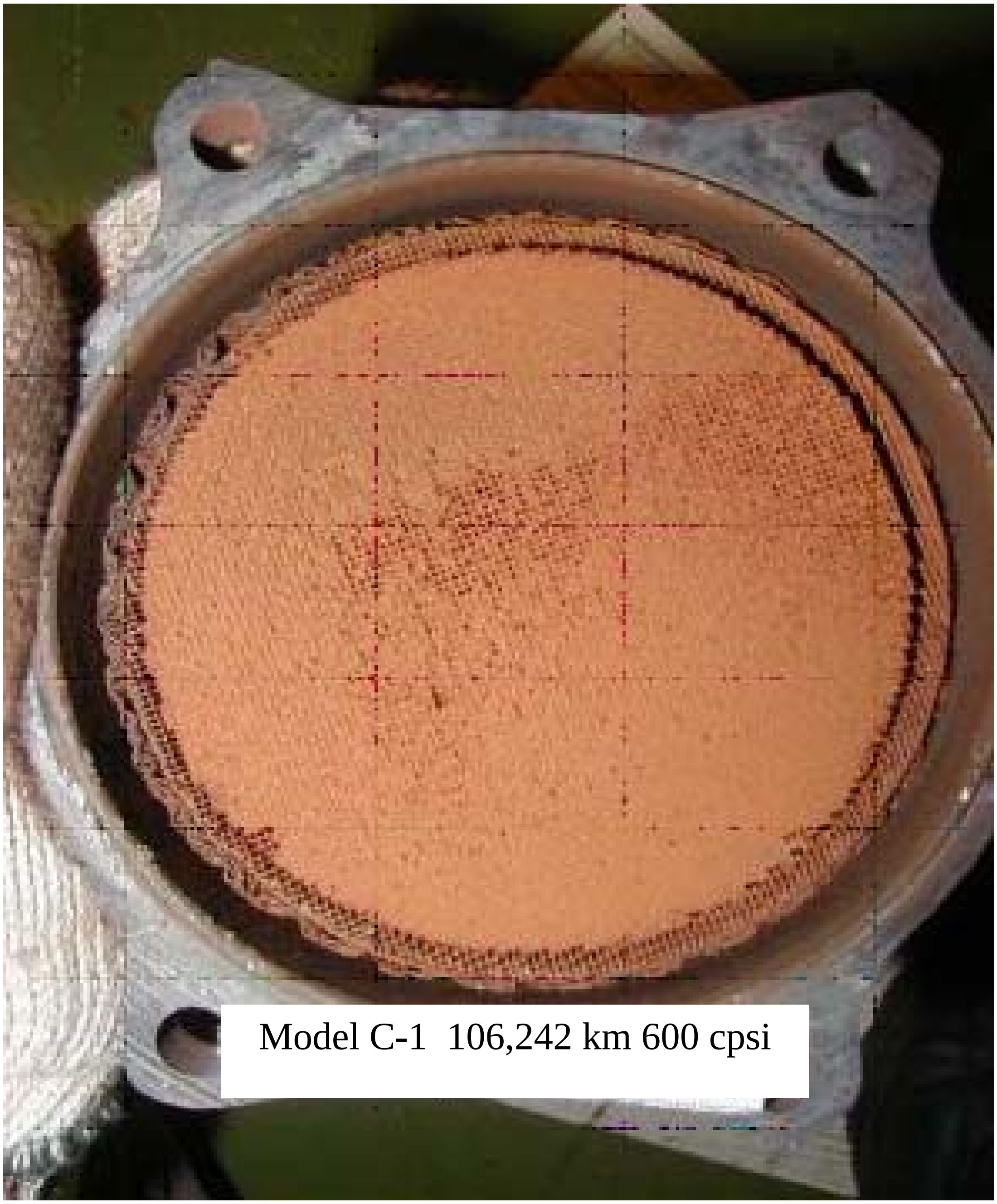
- Attachments 10a 10b provide temperature data that was available from models C-2 and C-3:
    - FTP and US06 temperature traces are plotted in comparison to the driving traces for models C-2 (2002 MY) and C-3 (2004 MY).
    - Note that Model C-3 was not SFTP certified until MY2004. Therefore the temperature traces provided may not represent the temperature for the earlier model year where plugging had been observed in the field. It is possible that temperatures would have increased with the MY2004 SFTP compliant calibrations. At higher temperature, the MMT plugging tendency would be expected to be increased.
    - The temperature traces for Model C-2 should represent the temperatures for the relevant model years where plugging has been observed as the temperature data comes from a MY vehicle that actually experienced plugging in-use.

ATTACHMENTS FOLLOW ON THE NEXT PAGE

Best Viewed in Color

Attachment 1a

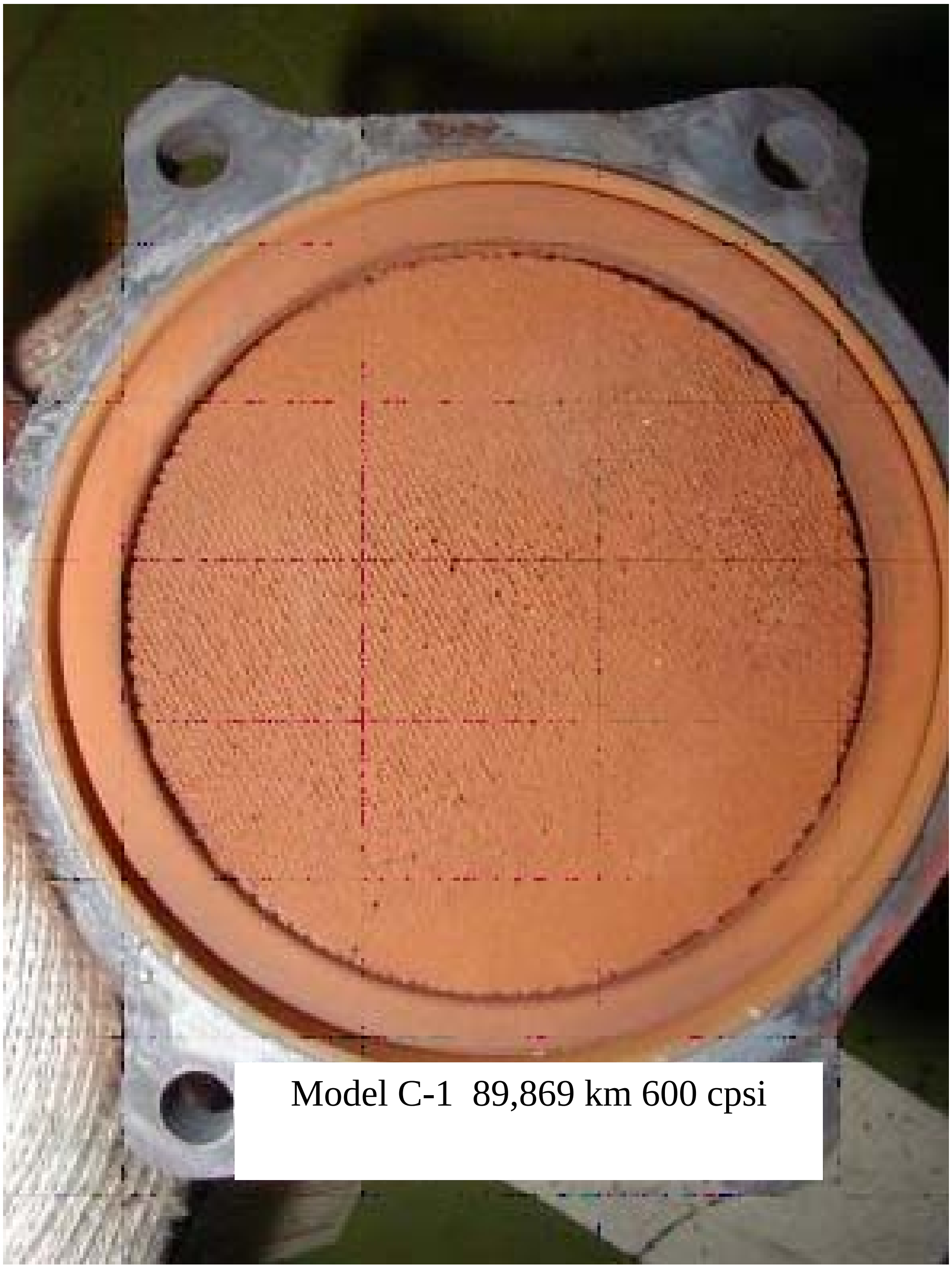
Plugging of 600 cpsi Close Coupled Catalyst Used in Canada



Best Viewed in Color

Attachment 1b

Plugging of 600 cpsi Close Coupled Catalyst Used in Canada



Best Viewed in Color

Attachment 1c

Plugging of 600 cpsi Close Coupled Catalyst Used in Canada

Best Viewed in Color

Attachment 1d

Plugging of 900 cpsi Close Coupled Catalyst Used in Canada

Model C-1 45000km 900 cpsi

Best Viewed in Color

Attachment 1e

Plugging of 900 cpsi Close Coupled Catalyst Used in Canada

Model C-3   85000km 900 cpsi

Best Viewed in Color

Attachment 2

Example of a Partially Plugged Catalyst from China

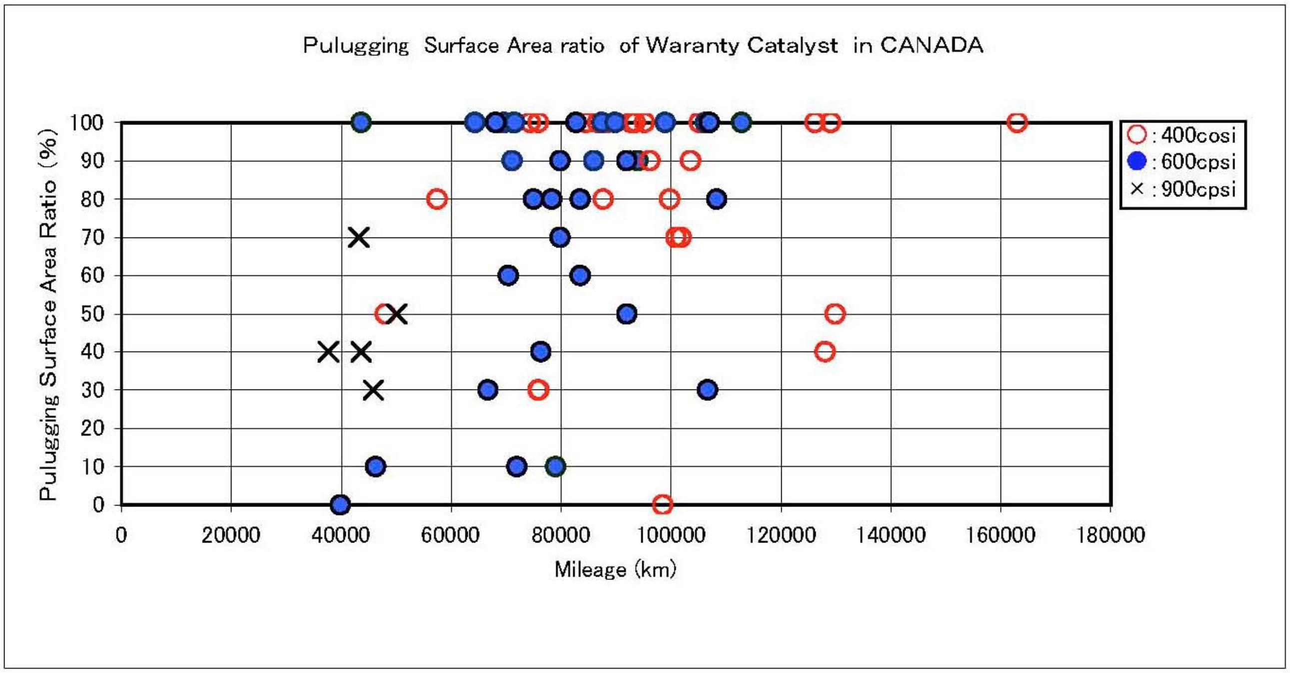
mileage: 32000km

- **This is a 900 cpsi catalyst from an SUV with the same engine as Canadian model C-1.**

Best Viewed in Color

Attachment 3

Warranty Analysis: Percent Plugging vs. Mileage



NOTES:

1. The inspected catalysts illustrated on this chart are from a combination of models. The 600 and 900 cpsi catalysts were from models C-1, C-2, and C-3. The 400 cpsi catalysts were from a number of older models.
2. There are as many red dots (400 cpsi catalysts) on this chart as any of the other categories. However, this does not indicate that 400 cpsi catalysts were plugging at the same frequency as the higher density catalysts. The plugged 400 cpsi catalysts came from a greater number of models that spanned a greater number of model years..

OBSEVATIONS:

1. The lower threshold for the 900 cpsi catalyst appears to be in the 40,000 km range.
2. The lower threshold for the 600 cpsi catalyst appears to be in the 60,000 to 70,000 km range. There is one significantly plugged catalyst as a lower mileage, but it appears to be 60,000+ miles before the frequency of plugging begins to rise substantially.
3. The lower threshold for the 400 cpsi catalyst is less defined, but the threshold where the frequency appears to increase substantially is in the 70,000 to 80,000 km range. The higher frequency of 400 cpsi catalysts at very high mileage is a reflection of two things; (1) they come from older vehicles that had more opportunity to accumulate more miles with exposure to MMT, and (2) it takes longer for these lower density catalysts to plug.

Attachment 4

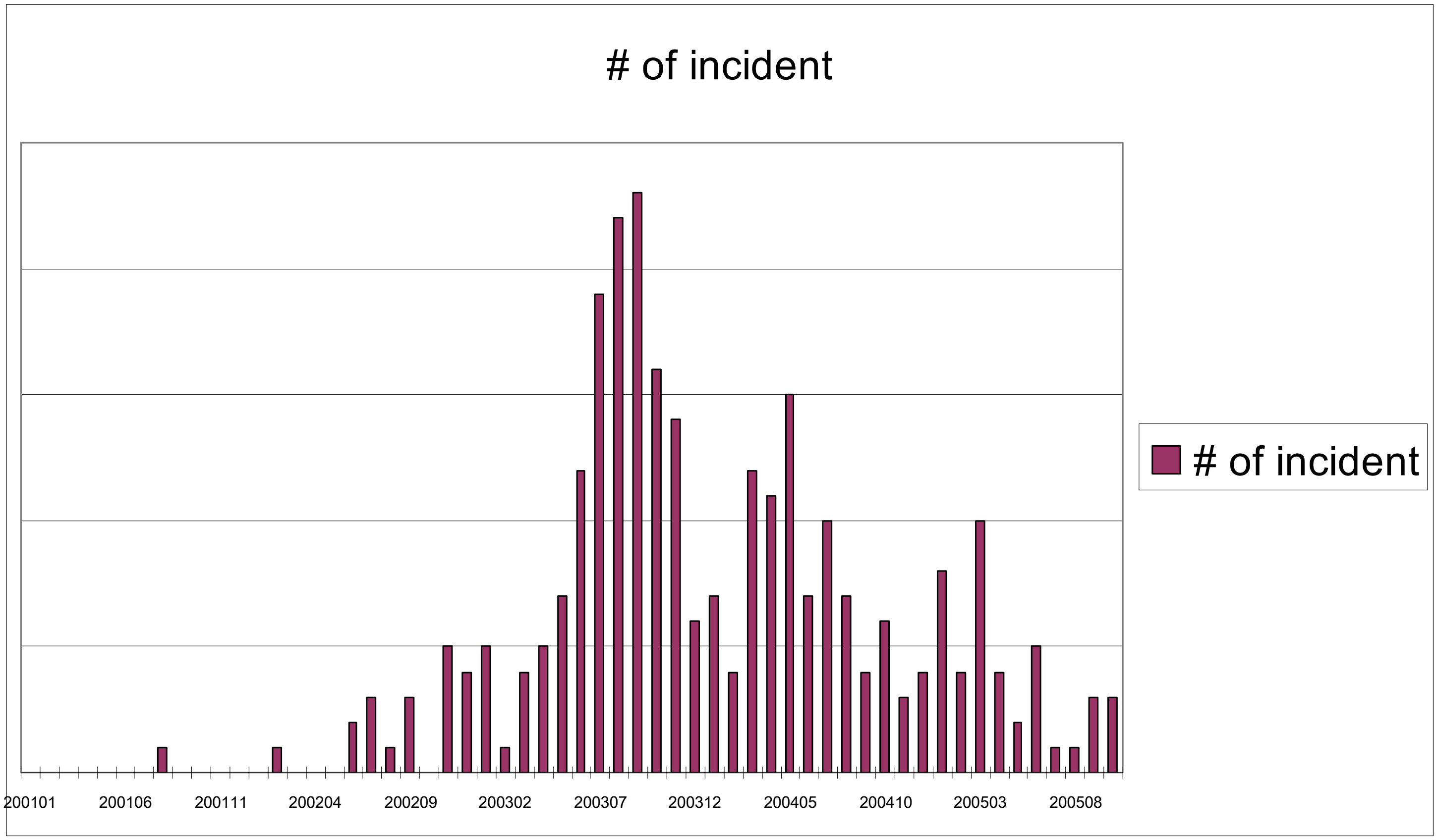
Warranty Analysis: Ratio of Canadian Divided by USA Warranty Rates

		Ratio of Canadian Total Catalyst Warranty Replacement Rate Divided by USA Total Catalyst Warranty Rate	
		MY2001 HDCC (600 cpsi)	MY2002 HDCC (900cpsi)
Model C-1 with I4 cylinder engine	Simple warranty percentage analysis	20.9	12.4
	Weible analysis projected to 100,000 km	65.0	29.5
Model C-2 with V6 cylinder engine	Simple warranty percentage analysis	1.7	6.3
	Weible analysis projected to 100,000 km	2.7	22.8
Model C-3 with V6 cylinder engine	Simple warranty percentage analysis		14.1
	Weible analysis projected to 100,000 km		24.5

Best Viewed in Color

Attachment 5

Warranty Analysis: Number of Catalyst Replacement Incidents per Month due to MMT Plugging



The above is a plot of warranty incidents involving "problem codes" associated with MMT plugging versus calendar date shown in the form year/month. **This is a combined plot for all three of models that used <u>900 cpsi close coupled</u> catalysts.** Remember MMT phase out occurred basically in the first half of 2004.

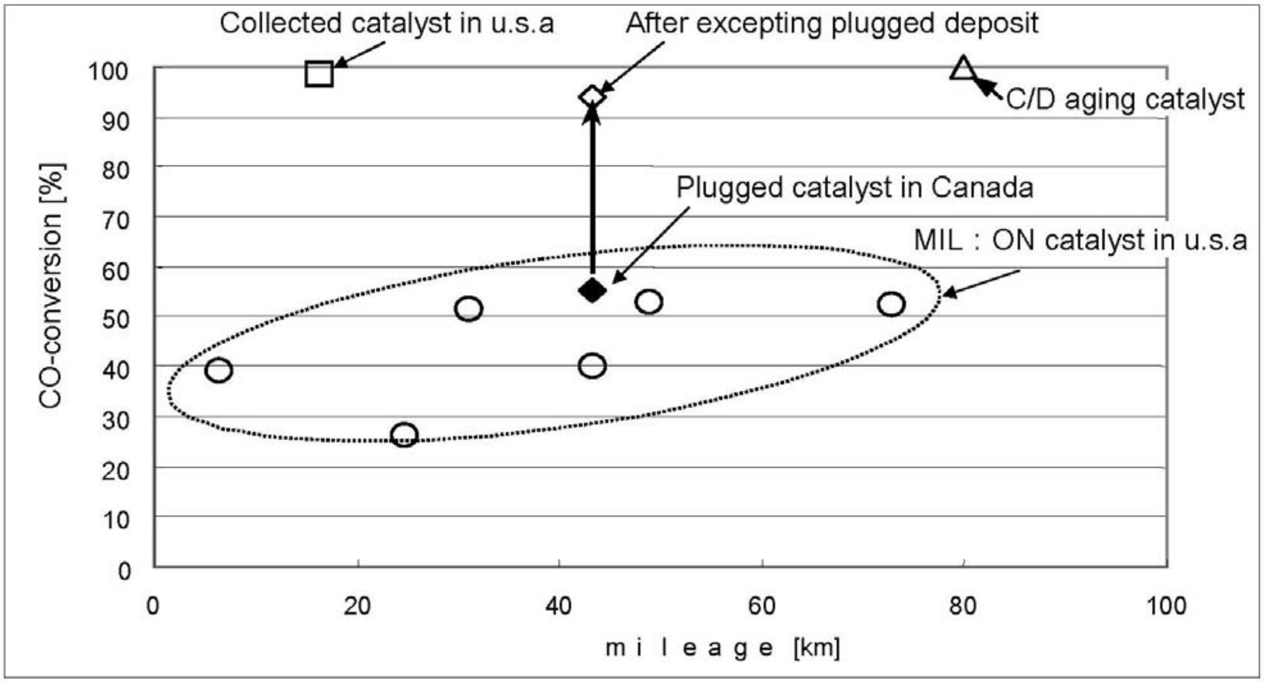
These are incidents "judged" to be MMT caused catalyst replacements and not total catalyst replacements. The number of incidents was determined as follows:

> A sample of catalysts was inspected from those replaced prior to the removal of MMT from most of the fuel. This included inspection of 100% of replaced catalysts for a period of about a month. From this inspection the "problem codes" that were used by dealers to report catalyst replacements that were caused by MMT were identified. The incident per month data reported the above chart then includes all warranty incidents, before and after MMT was removed, <u>where dealers gave those identified problem codes as the reason</u>.

Best Viewed in Color

Attachment 6

Catalyst Performance with Manganese Deposits Removed



Discussion:

- Catalyst performance recovers when the plugged materials are removed.*

  *[NOTE: The removal of the plugged material from the catalytic converter substrate material was conducted in a laboratory environment. The deposit material was removed mechanically. In this instance, the removal process was successful; however, there is a possibility of cracking the catalytic converter substrate and peeling off of the precious metal which may decrease the performance of catalyst. This process is not viable for use in the field or a service facility.]

- The catalysts shown as open circle dots were damaged catalysts from the USA where no MMT was used. These catalysts had no indication of manganese deposits. These were warranty return catalysts replaced due to an OBD MIL illumination. These were plotted to illustrate that the manganese-plugged catalyst had a similar performance level as a catalyst that would trigger an OBD MIL. Its performance could almost completely be recovered by removal of the deposits.

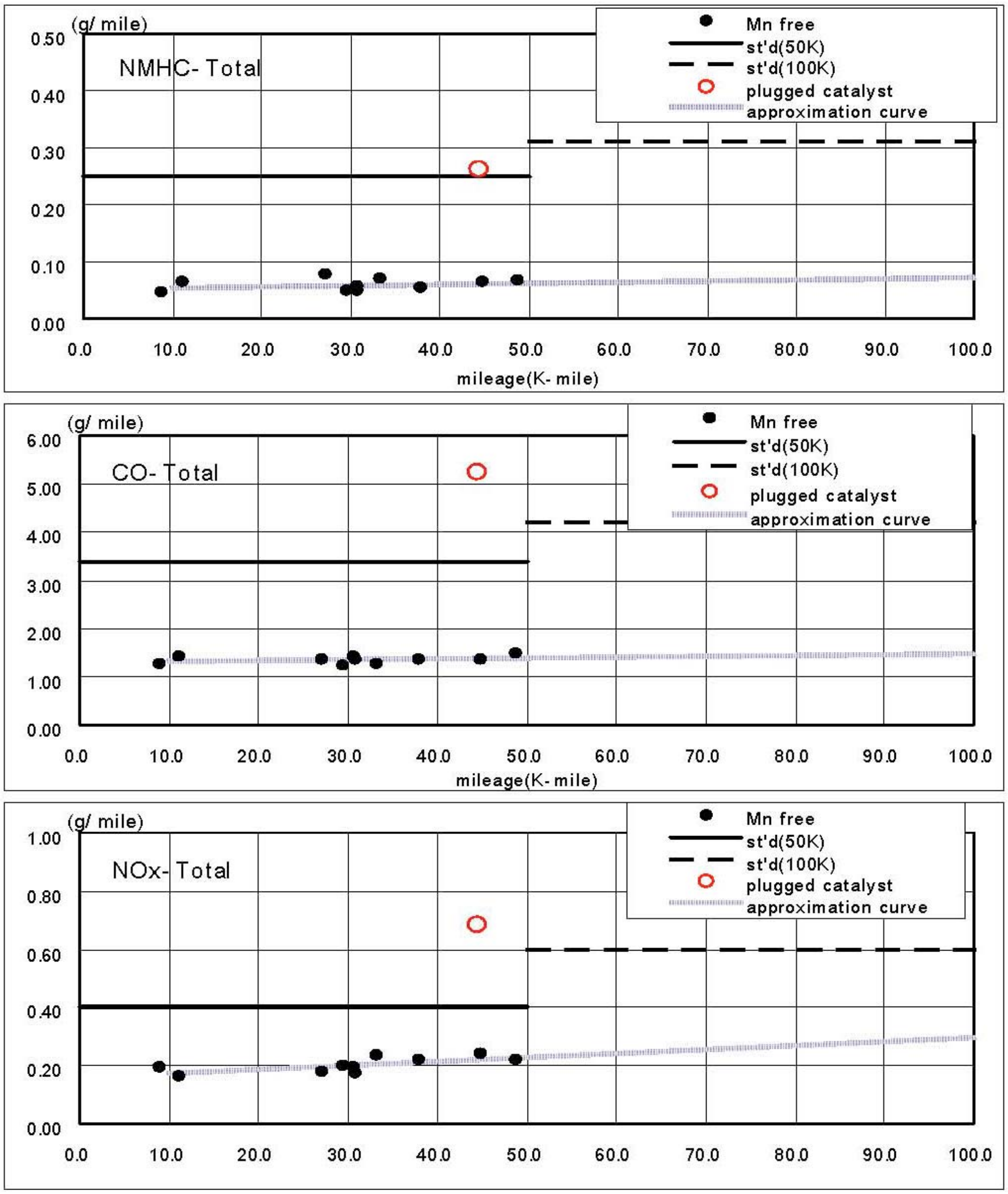
- The catalysts represented by the open square and open triangle symbols illustrate the expected performance of undamaged and unplugged catalysts. The catalyst represented by the triangle was a catalyst aged via certification type durability aging procedures. The catalyst represented by the open square was a properly operating catalyst from and in-use vehicle form the US market.

Best Viewed in Color

Attachment 7

Emissions from Plugged Catalyst

<u>This data was obtained from a 600 cpsi catalyst from model C-1</u>



NOTES:

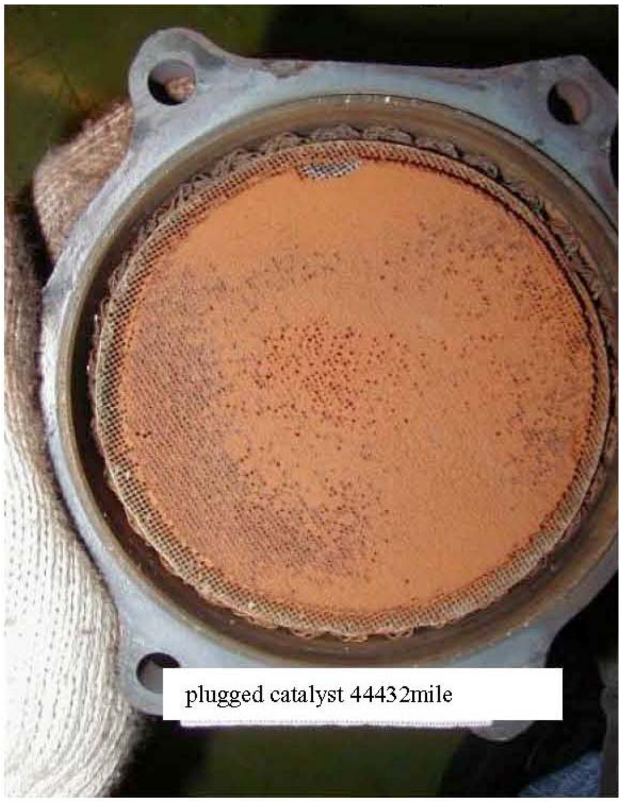
1. The black dots are from voluntary "in-use" whole vehicle testing of USA 2001 MY model C-1. Vehicles were procured from an MMT-free area.
2. The red dot is a single plugged catalyst (visually estimated to be 90% plugged) collected from a Canadian vehicle. This catalyst was tested on a "slave" test vehicle (i.e., the whole vehicle was not retrieved from the Canadian market. A picture of the face of this catalyst is on the next page along with a picture of a typical USA catalyst operated on MMT free fuel.
3. The solid and dashed horizontal lines represent the 50k and 100k emissions standards respectively.

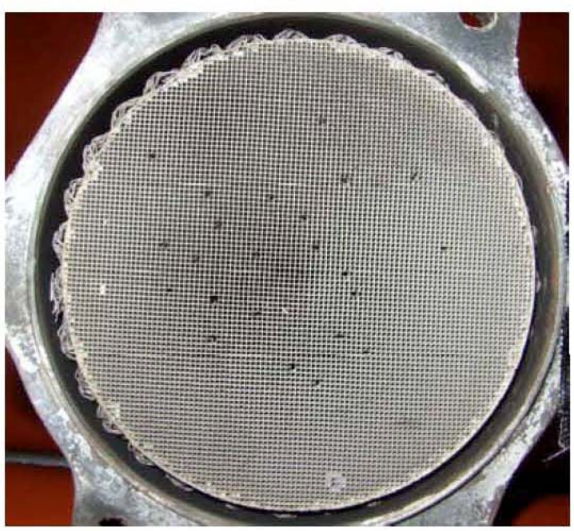
Best Viewed in Color

Attachment 7 (continued)

Picture of the manganese-plugged Canadian catalyst used in the above emission test compared to a typical USA catalyst taken from a vehicle driven in an MMT free area.

<u>This is the 600 cpsi catalyst from Model C-1</u>





Mn free catalyst 48773miles

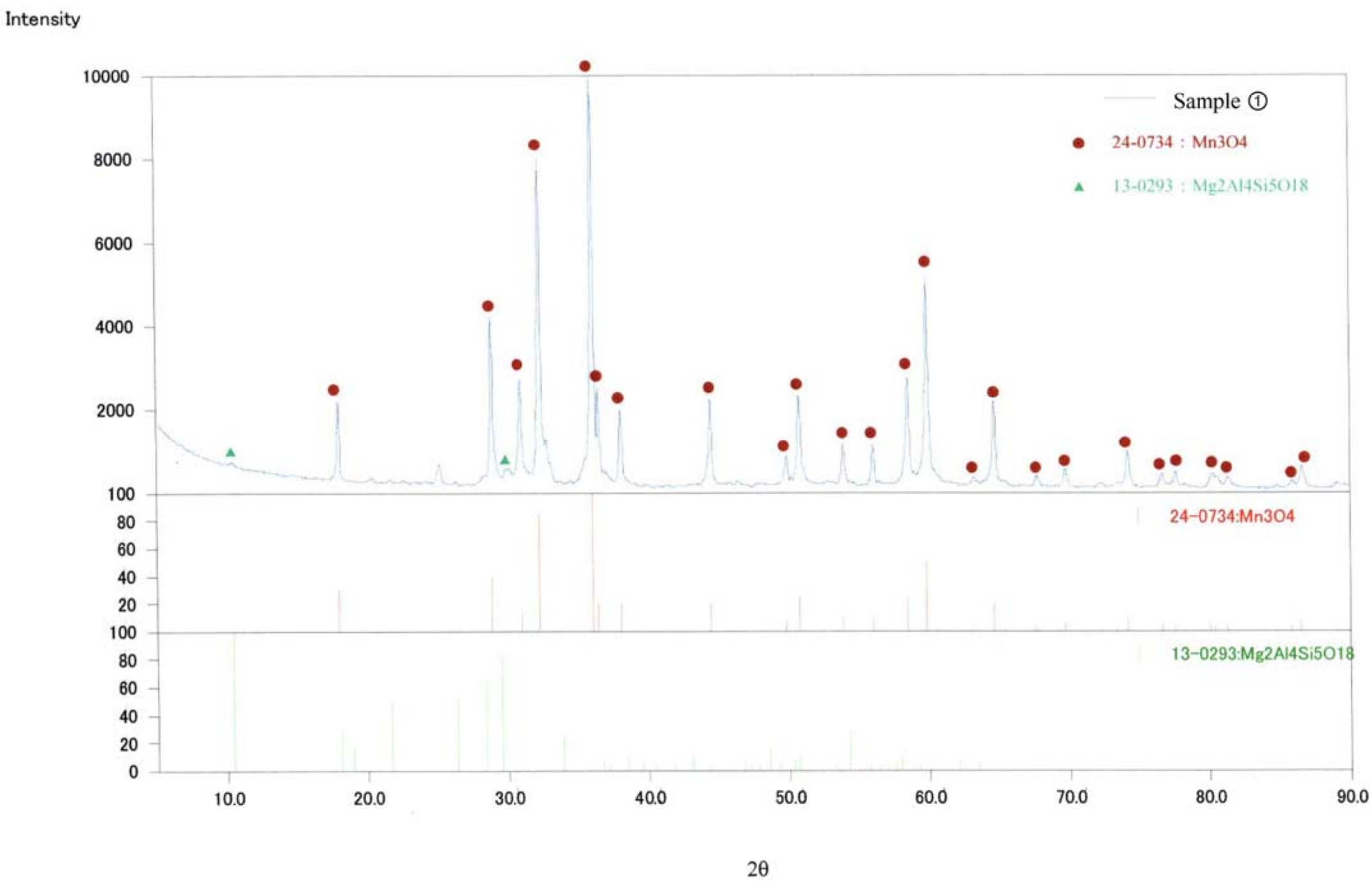
Best Viewed in Color

Attachment 8

Analysis of Deposits

Analysis of plugged catalysts found that Mn_3O_4 was the main component of plugging deposits.

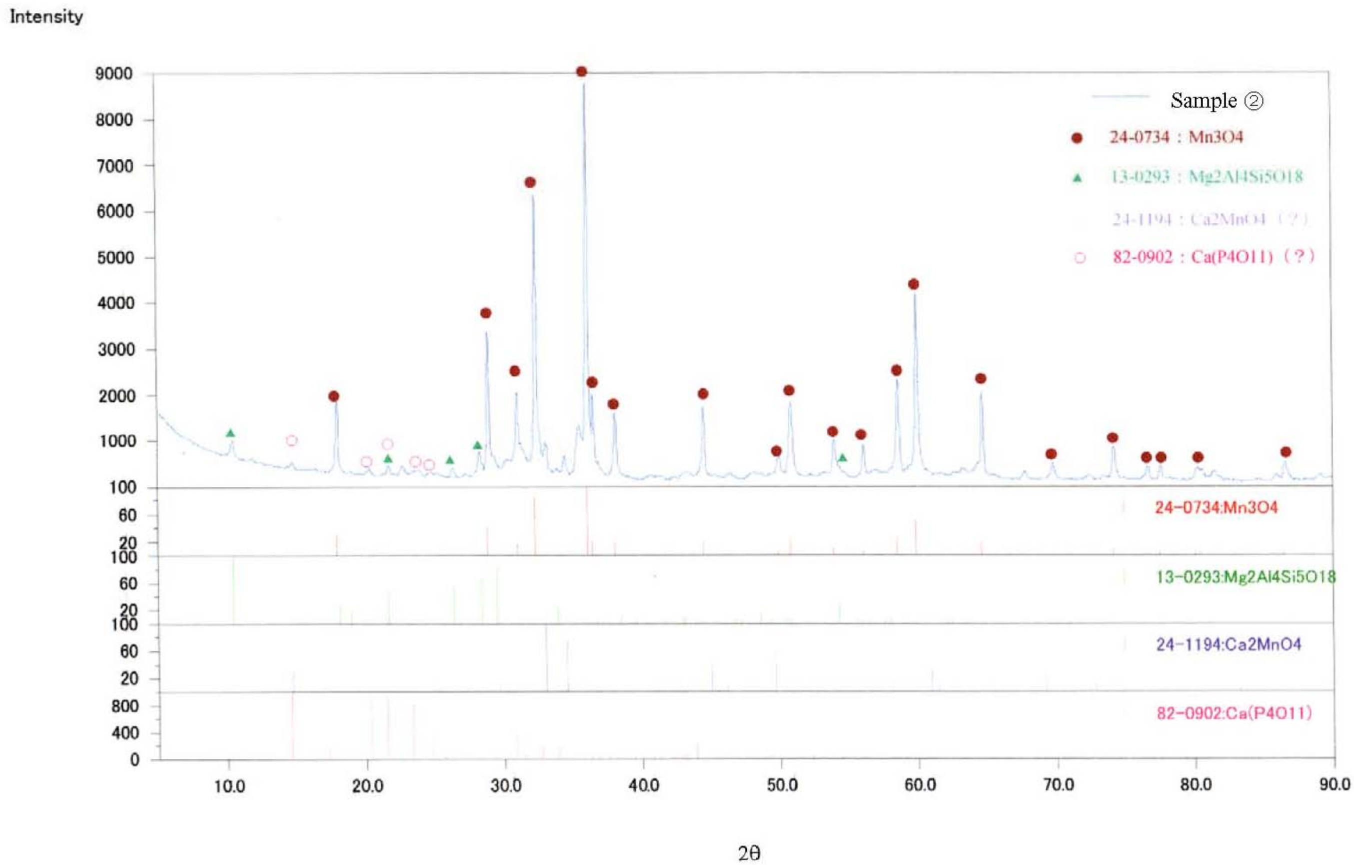
Sample #1



Best Viewed in Color

Attachment 8 (continued)

Sample #2

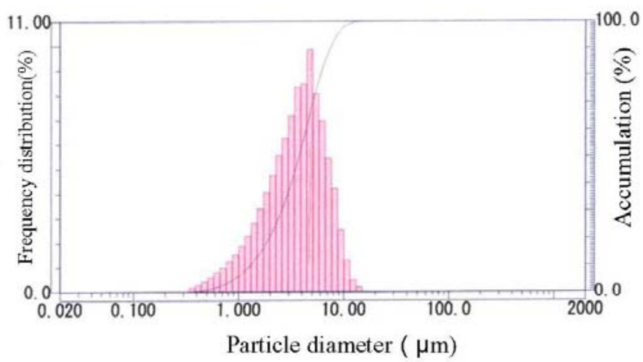


Best Viewed in Color

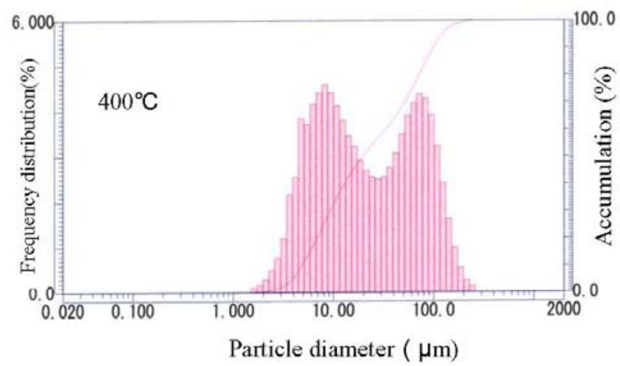
Attachment 9

Sintering of plugging deposit after calcinations

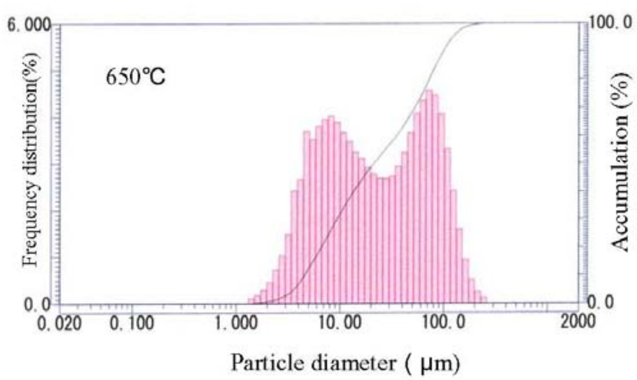
- Manufacturer C believes high temperature may be one of the factors that may cause catalyst plugging by MMT
- Manganese oxide deposits which stick on the catalyst appear t o grow in high temperatures and the deposits clog the catalysts.
- Deposits that were collected (from the call-in catalyst that was pounded and sonicated in mortar) is called the preheated sample. The grain size distribution of the sample was analyzed by a Laser Scattering Particle-Size Distribution Analyzer (LA-920, made by Horiba). The distribution of particle size for samples heated at 400, 600 and 900 degrees C are shown below.
    - "Calcinations" means process of heating in the air.
    - "Sintering" means growth of particulate, expressing the process of heated .. compound in the air."



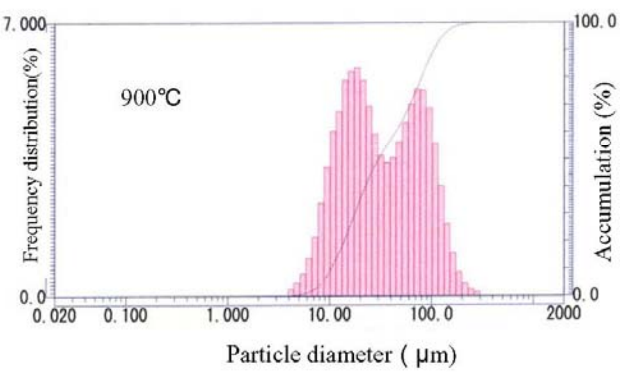
Before calcination



After calcination 400℃×32h



After calcination 650℃×32h



After calcination 900℃×32h

Best Viewed in Color

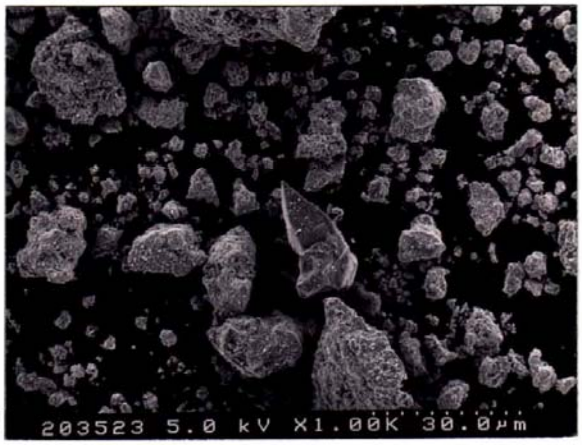
Attachment 9 (continued)

Sintering of plugging deposit after calcination

(b)

After calcination 400℃×32h

(b)



After calcination 650℃×32h

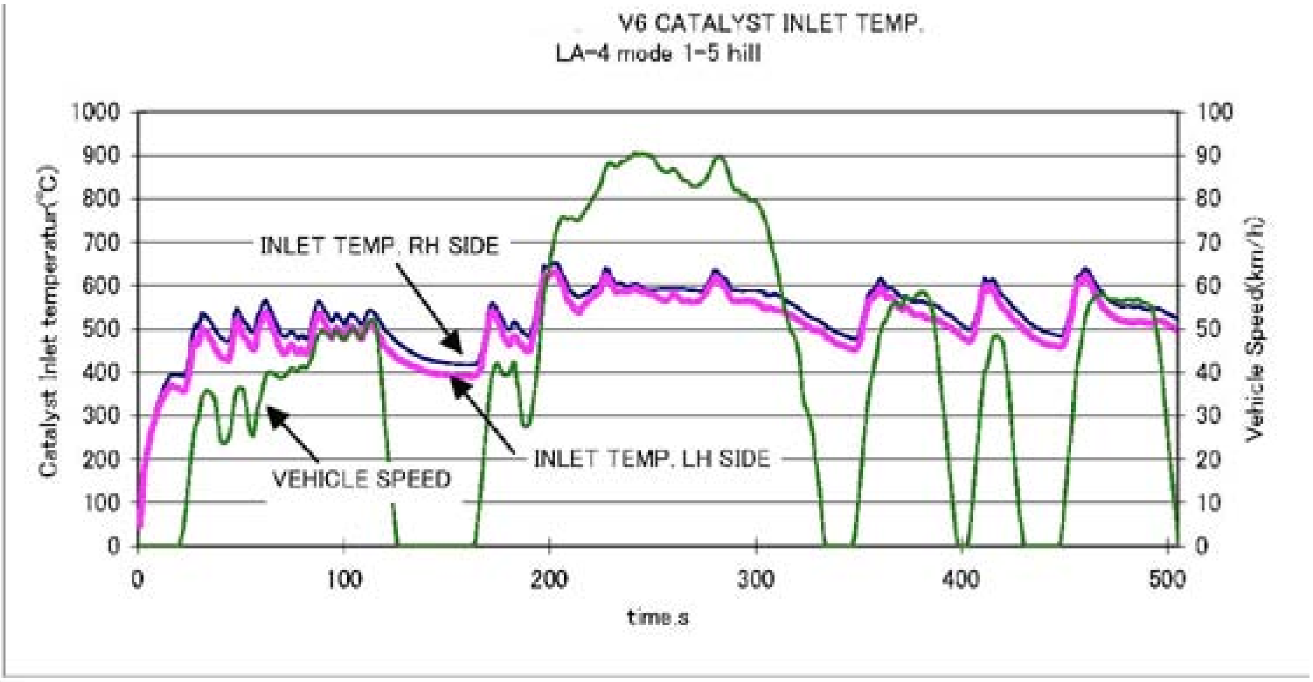
(b)

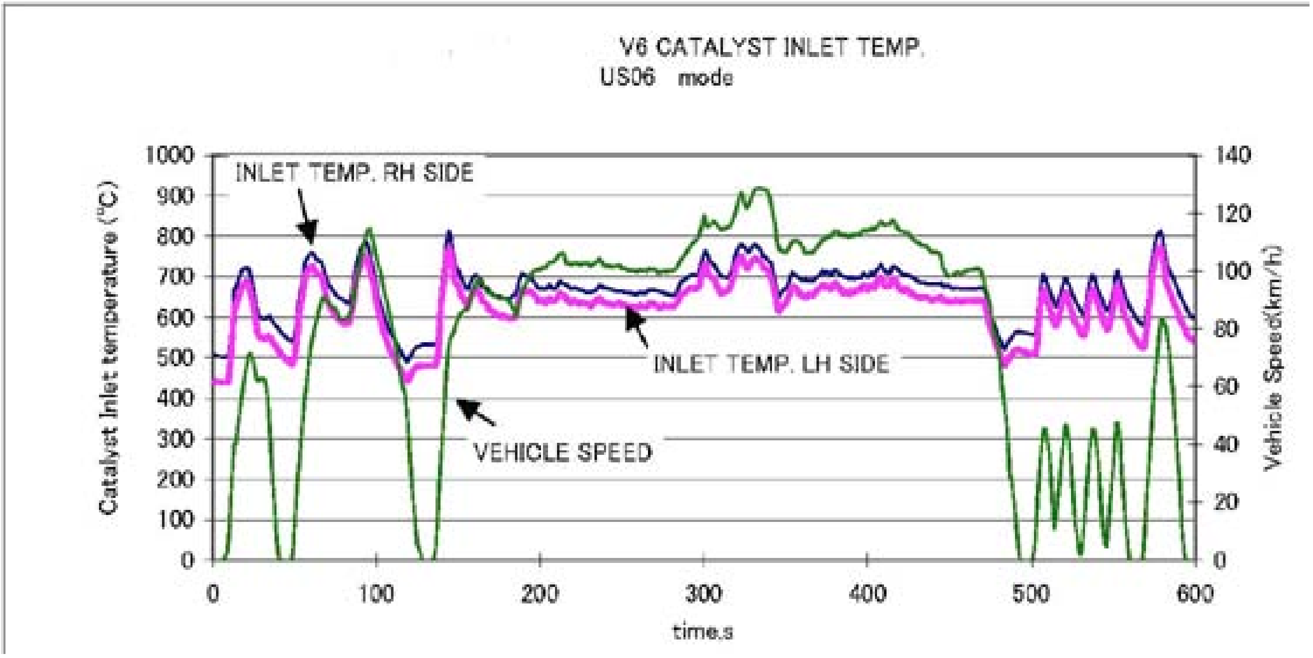
After calcination 900℃×32h

Best Viewed in Color

Attachment 10a

FTP and US06 temperatures for Model C-2 measured on a MY2002 vehicle



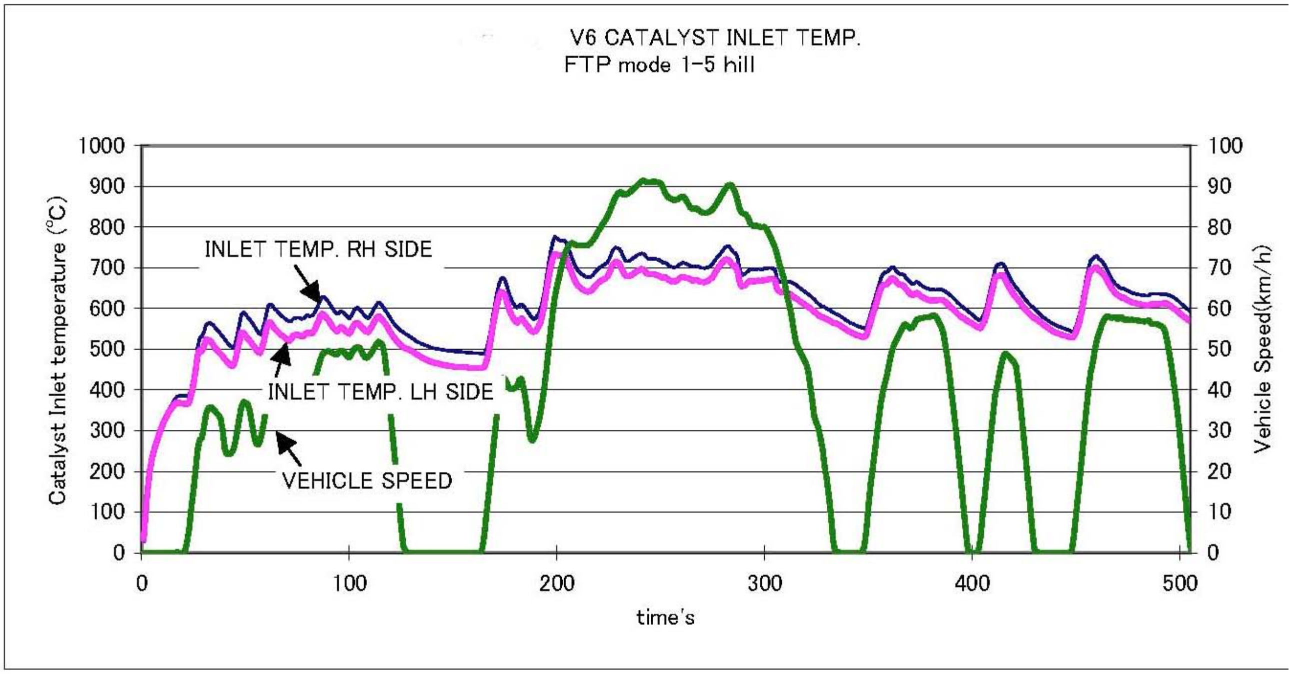


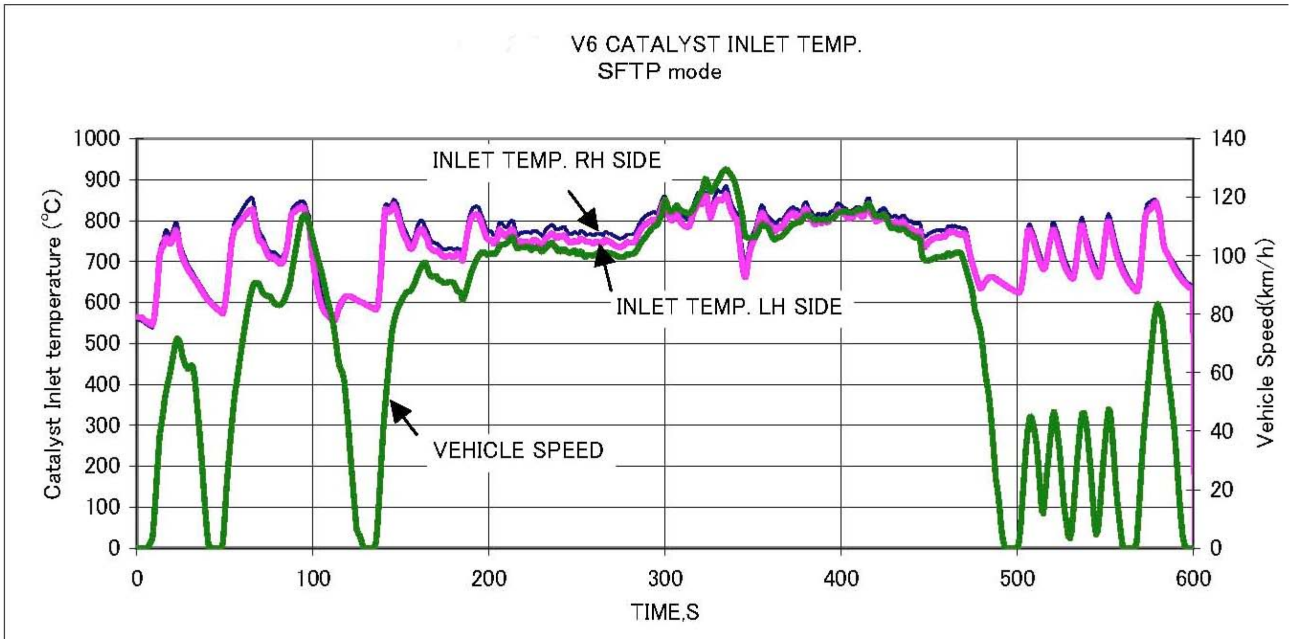
Best Viewed in Color

Attachment 10b

FTP and US06 temperatures for Model C-3 measured on a MY2004 vehicle

[Note: This may not represent the temperature characteristics of prior model years as 2004 was the first year the vehicle was calibrated to meet SFTP standards as well as tier 2 bin 5 standards. Pre-SFTP certified vehicles may have had lower catalyst temperatures.]





Best Viewed in Color

Manufacturer D

Use and Experience with High Density Close Coupled (HDCC) Catalyst Systems in the Canadian Market with Exposure to MMT®

Manufacturer "D" General Information

High Density Close Coupled (HDCC) Catalysts Used Prior to MY2004:

- Manufacturer D's first year with HDCC catalysts was the 2003 model year. In that model year, 7 vehicle models were introduced that used such systems.
  [NOTE: Throughout this report the term high density catalyst means a catalyst with a substrate of 600 cells per square inch or greater.]
- Two of these models are described in further detail in this report. The first was an early introduction MY2003 product that had enough mileage accumulation exposure, during the period before MMT use was voluntarily halted in Canada, to experience catalyst plugging from manganese compounds. The second model was a typical MY2003 vehicle that did not have the opportunity for sufficient MMT exposure to experience significant plugging in the field. However, some testing was performed on this model using fuel containing MMT.

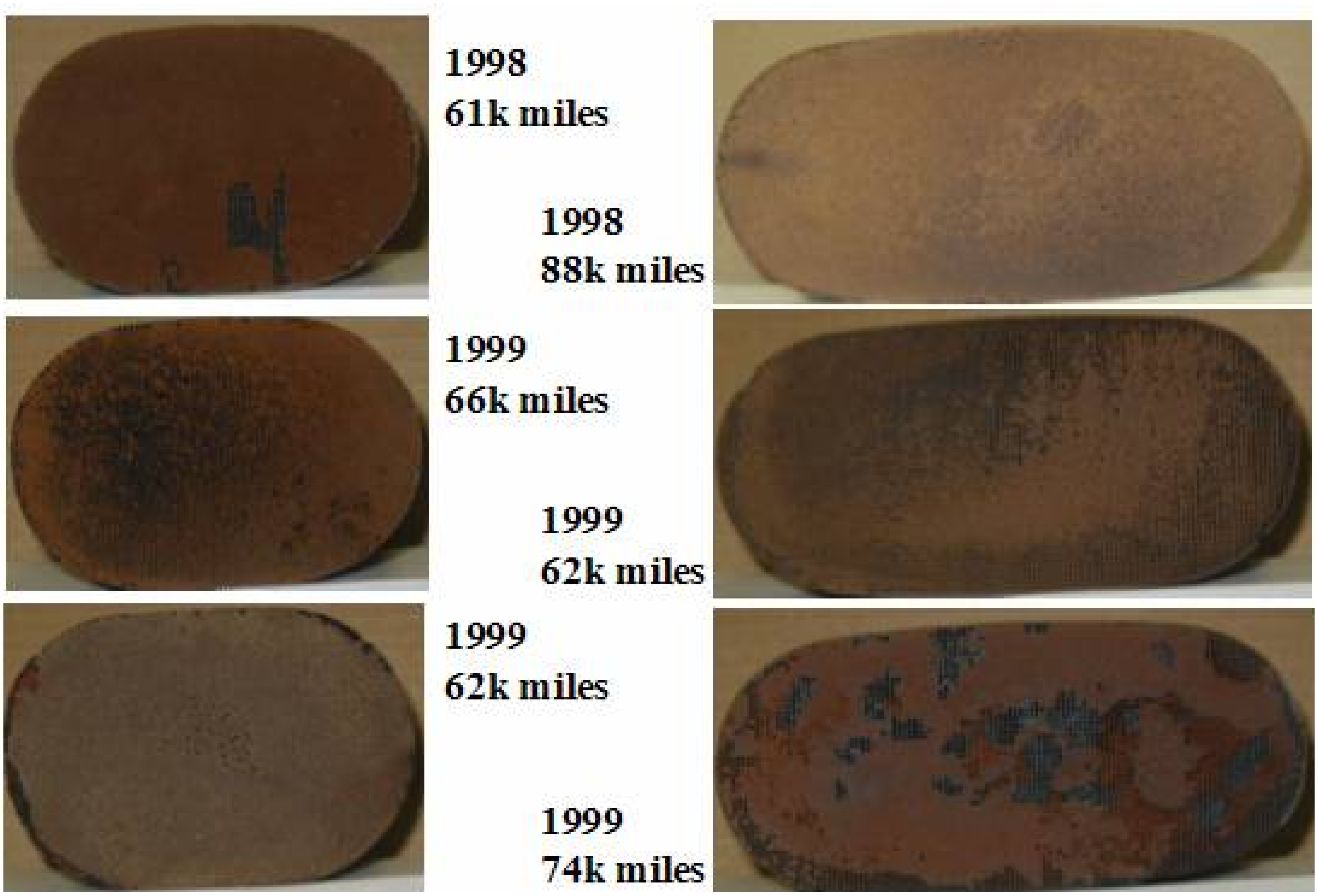
  [NOTE: In general MY2003 vehicles were too new to have had enough exposure to fuel containing MMT to experience MMT problems to the extent that could be detected by customers. Frequent incidents have been reported but MMT exposure was not sufficient to have exhibited systematic problems amenable to analysis, such as observing significant shifts in warranty repair frequencies. Hence, this report does not describe, or attempt to analyze, most of the MY2003 models that were sold. However, since the first of these vehicles was launched very early in calendar year 2002, a significant fraction of this vehicle model had exposure to fuel containing MMT (similar to what a typical MY2002 vehicle would have had).]

  - The first of these two models will be designated as **Model D-1**.
    - This was an early introduction MY2003 passenger car with a V-type engine. It was certified to "interim" Tier 2 bin 7 standards.
    - It used an HDCC on each bank of the engine. 400cpsi catalysts were downstream of each of these HDCC catalysts.
    - The engine was mounted in a North-South (i.e., crank shaft pointing in the vehicle's forward direction) configuration with the exhaust manifolds oriented one to each side, directing the exhaust flow rearward and downward toward the HDCC catalyst.
  - The second of these two models will be designated as **Model D-2.**
    - This was a fall 2002 calendar year introduction (i.e., "typical") MY2003 passenger car with a V-type engine certified to interim Tier 2 bin 8 standards.
    - This model used one HDCC on each bank of the engine. The exhaust flow from these two catalysts then merged into a single downstream 400cpsi conventional catalyst.
    - This engine was mounted transversely (East-West or with the crank shaft pointing perpendicular to the forward direction of the vehicle).

<u>Experience with Catalyst Plugging</u>:

- Catalyst plugging from manganese oxide deposits had been observed for years before the introduction of high density catalysts. Plugged catalysts have been found on a number of models using older technology (400 cpsi) catalysts. Figure 1 provides a few sample catalyst front face pictures from such cases. The plugging resulted in driveability and performance differences which led customers to return to the dealerships for repair.

Figure 1: Examples of isolated plugging cases involving 400cpsi catalysts.



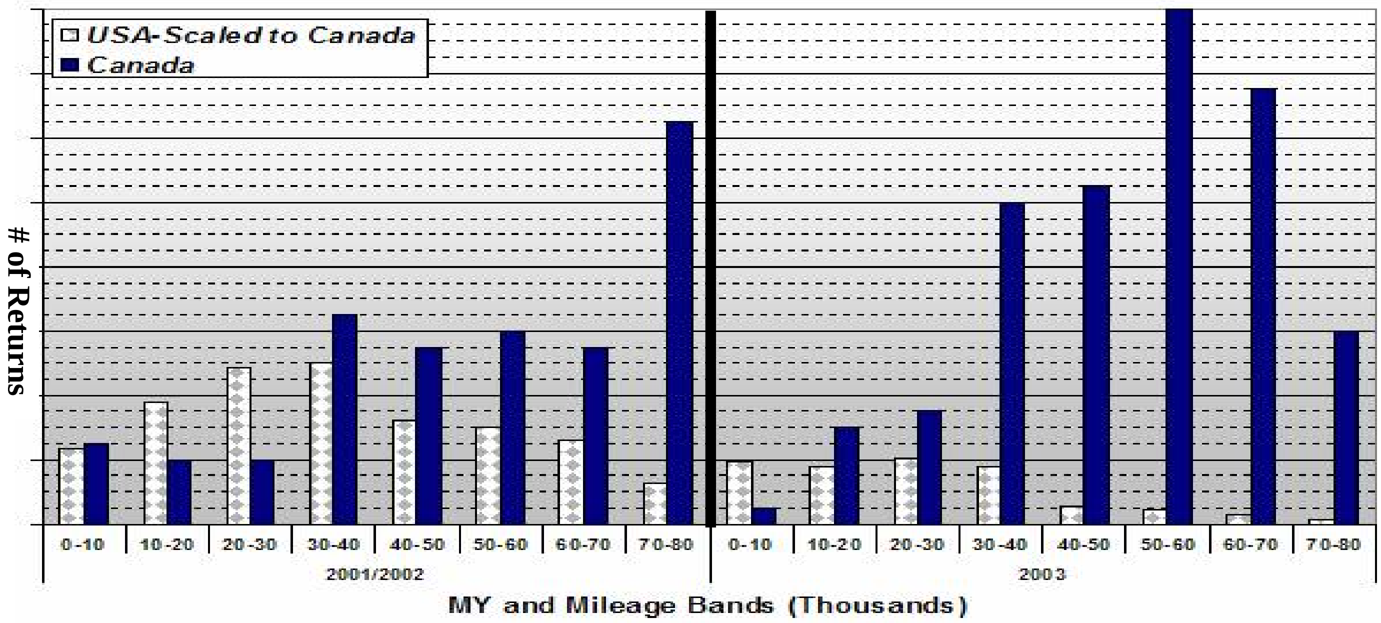
- This experience changed with Model D-1. A significant number of warranty repairs involving catalyst plugging from manganese oxide deposits was observed on Model D-1.
- Sample pictures of a plugged Canadian and clean unblocked US catalyst from model D-1 are shown in Figure 2.

Best Viewed in Color

Figure 2: Inlet catalyst Model D-1 pictures retrieved from the U.S. and Canada.

- An analysis of warranty rates for Model D-1 shows a substantially higher rate in Canada than the USA.
    - The number of catalyst returns (normalized to Canadian sales volumes to account for the fact that US sales far exceeded Canadian sales) was plotted in model year and mileage bands shown in Figure 3.
        - This illustrates that Canadian return frequency was considerably higher than the comparable USA baseline for MY2003. The significant difference shows up in the 30,000 to 40,000 mile range (i.e., the lower plugging threshold range).
        - This analysis also indicates that even for model years 2001/2002 the Canadian return rate was higher. However for these cases the difference became significant at higher mileages (as shown below in the 70,000 to 80,000 mile range).

Figure 3: Model D-1 Catalyst returns for the Canadian and US market



NOTES:

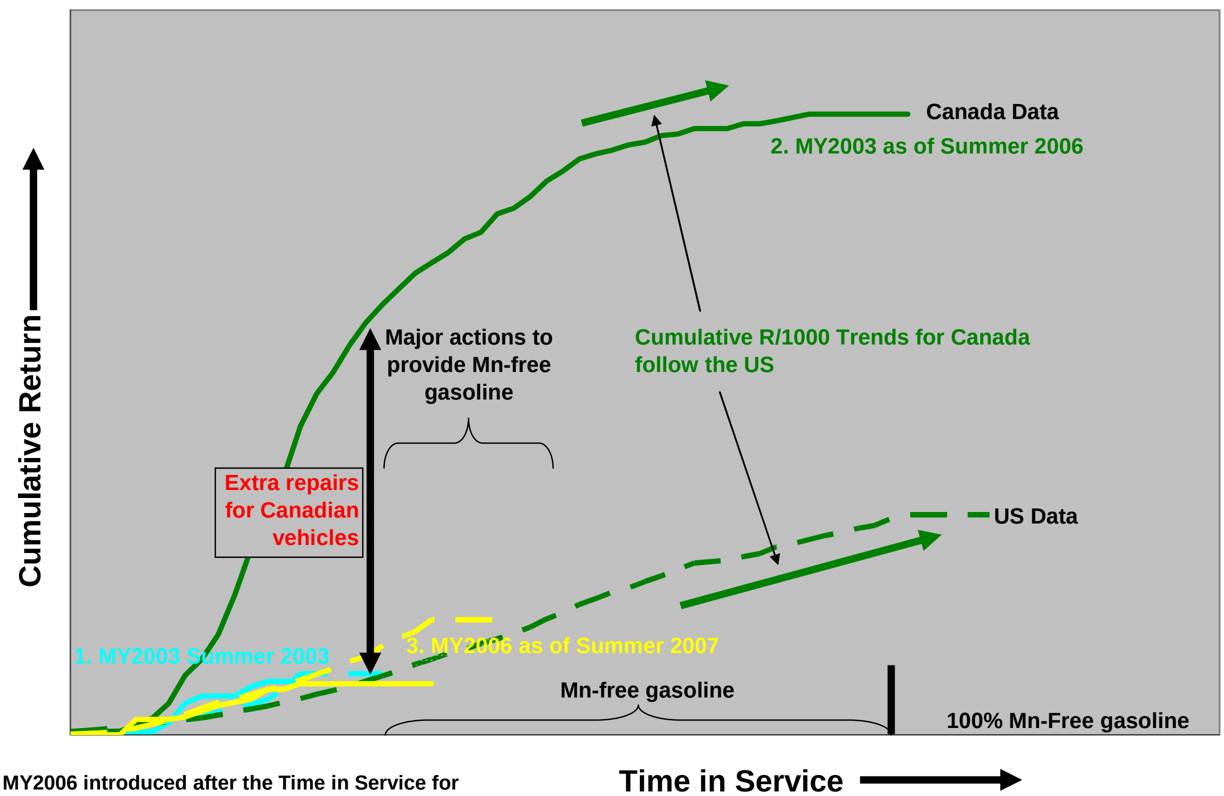
1. The units for the vertical and horizontal scales are not shown on Figure 3 and 4 for confidentiality reasons. However the shape of the curves illustrates the important points.
2. This figure is based on warranty data from the summer of 2004.

-
    - The cumulative returns for catalysts as a function of time in service for MY2003 Model D-1 are shown in Figure 4.
        - The Canadian catalyst repair rate was clearly higher than the rate for the comparable time periods in the USA (where MMT was not used).
        - The repair rate in Canada appeared to rise almost exponentially until the time when refiners stopped adding MMT to the fuel. As MMT disappeared from the fuel, the growth in the cumulative repair rate began to slow.

Best Viewed in Color

- By the summer of 2006 when fuel surveys confirmed that MMT was essentially gone from the Canadian fuel supply, the shape of the Canadian repair rate curve tracked the USA curve in near parallel fashion.

Figure 4: Model Year 2003 Model D-1 Cumulative Return (for all catalyst warranty repairs) vs. Time in Service for Canada and US as of Summer 2003 and 2006 (MY2006 for summer 2007 shown for comparison)



MY2006 introduced after the Time in Service for "Major actions to provide Mn-free gasoline".

NOTES regarding Figure 4:

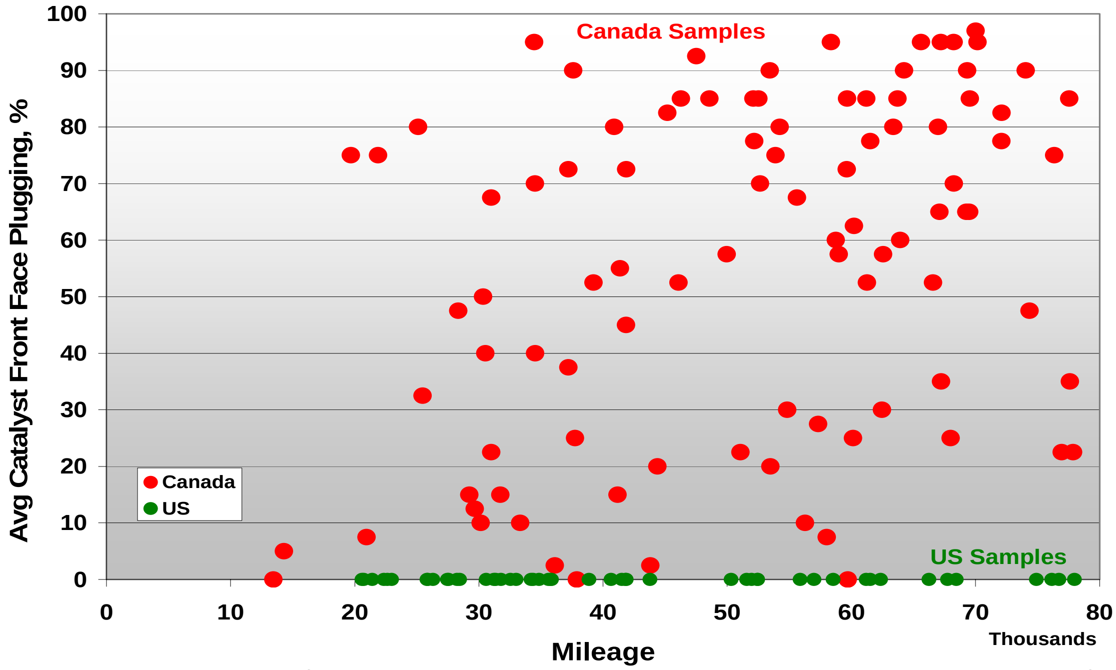
1. The repair rates in Figure 4 involve a computation of numbers of repairs divided by numbers of vehicles that have reached each unit of time in service. This should not be confused with analyses by others who have plotted repair rates as a simple percentage of number of repairs divided by total model year sales. In this analysis, at any given point on the time in service scale, only the number of vehicles for MY2003 model D-1 that had passed through that time in service point at the time when the analysis was conducted are included in the ratio (or Cumulative R/1000) computed for that point.
2. The analysis taken during summer of 2003 ("1. MY2003 Summer 2003") does not show a substantial difference between the Canadian and US lines due mainly for the following two reasons: 1. few vehicles would have reached the time in service at the time of Summer 2003 analysis (some of the MY2003 vehicles were not completely sold) and 2. for those vehicles that would have reached that time in service, an even smaller fraction would have accumulated enough miles during that period to have had enough exposure to MMT to have had a chance to experience plugging.
3. The curve for the summer of 2006 ("2. MY2003 Summer 2006") shows the most dramatic difference between Canada and the USA. While MMT remained in the fuel during much of the

time leading up to summer of 2004 and then not present by the summer of 2006, the biggest reductions in MMT content had already occurred throughout most of the country during the first half of 2004, especially in the high population areas. The fraction of the Canadian MY2003 Model D-1 fleet that had reached or exceeded the time in service indicated by the beginning of the braces '{' on the graph would have done so during the period when the highest amounts of MMT remained in the fuel. Hence, one would expect to see the highest rates of return for MMT associated repairs to have occurred at this point (the slope of the curve is steep). This was in fact what happened, and what the analysis shows. Then coinciding with the availability of Mn-free gasoline the slope appears to have declined to follow similar trends as found in the US.

4. Since, major actions by the oil industry to stop using manganese in gasoline prevented enough time exposure to have a measurable return effect on other, later, models. The MY2006 Model D-1 was overlaid onto the plot for comparison since it was the first model year for D-1 where the predominant mileage accumulated occurred with Mn-free gasoline. Thus data shows for a similar time in service as was found for MY2003 that the warranty trends for MY2006 follows a similar pattern between Canada and the US.

- Inspection of warranty-return catalysts confirms the hypothesis that the differential Canadian warranty repair rate is largely due to catalyst blockage resulting from manganese oxide deposits. For each inspected catalyst, percent plugging is plotted versus mileage accumulated in Figure 5. [NOTE: Percent plugging was determined by visual inspection using a conservative method that computed the percentage as the total number of fully plugged cells divided by the total number of available cells. These data exclude catastrophic damage due to mechanical or physical issues, which account for a minor and limited number of returns.]

Figure 5: Percent plugging vs. mileage for warranty returns from Canadian Model D-1 vehicles and US Model D-1.

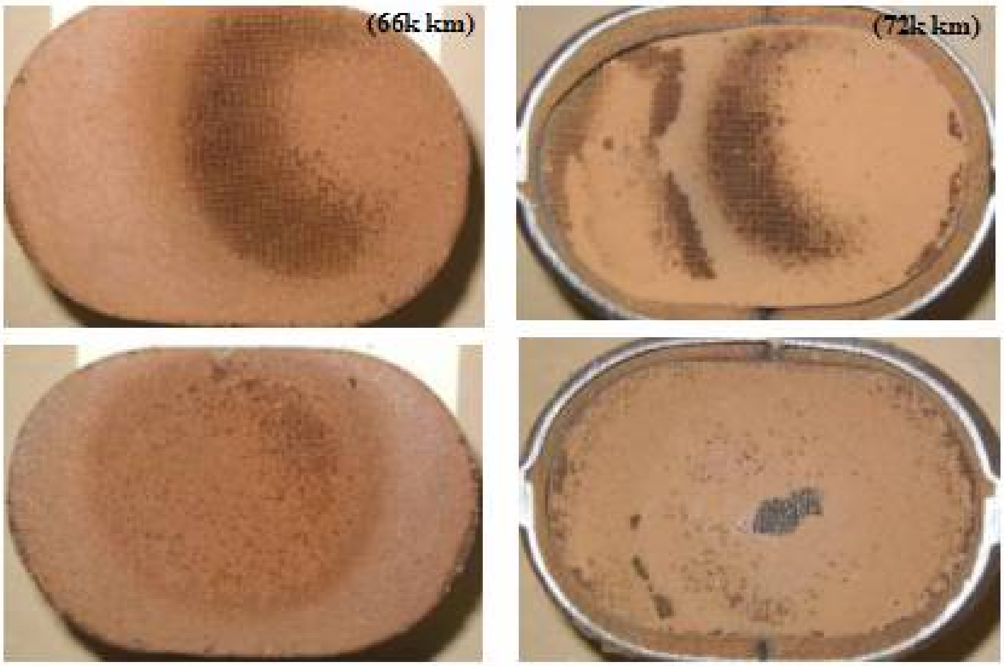


   o The plot of % plugging vs. mileage includes all catalysts inspected as of the date of the analysis (approximately summer 2004) regardless of the reason for their replacement. This includes some catalysts replaced for

reasons other than plugging (there are other reasons for catalyst replacement) that still showed minor manganese oxide contamination.
  - The frequency of highly plugged catalysts appears to increase considerably in the 30,000 to 40,000 mile range for the Canadian samples, while as expected the US samples do not show signs of blockage.

- Additional pictures of plugged catalysts typical of the plugging level that triggered customer complaints are included in Figure 6.

Figure 6: Additional pictures of plugged HDCC catalysts from Canadian Model D-1 vehicles.



Future Technology Plans:

- Manufacturer D has used, and expects to continue to use, HDCC catalysts for compliance with Tier 2 standards for all gasoline fueled light-duty vehicles and trucks sold in Canada. Systems using a second, downstream, catalyst will likely continue to use 400 cpsi catalysts in that position.
- Manufacturer D has concluded that no other technologies would be as effective as use of HDCC catalysts to meet the lower Bins (Bin2 to Bin5) of Tier 2 emissions standards across all its vehicle lines.
- The need to meet lower emission standards drives the need to move catalysts closer to the engine resulting in increased catalyst inlet and front-face temperatures.

Emission Testing and Mechanism Analysis:

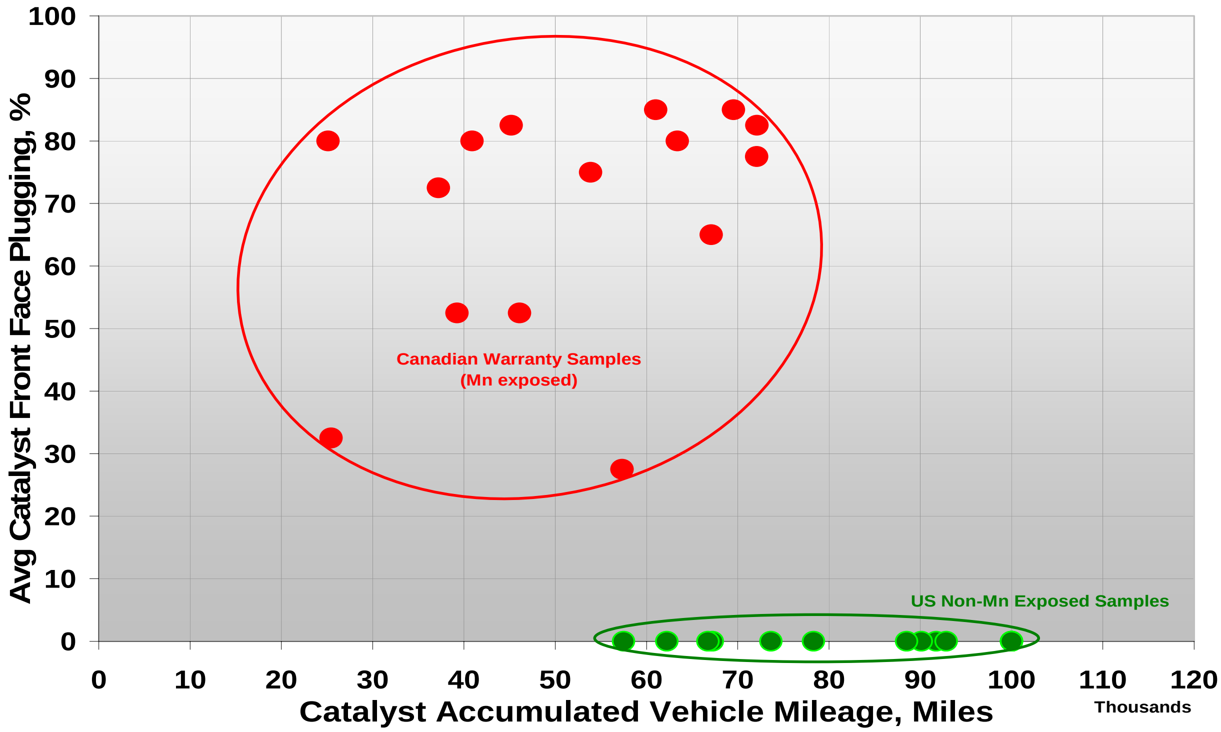
1. Emission Testing

- Model D-1 vehicle emission system testing using high cell density 2003MY Canadian catalysts returned under warranty was completed on surrogate Model D-1 vehicles. Catalyst systems were inspected for physical damage and evaluated as-received from the Canadian Warranty Parts Evaluation Center using the FTP and US06 testing protocols. Comparisons for Canadian (Mn exposed systems) to US (Non-Mn exposed systems) were completed. US catalysts were obtained from US customer fleets (i.e., these were not artificially aged catalysts).
  - Model D-1 was chosen as the candidate vehicle for further examination regarding the effects of manganese contamination on catalytic emission systems due to its early introduction, first detection of catalyst blockage and warranty return differences between the US and Canada.
  - Model D-1 vehicles were acquired to represent the two markets. The vehicle from the Canadian market is assumed to have been exposed to manganese (referred to as the Canadian Reference). This vehicle was acquired after the study started, having approximately 115K miles, while the vehicle that initiated the study (due to vehicle availability) was one acquired from the US market assumed to have no manganese exposure having approximately 100K miles (referred to as the US Reference Vehicle). Thus, some Canadian catalysts were tested only on the US reference vehicle due to test scheduling and vehicle availability.
    - Each reference Model D-1 vehicle was received and tested as is without modifications or changes other than the catalyst system.
      [NOTE: The as received FTP emission test results for the US reference vehicle were 0.0370 g/mile NMHC, 0.4510 g/mile CO, and 0.0280 g/mile NOx. The Canadian reference vehicle was tested with the basic vehicle in the as received condition but with a new complete catalyst system installed. FTP emissions were 0.0473 g/mile NMHC, 0.6600 g/mile CO, and 0.0167 NOx and US06 emissions were 0.02232 g/mile NHMC, 2.7017 g/mile CO, and 0.0550 g/mile NOx.]
    - Although the Canadian Reference vehicle was driven in the Canadian market, mileage accumulation occurred under uncontrolled customer driving and refueling was not controlled, therefore there is fundamentally no-way to assess total manganese-containing gasoline exposure for the contaminated vehicle or components. The basic assumption is that a Canadian vehicle had the opportunity to see much more manganese relative to a vehicle registered and driven in the US market.
  - In earlier manufacturer reports, individual components were identified as critical to assessing the complete tailpipe emission impact, thus the need to test catalysts on complete vehicles representing its respective market. Therefore, care was taken to reinstall the original as-received vehicle sensors on each of the additional catalyst systems as the pieces were tested.

Best Viewed in Color

- Summary observations are as follows:
  - Visual observations of Canadian systems used in this study showed front face blockage ranging from approximately 25% to 85% with no other visible signs of damage. US baseline systems showed no blockage (0%). See Figure 7.

Figure 7
Average Catalyst Front Face Plugging as a function of accumulated miles for samples emission tested on FTP and US06.



- When comparing average tailpipe emissions measured for US catalysts (no Mn exposure) to the average of the Canadian catalysts (Mn exposed) retrieved from warranty, (see Figure 8) Canadian catalyst system criteria pollutant results across the FTP indicated an average tailpipe increase of 103% in NMHC, 97% in CO and a 17% increase in NOx. Those catalysts which were tested on both the US and Canadian Reference vehicles, and are referred to as "Paired" appear with an asterisk (*) in its label. [NOTE: Data points on figures 8 and 9 represent the average of replicate tests. Multiple tests (typically three) were performed on each catalyst sample. All testing was performed using Indolene.]
- In US06 testing, a 1142% increase in NMHC, a 210% for CO and a 393% increase in NOx were observed. Figures 8 and 9 provide FTP and US06 data, respectively.
- The order of magnitude increase in emissions for NOx on the US06 compared to FTP could be an indication of the greater space velocity differences encountered during US06 testing. The lack of performance from the blocked cell channels (caused by manganese deposits) stresses the catalytic conversion performance of the open channels.
- Furthermore, the increases in tailpipe emissions occurred for the Canadian catalysts even though they accumulated an average of approximately 30,000 fewer miles compared to the US systems which had accumulated in excess of 90,000 miles.
- It must be emphasized that this study does NOT characterize average Canadian fleet emissions, only the emissions associated with a set of catalysts that were replaced under the warranty program.

Best Viewed in Color

Figure 8: FTP Tailpipe Emissions for US and Canadian Catalysts tested on US and Canadian Reference Vehicles as a function of front face plugging.

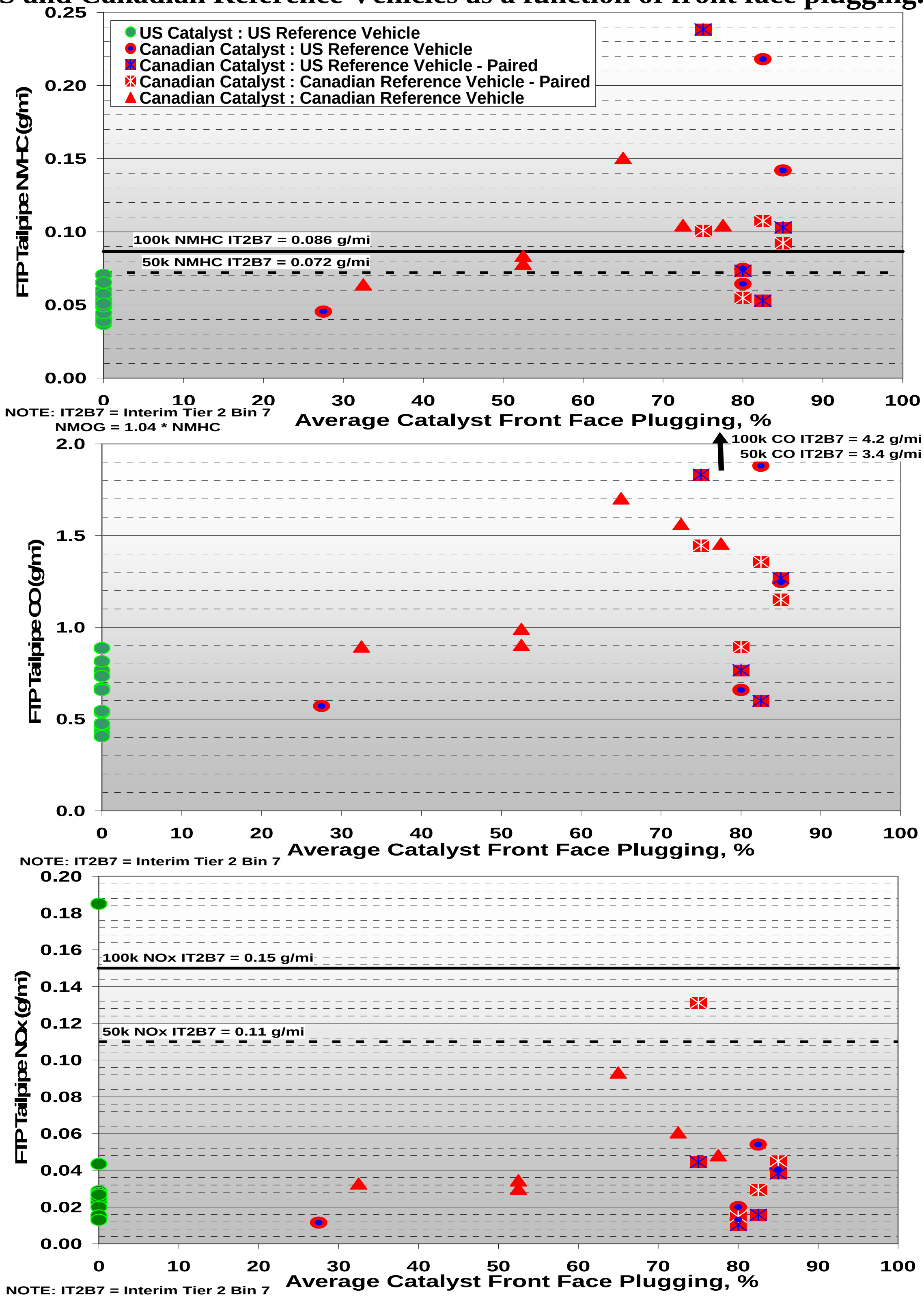
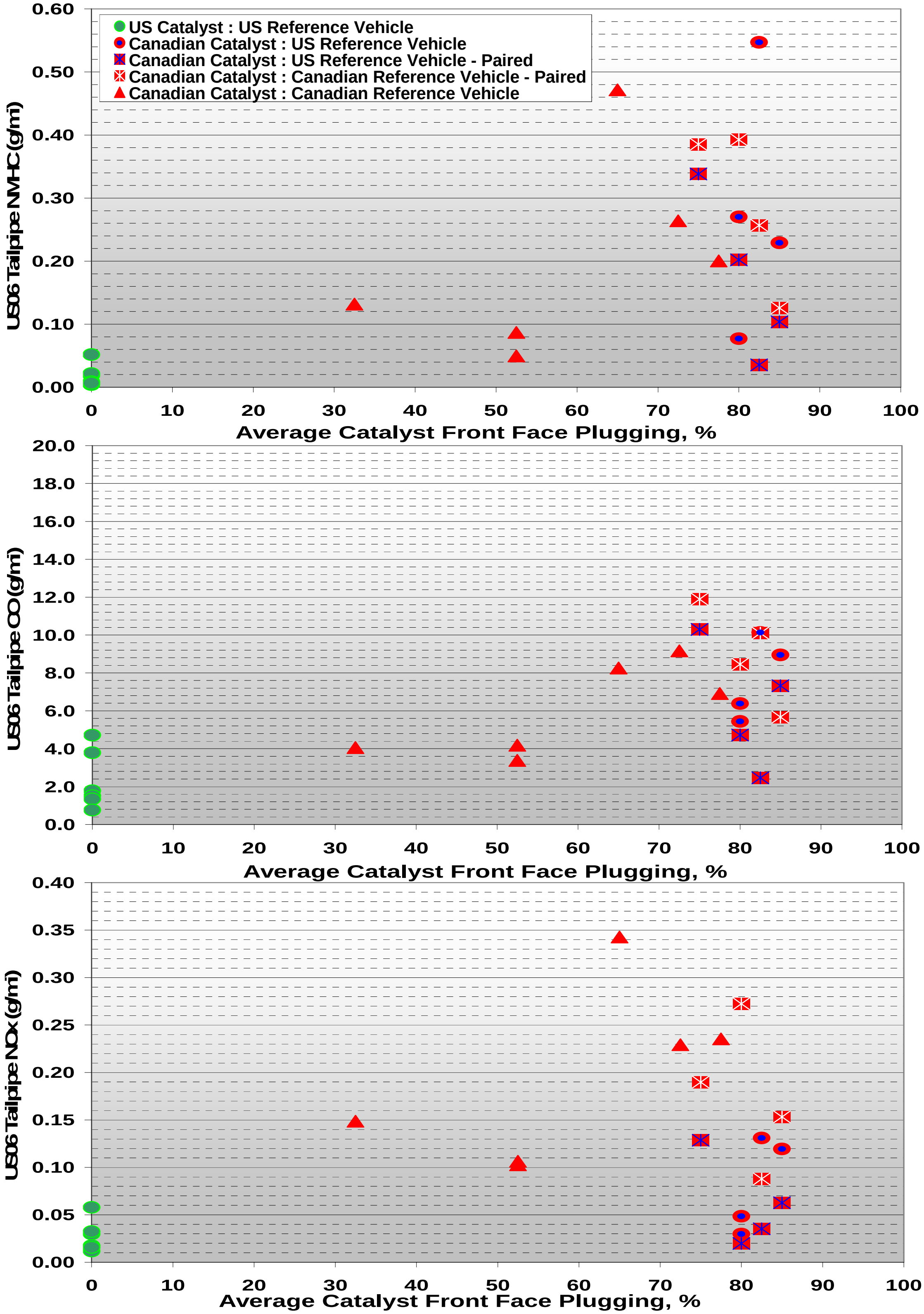


Figure 9: US06 Tailpipe Emissions for US and Canadian Catalysts tested on US and Canadian Reference Vehicles as a function of front face plugging.



2. Catalyst Microscopy and Characterization

- Manufacturer D conducted microscopy and microprobe analysis (pictures) showing plugging deposit particle structure and X-Ray Florescence and X-Ray Diffraction analysis of deposits. Figures 10 and 11 show the results of this analysis. It was concluded that:
    - Mn-containing deposits are not chemically bound to the catalyst surface.
    - Deposits were mainly Mn_3O_4 with 10% to 15% oil-derived compounds present.
    - There was no evidence of excessive oil consumption.
    - Deposit analysis resulted in less than 0.1wt% carbon content.
    - There was no evidence of abnormal thermal deterioration.
    - There was no evidence of unusual thermal conditions (i.e., no conditions that could have caused melt-down or other damage to the substrate).

Figure 10
Catalyst characterizations performed on Model D-1 Canadian sample.

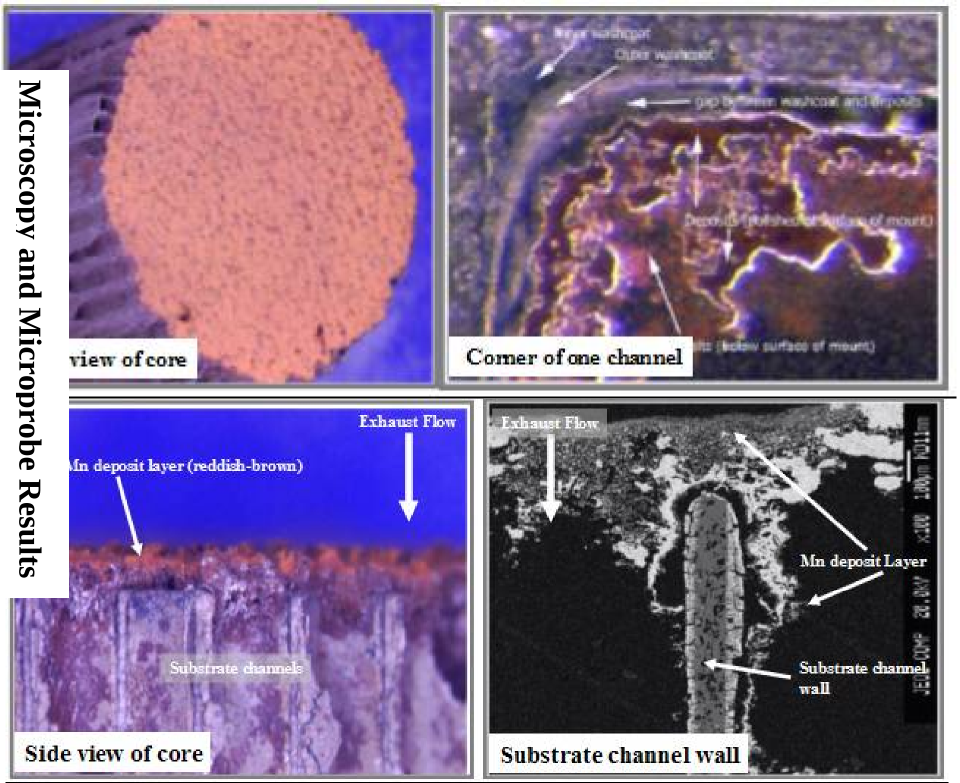
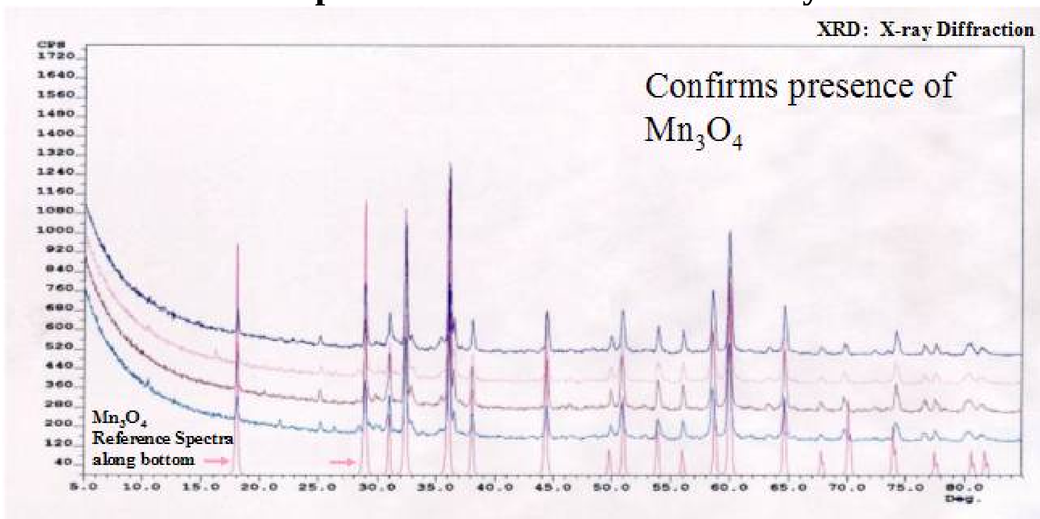


Figure 11: X-Ray Florescence and X-Ray Diffraction analysis of deposits On Sample Model D-1 Canadian Catalysts



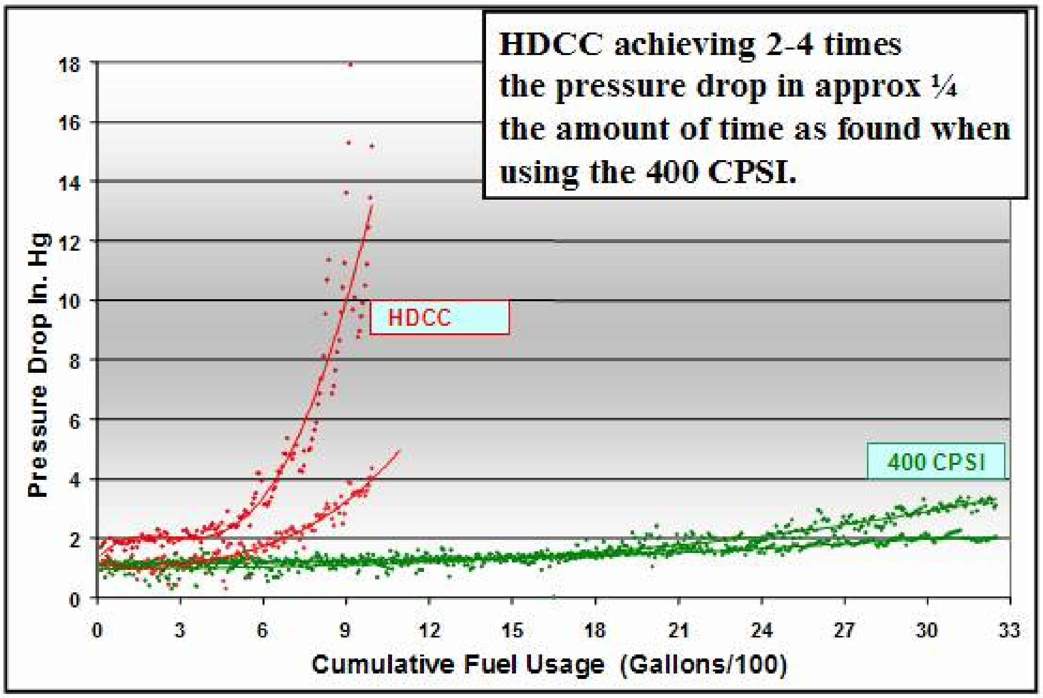
XRD (scraped deposit)	XRF (wt%) Scraped Deposit Mn	P	Ca	Zn	S	Core (1")	Mn	P	Zn	S	BET (Core) (m^2/g cat)	OSC (Core) (µmol O /g Cat) (500°C)
Mn_3O_4	61	3.8	1.88	0.96	0.005	In	5.66	0.36	0.12	0.002	18.4	121
						Out	0.49	0.03	0.01	0.006	28.3	
Mn_3O_4	59	4.8	3.38	1.84	0.034	In	3.99	0.3	0.15	0.008	20.3	
						Out	0.54	0.04	0.01	0.069	26.9	
Mn_3O_4	60	3.9	1.77	1.21	0.000	In	9.33	0.64	0.26	0.003	12.3	107
						Out	1.49	0.08	0.04	0.014	20.1	
Mn_3O_4	64	4.1	2.16	1.65	0.000	In	6.46	0.44	0.19	0.013	15.3	
						Out	1.37	0.07	0.02	0.052	18.8	
Mn_3O_4	58	3.4	1.80	1.00	0.005	In	5.15	0.4	0.17	0.043	11.6	92
						Out	1.23	0.06	0.04	0.028	17.3	
Mn_3O_4	57	3.3	1.82	1.03	0.009	Out	4.24	0.33	0.15	0.045	10.7	
						Out	1.09	0.06	0.03	0.040	17.1	

3. Engine-Dynamometer Testing

- An engine dynamometer testing program was conducted to determine if HDCC catalyst plugging caused by MMT could be reproduced. The testing was to also determine if plugging would occur at a faster rate for HDCC than for 400cpsi catalysts. Results of this testing are shown in Figure 12.
  - The engine used was the same as those used in Model D-1.
  - Testing was performed using fuel with the Canadian maximum allowed MMT concentration (18 mg/L).

- Dynamometer operation continued until catalyst substrate backpressure increased significantly.
- The program compared a HDCC catalyst system versus a 400cpsi system.
- Pressure drop data is plotted as a function of cumulative fuel usage.
- For the conditions tested and catalyst inlet temperature ranging from about 780C to 850C, the HDCC catalyst achieved 2 to 4 times the pressure drop in approximately one fourth of the time of the 400 cpsi catalyst. See Figure 12.
- Figure 13 shows details of the faces of the tested catalysts.
- Figure 14 shows spark plug and exhaust oxygen sensor Mn Oxide accumulation.

Figure 12: Engine-dynamometer testing using the engine and exhaust system from model D-1.



NOTES:

1. The two lines plotted for each of the HDCC and 400 cpsi catalysts are for the two separate front catalysts on each bank of the V engine.
2. The 400cpsi catalyst showed deposit accumulation at the end of engine-dynamometer test, equivalent to approximately 20-30% front-face blockage. Since the 400cpsi testing was 4 times as long as the HDCC, considering limited resources, testing was not continued for the 400cpsi until a similar level of backpressure developed as was found on the HDCC.

Figure 13: Engine-dynamometer testing – HDCC time progression catalyst photos from Model D-1.

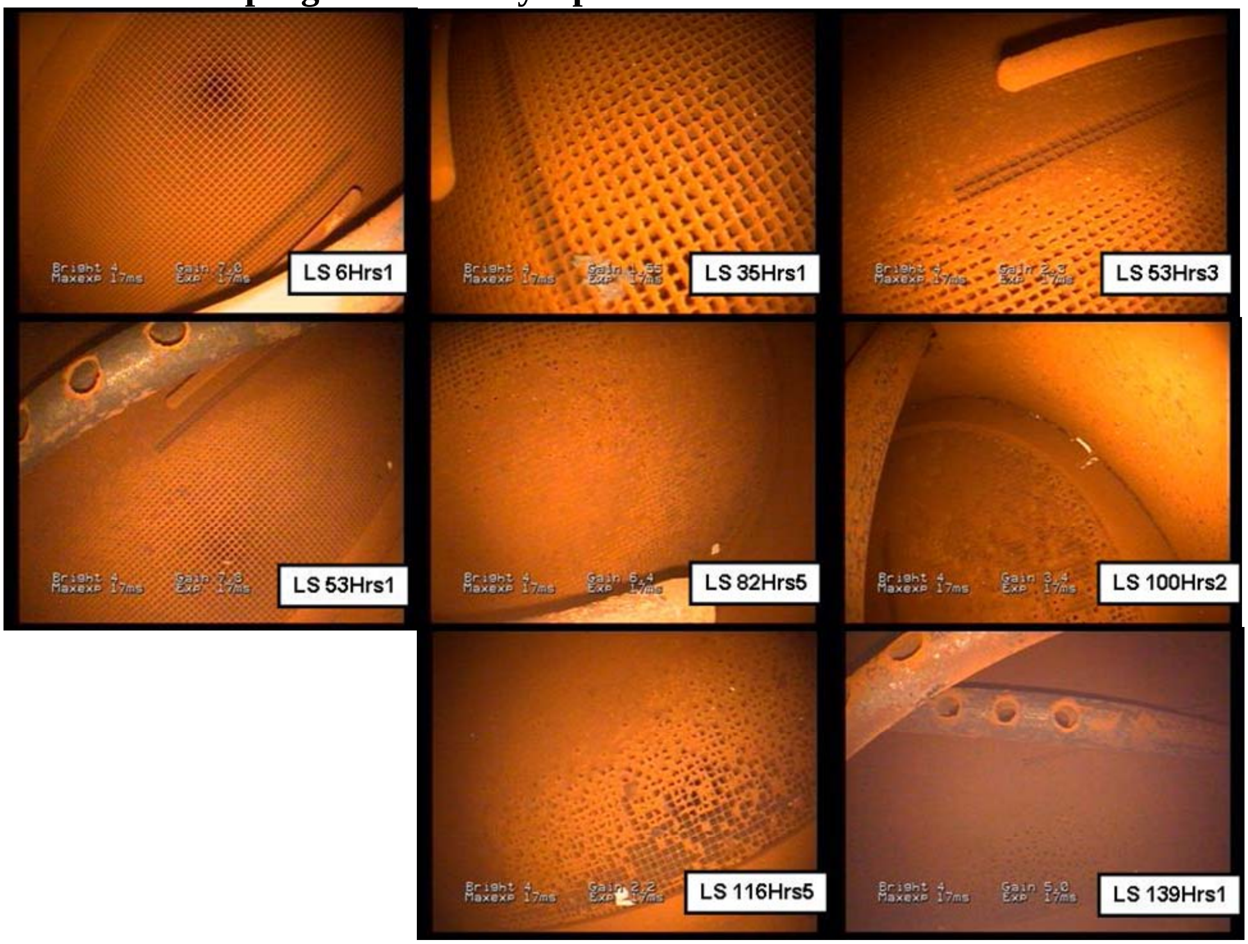


Figure 14: Engine-dynamometer testing – Component Pictures from Model D-1.

Spark Plug tip

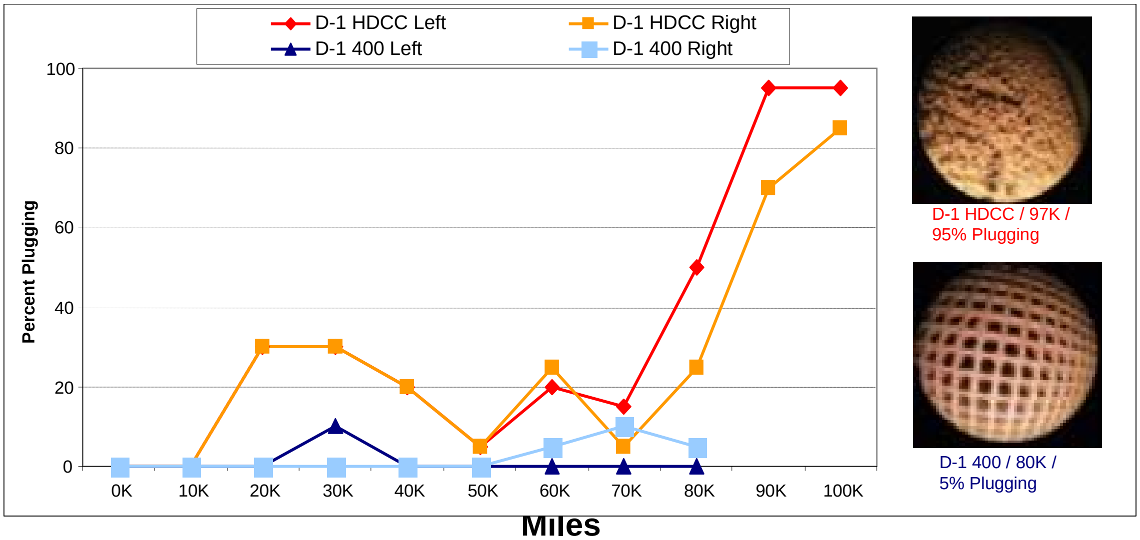
Oxygen Sensor Exposed (metal sheath removed)

4. Vehicle Mileage Accumulation Testing

- Manufacturer D examined plugging in relation to mileage for two pairs of vehicles that accumulated mileage using an EPA approved "whole vehicle durability" protocol. Results are plotted as % plugging vs. mileage in Figures 15 and 17. Figure 16 shows details of the front catalyst faces for Model D1. Figure 18 shows similar details for Model D2 catalysts.

    - Tests were run using fuel with MMT at the 18mg/L concentration.
    - Vehicles were operated until the substrates exhibited plugging sufficient to result in substantial drivability issues.
    - Testing was performed on MY 2003 Model D-1 (i.e., the one with the in-use plugging experience) and MY 2003 Model D-2.
    - For each vehicle type, one production vehicle was run using production HDCC and a second production vehicle with 400cpsi catalysts as had been used in earlier calibrations, prior to the change to HDCC.
    - Model D-1 remained under 40% plugged through 70,000 miles, but then plugging quickly increased to ~80% by 90,000 miles for the HDCC catalyst. The 400 cpsi catalyst did not exceed 10% plugging over the same mileage.
    - Model D-2 demonstrated plugging at a faster rate than Model D-1. One side of the HDCC catalyst system reached 80% plugged in 40,000 miles while the other side required nearly 70,000 miles to reach the same degree of plugging. The 400 cpsi catalyst system demonstrated almost no plugging for one bank but up to about 30% plugging for the other bank after 80,000 miles.
    - The testing also showed that one bank of Model D-2 appeared to be more susceptible to plugging than either catalyst bank for model D-1.
    - In Canada, Model D-2 did not exhibit significant warranty repair cases while MMT was in the fuel whereas significant returns were observed with Model D-1. Considering that Model D-1 was introduced earlier than Model D-2 and considering the rate of mileage accumulation while exposed to fuel containing MMT, this was not unexpected. It was not possible to confirm the relative plugging sensitivities of these two models in actual field experience since the Canadian oil industry voluntarily stopped using MMT before Model D-2 could accumulate sufficient mileage to experience a plugging problem. However this testing indicates that had MMT remained in the fuel, Model D-2 would have likely experience more frequent plugging cases than Model D-1, and at lower mileages. See Figure 17.

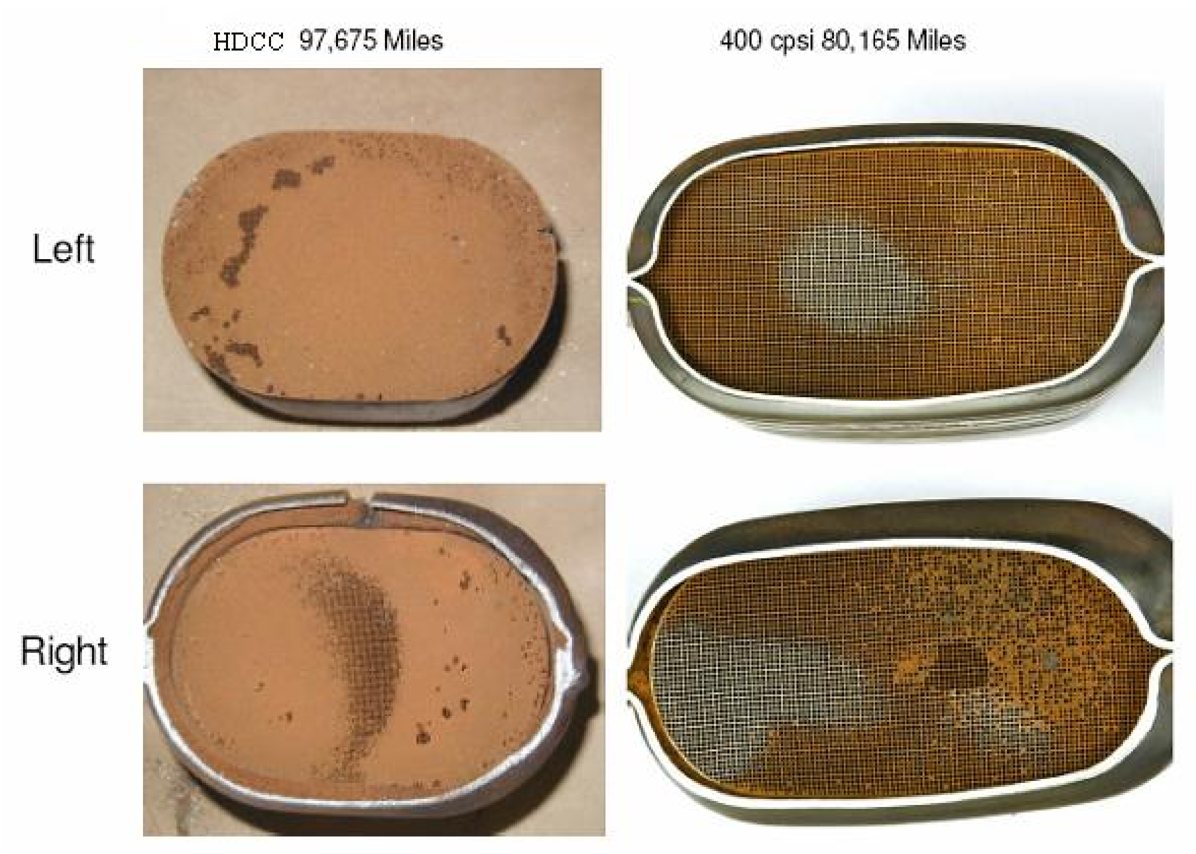
Figure 15: % Plugging vs. Vehicle Miles Accumulated with Model D-1.



NOTES:

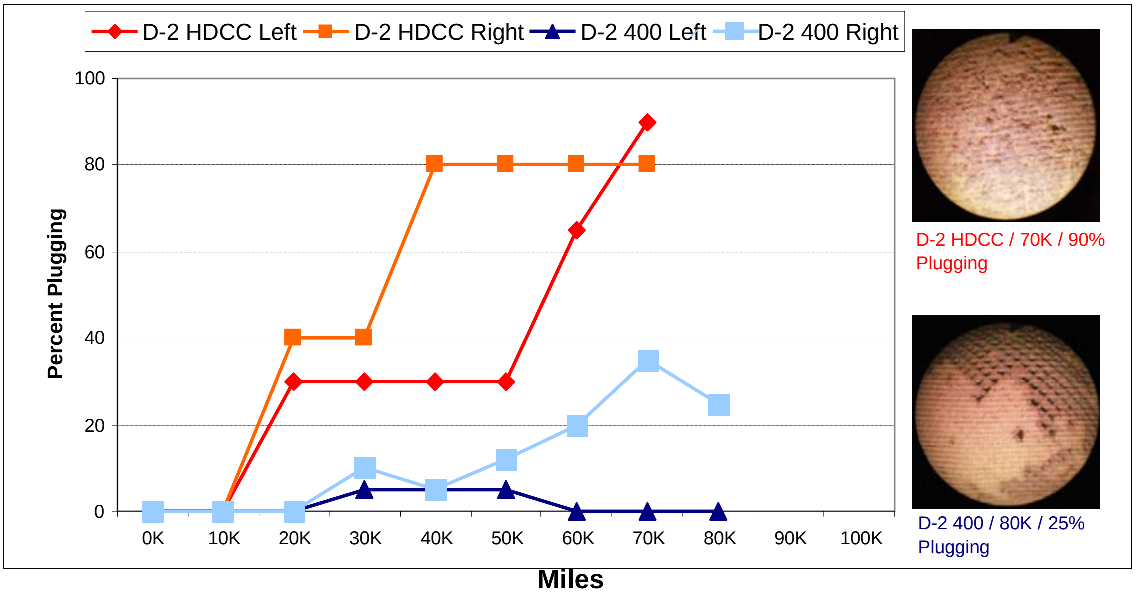
1. The two upper curves are for the two HDCC catalysts used on each side of the V engine and the two lower curves are for the two 400 cpsi catalysts used on each side.
2. Percent plugging was determined by visual inspection using a conservative method that computed the percentage as the total number of fully plugged cells divided by the total number of available cells.

Figure 16: End of test Model D-1 front face light-off catalyst photo, HDCC vs. 400cpsi.



Best Viewed in Color

Figure 17: % Plugging vs. Vehicle Miles Accumulated with Model D-2



NOTES:
1. The two upper curves are for the two HDCC catalysts used on each side of the V engine and the two lower curves are for the two 400 cpsi catalysts used on each side.
2. Percent plugging was determined by visual inspection using a conservative method that computed the percentage as the total number of fully plugged cells divided by the total number of available cells.

Figure 18: End of test Model D-2 front face light-off catalyst photo, HDCC vs. 400cpsi.

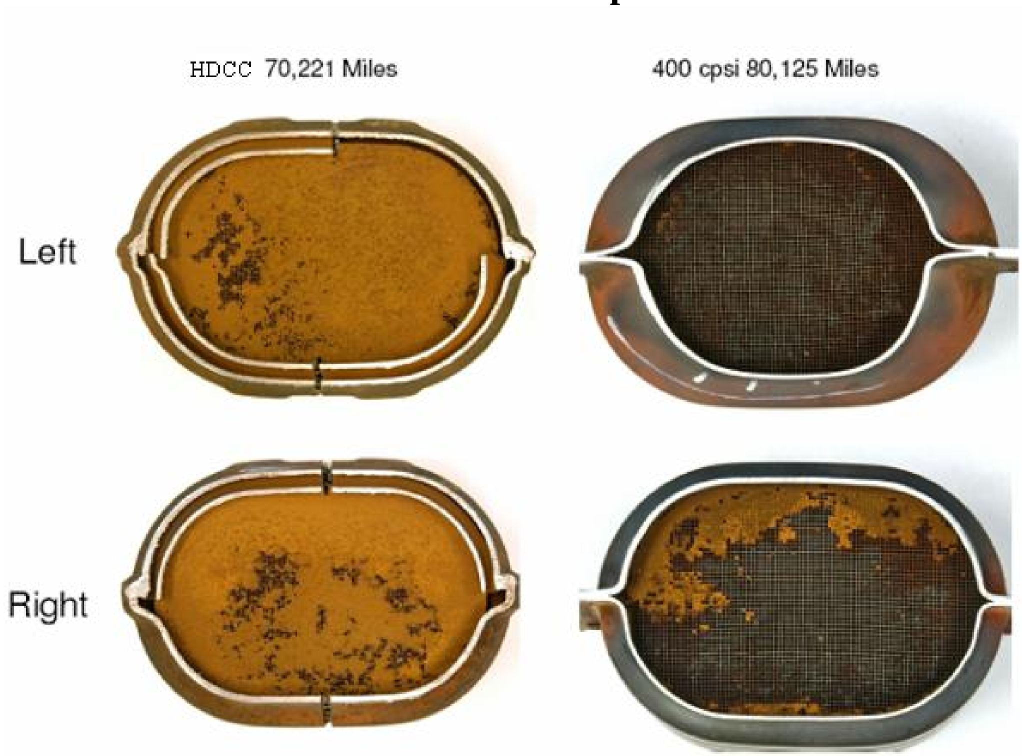
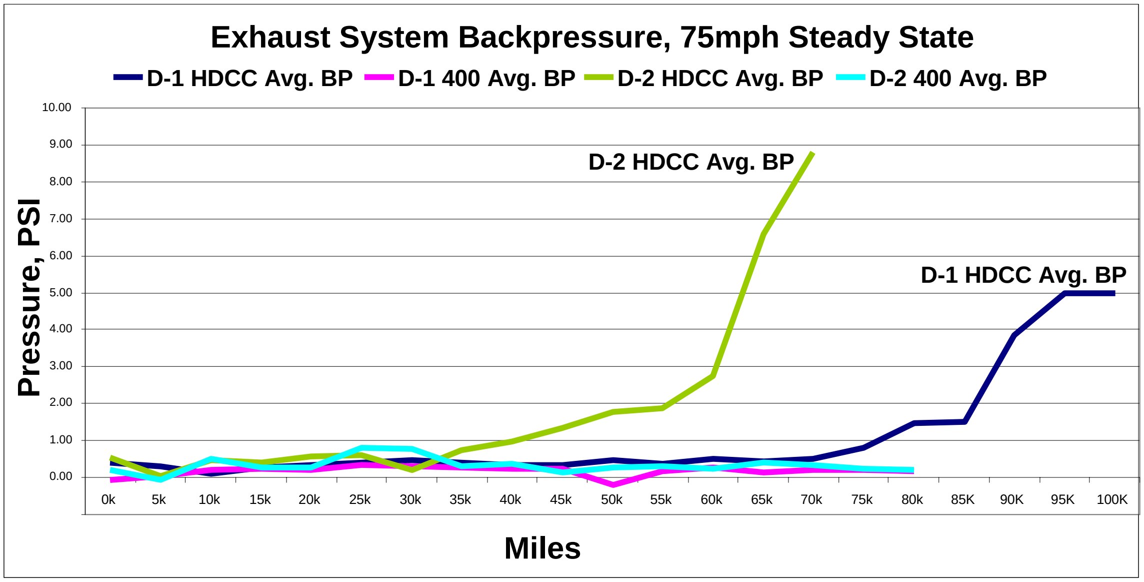


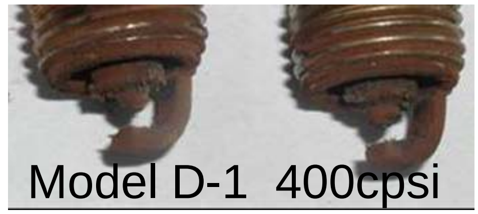
Figure 19: Backpressure versus mileage for Model D-1 and D-2.



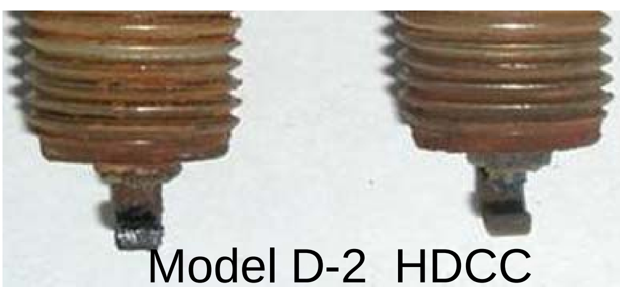
- Increased backpressure leads to poor vehicle performance which typically brings customers in for repairs. The vehicle mileage accumulation confirmed the build up of deposits (increasing exhaust system backpressure) on the high cell density substrates relative to the 400cpsi substrates, see Figure 19.
- Manufacturer D suggests that the differences in plugging rates can be explained by the combination of a shorter hydraulic diameter, or smaller individual cell openings (translating into a "shorter bridge" for deposits to grow across to completely block the channel opening), as well as the greater number of initiation sites (i.e. larger number of wall intersections on the HDCC cats) contribute to increased blockage.
- Manufacturer D illustrates, in Figure 20, how the combusted by-products of manganese-containing gasoline accumulate on the oxygen sensors (both ahead of and behind the light-off catalyst) and spark plugs (two are shown here). 8 of the 24 oxygen sensors failed to achieve minimum specifications and vehicles experienced incidences of fouled spark plugs.

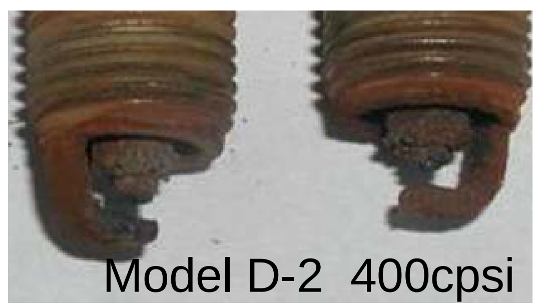
Figure 20

Oxygen Sensors and Spark Plug sample photos from mileage accumulation program for Model D-1.



Oxygen Sensors and Spark Plug sample photos from mileage accumulation program for D-2.

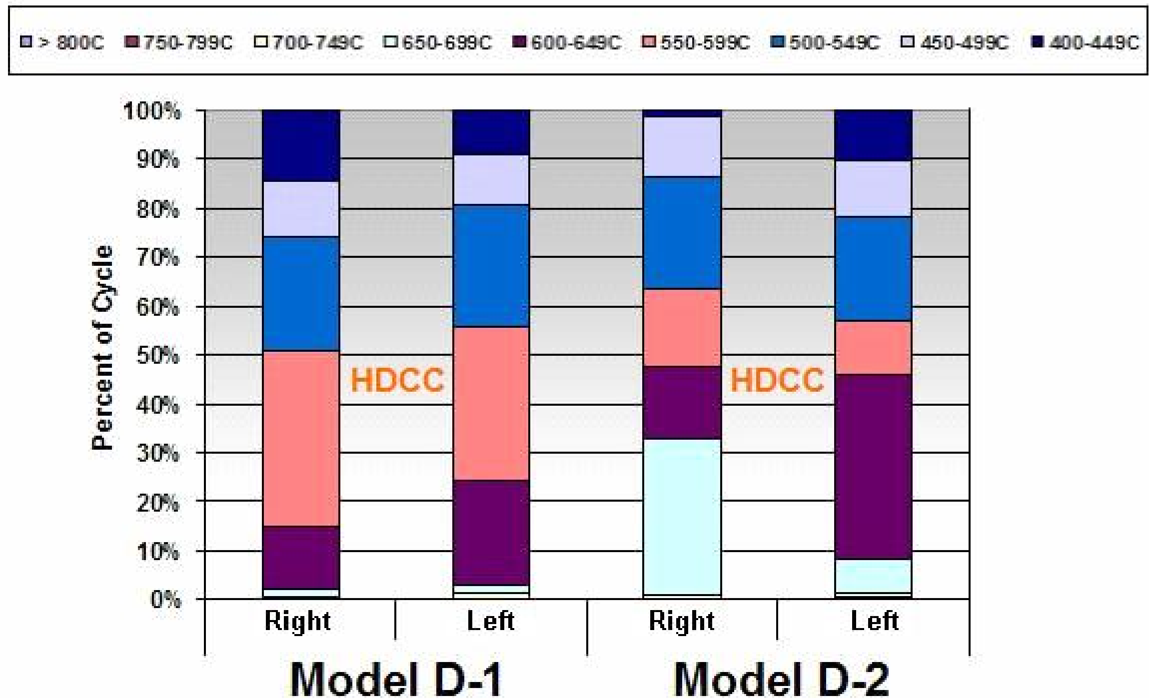




Best Viewed in Color

- Figure 21 illustrates catalyst inlet temperature distribution data for both Model D-1 and D-2 collected during a controlled vehicle testing program using an EPA-approved whole vehicle durability protocol.

Figure 21: Distribution of catalyst inlet temperatures during vehicle mileage accumulation for Model D-1 and D-2



- Model D-2 shows a greater frequency than Model D-1 of operation at temperatures above 650 °C. In previous figures, plugging observations indicate that Model D-2 exhibited plugging at a faster rate than model D-1 using comparable vehicle durability testing.
- The same catalyst bank (right side) for Model D-2 experiencing the higher operating temperatures was the side that displayed a faster rate of plugging during the controlled vehicle testing.
- Temperature (as shown in previous studies) is one of several key factors involved in increasing the propensity for the accumulation of manganese containing deposits on the catalyst front-face. There is little control or no capability to control these factors due to the constraints imposed by the increasing stringency of the regulations and space limitations within the products.

Manufacturer "D" Conclusions

- Manufacturer D firmly believes that both the Canadian field experience and laboratory testing clearly shows that gasoline containing MMT harms engine components, vehicle performance, and emission control equipment resulting in adverse impacts to tailpipe emissions. These impacts result in major customer dissatisfaction due to general performance issues and costly repairs.

- Catalyst analysis identified compounds containing manganese in the deposits formed on the front-face. Manganese oxides were the only deposits of significant magnitude found in failed catalysts. Other identified compounds were present only in typical quantities.

- The only source of manganese (and, hence, manganese oxides) is from the fuel.

- Experience proves that if vehicles with HDCC catalyst systems are sufficiently exposed to an exhaust stream laden with manganese oxides, catalytic converters will accumulate deposits. These deposits can build, and lead to catalyst plugging and the associated vehicle and component problems.

- HDCC vehicles sampled in the US do not encounter plugging issues as found in Canada even when observing high mileages. Canadian samples whether HDCC or conventional showed plugging issues with the former appearing at lower mileages with greater frequency.

- Canadian refiners used MMT over a long period of time. The concentrations used varied by refiner, according to the individual refiners' immediate octane needs, throughout months of production. While the average concentration a customer's vehicle was exposed to over those same months varied, it was nevertheless sufficient to damage catalytic converters and cause customer complaints.

- FTP and US06 Tailpipe emissions were shown to increase with catalyst exposure to manganese; aggressive vehicle driving, as found in US06, showed nearly an order of magnitude increase in emissions on a grams per mile basis.

- Laboratory tests demonstrated that other vehicles, with emissions controls systems similar to those of vehicles damaged in the field, are also susceptible to the same damage.

- Since Canadian refiners stopped using MMT, field problems due to manganese oxide damage and plugging have ceased. This occurred despite the rapid proliferation of HDCC emission control systems across the wide range of vehicles in the Canadian marketplace. Today, the Canadian market parallels the return behavior found in the US market.

Best Viewed in Color

Manufacturer I

Use and Experience with High Density Close Coupled (HDCC) Catalyst Systems in the Canadian Market with Exposure to MMT®

Manufacturer I Information

High Density Close Coupled (HDCC) Catalysts Used Prior to MY2004:

- Manufacturer I sold a MY 2002 vehicle model with a I4 engine that used a 600 cpsi close coupled catalyst followed by a 400 cpsi under floor catalyst.
- Engine/Vehicle Details:
  - ~ 2 liters
  - Twin cam
  - Multi-Port Fuel Injection
  - Vehicle weight - approximately 2,600 lbs.
  - Diagrams of the exhaust system and catalysts are in shown in Figure 1.
- Front Catalyst Details:
  - Close coupled catalyst was located 25 cm from the manifold flange.
  - The inlet pipe had a sharp bend but also had about a 10 to 15 cm straight pipe section leading into the catalyst.
  - The distance between the end of the exhaust flange and the closest engine exhaust port was approximately 10 to 12 inches.
  - The catalyst diameter was 12 cm at the front face and the inlet diameter was 6.5 cm.
  - The catalyst had a single bed and a volume of 0.8 liters.
  - Maximum design temperature for the front catalyst was 930^{o}C.
  - The catalyst construction was ceramic with 0.11 mm wall thickness.
- This engine was certified to the LEV standards within U.S EPA NLEV program.

Best Viewed in Color

Figure 1

Exhaust/Catalyst Diagrams

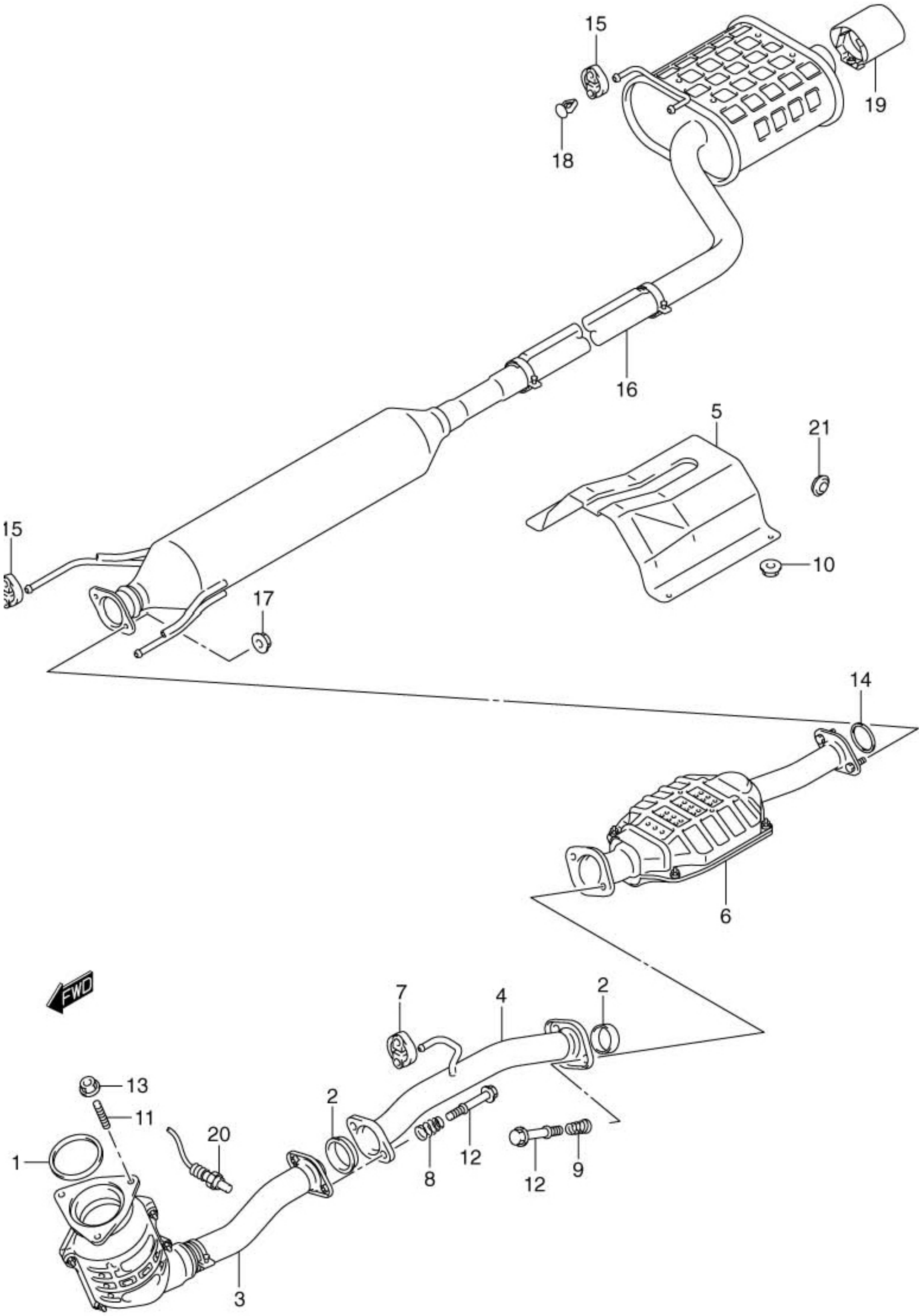
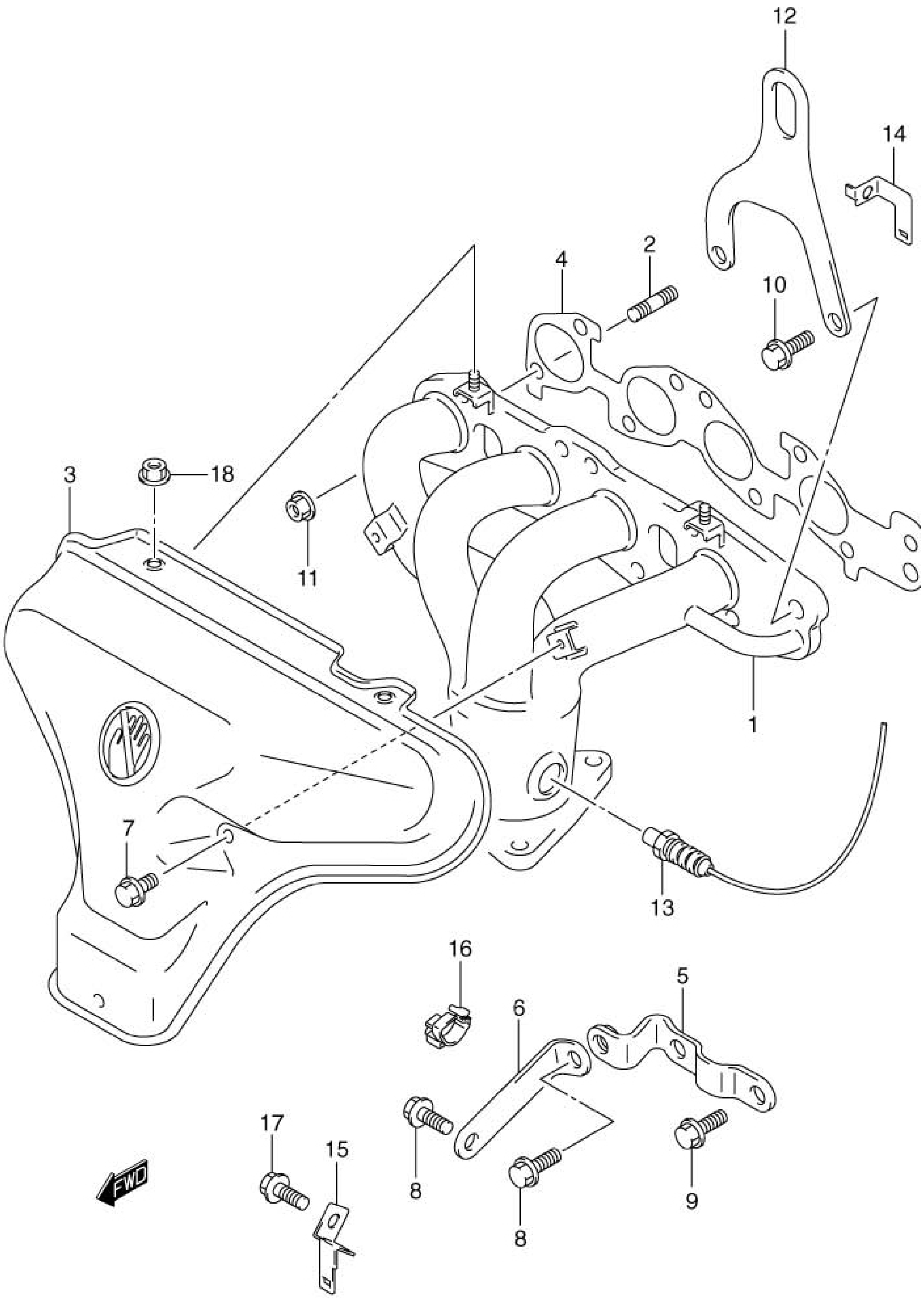


Figure 1 continued


12
14
4
2
10
3
18
11
1
7
13
16
5
6
17
15
8
8
9
FWD

Experience with Catalyst Plugging:

- This was a relatively low sales volume product in Canada. Given it was a 2002 model year vehicle, very few of them would have been expected to have accumulated significant mileage before MMT was removed from most Canadian fuel.
- Manufacturer I collected five consumer catalysts for inspection. These were catalysts returned after warranty repairs not related to MMT. Figure 2 provides pictures of the 5 catalyst faces (because of the number of pictures involved, this figure is attached at the end of this report. Mileages accumulated (in Canada) ranged from 30k to 143k kilometers.
    - All had the characteristic orange color associated with manganese oxide.
    - One exhibited significant plugging, although it had not yet triggered a drivability consumer complaint.
        - This catalyst was from a vehicle that had accumulated about 140,000 km.
        - It was estimated to be about 30 to 40% plugged primarily around the periphery.
        - The deposits looked like the characteristic color associated with manganese oxide.

Future Technology Plans:

- Manufacturer I has used and expects to continue for the foreseeable future to use HDCC systems for compliance with Tier 2 Bin 5 (and more stringent) emission standards.

Emission Testing and Mechanism Analysis:

- No emission testing or analysis of the composition of deposits was performed

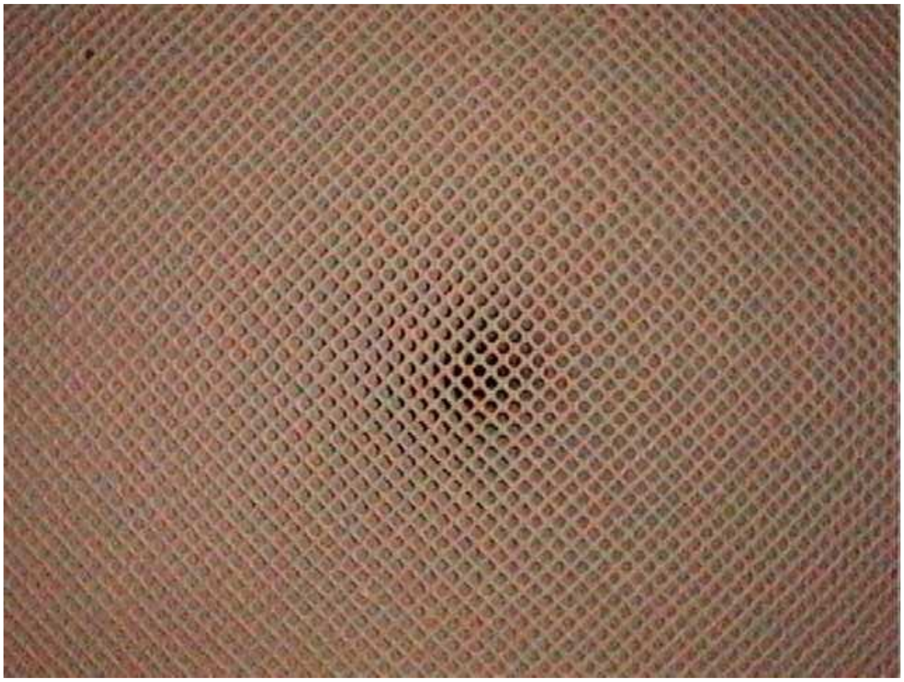
Summary Statement by Manufacturer I

Our only vehicle model using an HDCC system that was introduced into the Canadian market that had the opportunity to accumulate appreciable mileage during the period when MMT remained in the Canadian fuel supplies indicated the beginning of a manganese oxide plugging problem. With this early NLEV-LEV design that was not capable of meeting Tier 2 Bin 5 standards showing the preliminary signs of catalyst plugging, we are quite concerned that our newer fully compliant Tier 2 Bin 5 technology could experience more severe plugging problems if MMT was put back into fuel supplies. Design changes necessary to achieve compliance with Tier 2 and SFTP standards tend to result in higher catalyst operating temperatures. Additionally adding this technology to larger vehicles (SUVs and light trucks) that operate under higher load conditions can result in more vehicles driving under conditions that could result in catalyst operating temperatures above the critical range that others have reported. This could further aggravate manganese oxide plugging. Although we did not observe warranty repairs known to have been associated with catalyst plugging with our MY 2002 HDCC vehicle, we are concerned that even these vehicles might have developed more serious problems over time if MMT had remained in the fuel.

Best Viewed in Color

Figure 2
Pictures of Inspected Catalysts by Manufacturer I

Catalyst #1 @ 32224 km



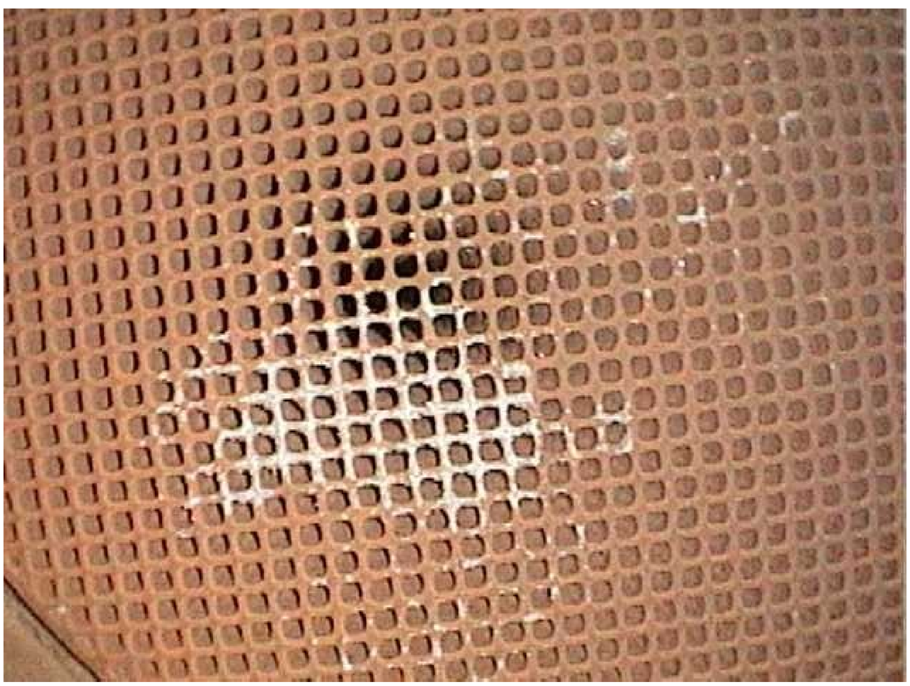
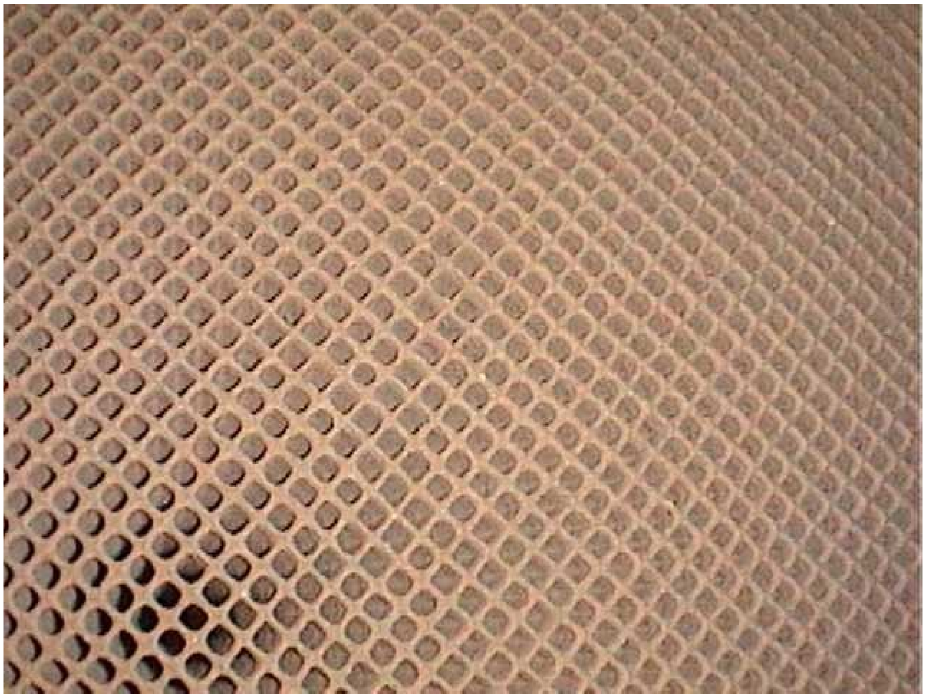
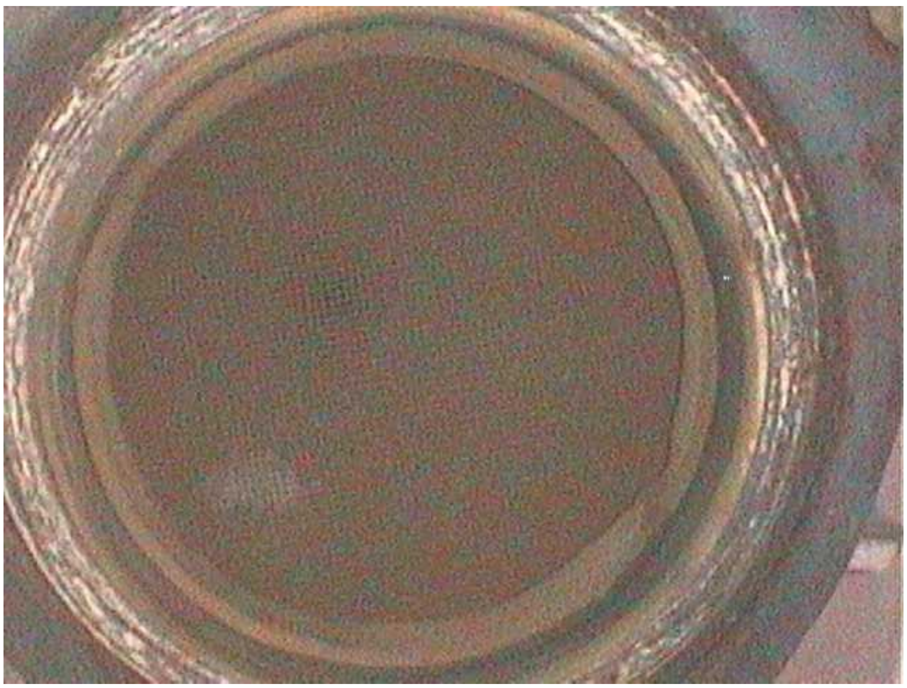


Figure 2 (continued)
Pictures of Inspected Catalysts by Manufacturer I

Catalyst #2 @ 33,460 km

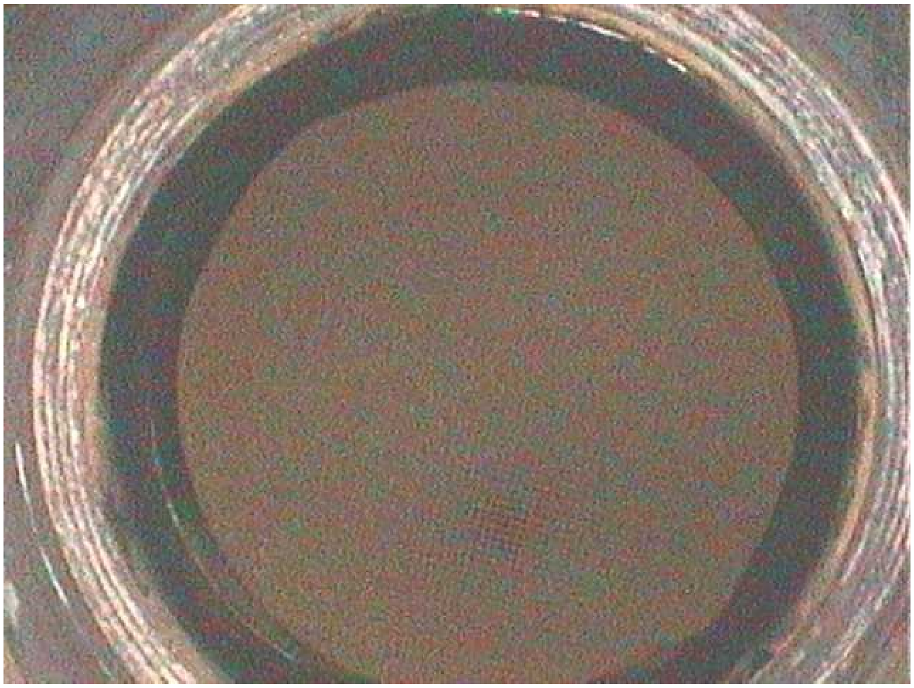




Best Viewed in Color

Figure 2 (continued)
Pictures of Inspected Catalysts by Manufacturer I

Catalyst #3 @ 43,662 km



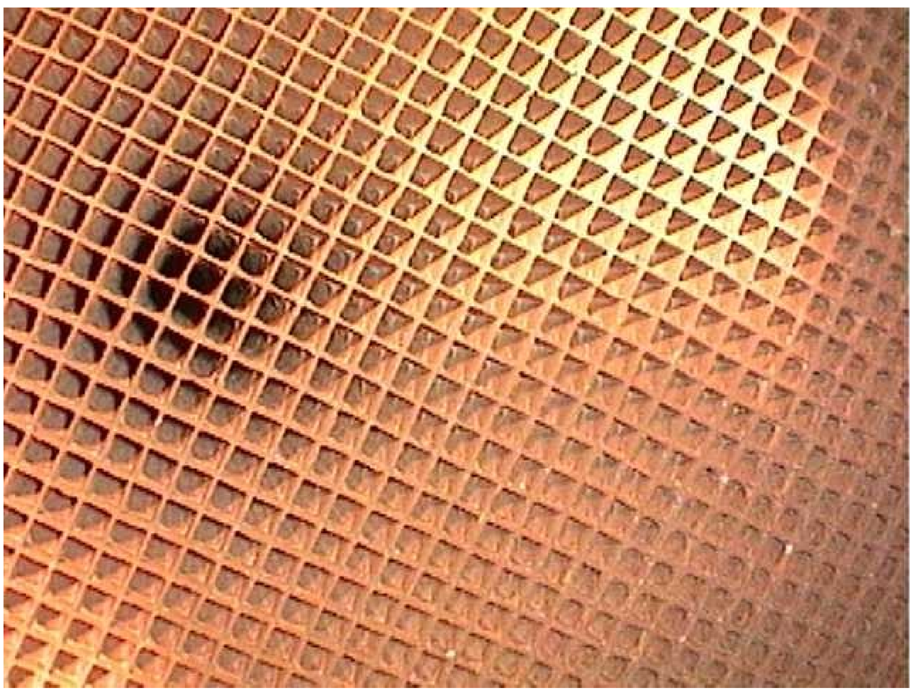
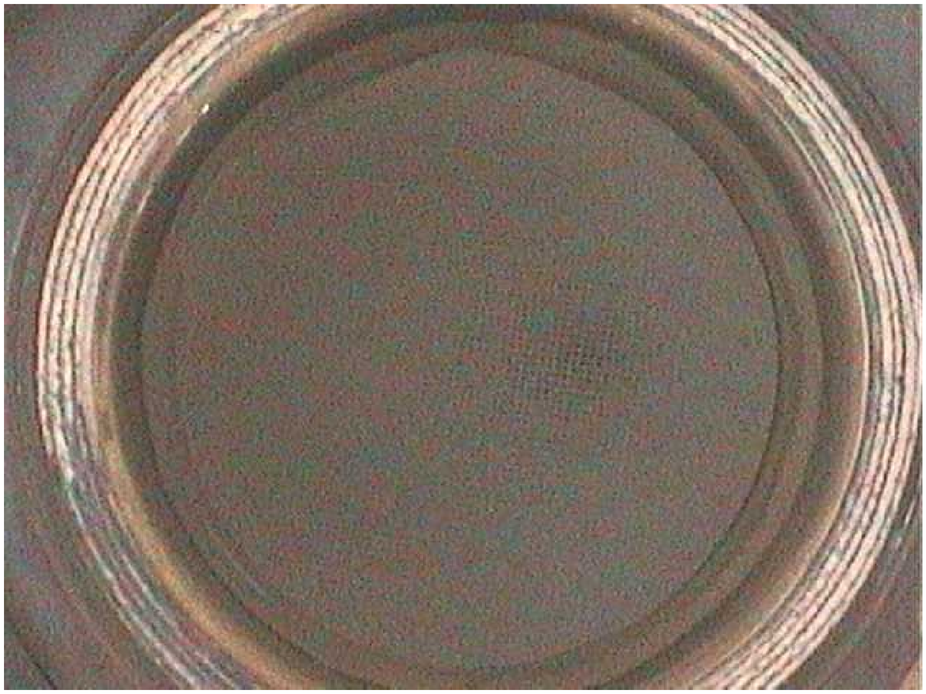
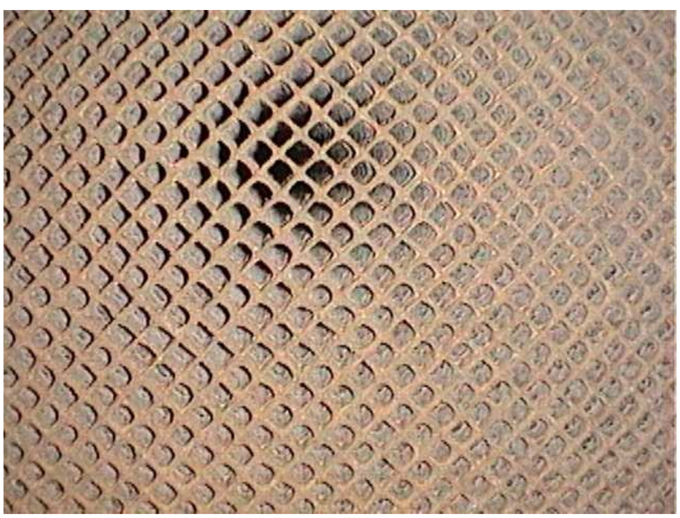


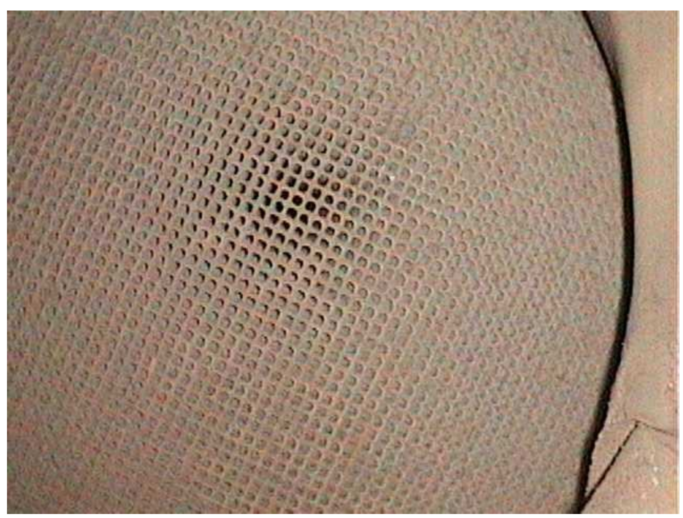
Figure 2 (continued)

Pictures of Inspected Catalysts by Manufacturer I

Catalyst #4 @ 102.576 km



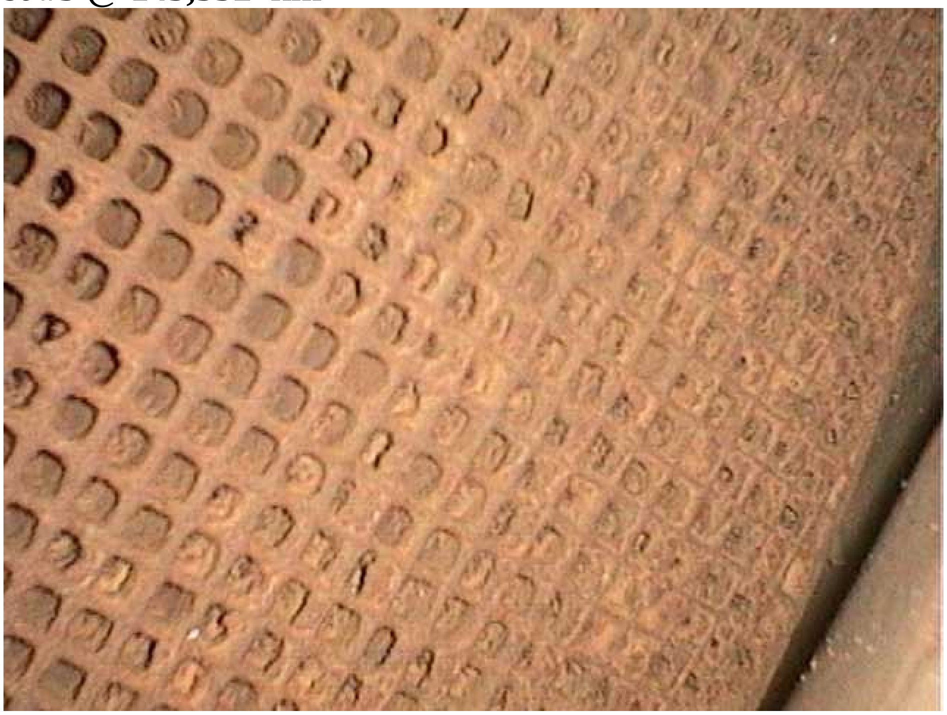


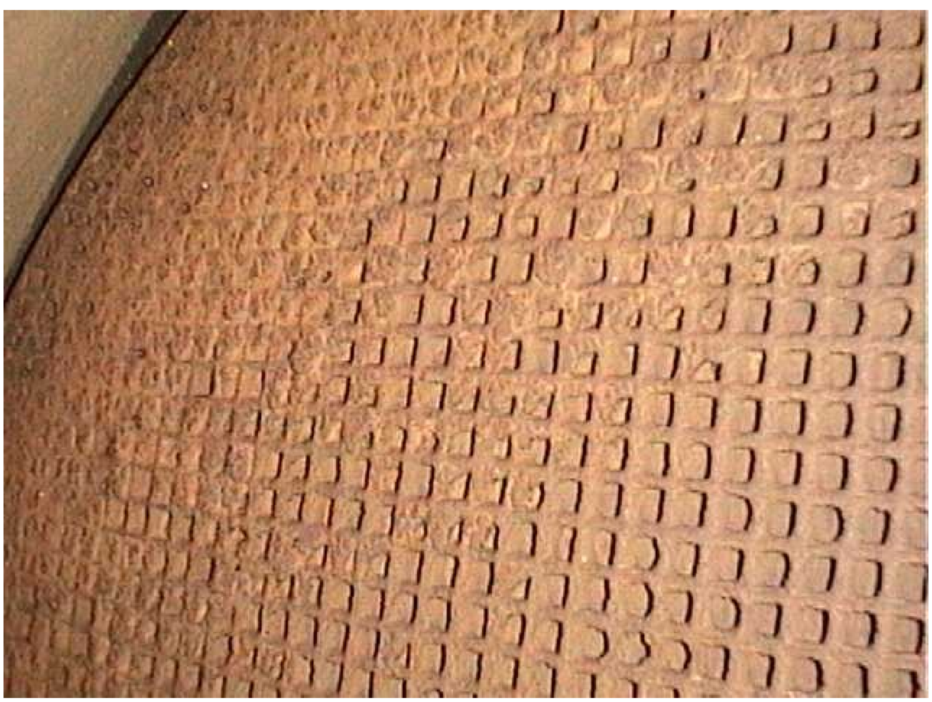


Best Viewed in Color

Figure 2 (continued)
Pictures of Inspected Catalysts by Manufacturer I

Catalyst #5 @ 143,332 km





Best Viewed in Color

Manufacturer J

Use and Experience with High Density Close Coupled (HDCC) Catalyst Systems in the Canadian Market with Exposure to MMT®

Best Viewed in Color

Manufacturer "J" Information

High Density Close Coupled (HDCC) Catalysts Used in Canada Prior to MY2004:

The following HDCC applications were sold prior to MY2004:

1. MY 2002 (and later) "midsize" (SUV) with a 6 cylinder engine.
   [NOTE: Throughout the remainder of this information report this vehicle will be designated as model J-1.]
   - It used a single 600 cell (4.3 mm wall thickness) ceramic catalyst located at a "mid-under-floor" or "under toe-board" location 16 inches downstream from the exhaust manifold outlet coupled with an insulated down-pipe.
   - This was Manufacturer J's first "near" Tier 2 bin 5 design, although it was certified to the less stringent LEV standard when it was released for the 2002 model year. This vehicle was certified to tier 2 bin 5 for MY 2004 with the catalyst in the same location and enclosed in the same casing. The catalyst substrate was changed to one with a thinner wall thickness (3.5 mm) and larger substrate (i.e., changed from 105 in^3 to 154 in^3 but with same inlet area of 17.1 in^2). Additional changes for the MY2004 design included addition of AIR for light-off and the appropriate engine calibration changes.

2. MY 2003 (and later) small wagon with a 4 cylinder engine. [NOTE: Throughout the remainder of this information report this vehicle will be designated as model J-2.]
   - This was an early introduction MY2003 vehicle (production began in early 2002); hence this vehicle would have accumulated higher mileage on average than the typical 2003 MY vehicle.
   - This was sold in three vehicle trim levels, each which had a distinct engine version. These included a performance upgraded front wheel drive, a base level performance front wheel drive, and an all wheel drive (AWD) vehicle. [NOTE: The same engine was used in the base and AWD vehicle but they were certified as two different engines under emissions regulations because a different catalyst was used.]
   - All three engine versions used a HDCC 600 cell ceramic catalyst and an additional downstream catalyst under the floor.
   - To allow for the packaging of the AWD system hardware, the AWD version used a slightly smaller catalyst integrated into the exhaust manifold and different exhaust pipe routing. The 2WD vehicles with both the performance upgraded and regular engines used the same catalyst and catalyst location. In all cases the catalyst was close coupled; however the catalyst for the AWD version was located slightly closer to the engine exhaust ports than the 2WD versions.

3. MY 2001 (and later) V8 high performance sports car.
   [Note: No plugging cases were observed with this vehicle.]
   - This vehicle had dual parallel catalysts that were manifold mounted on each side of the engine. A 600 cpsi catalyst was used on one side and a 350 cpsi catalyst on the other side. [Note: The high density catalyst was used on the one side because of packaging reasons (i.e., use of a high density design allowed the catalyst to be smaller in overall size to fit the small available envelope.)]

- The sales volume of this vehicle was low in Canada (about 60 per year).
- This vehicle was certified to LEV1 standards and even though it used the one high density catalyst, the remainder of the emission control system was not representative of tier 2 type technology.
- Catalyst warranty analysis on this vehicle indicated that there was a higher than normal replacement, however, the issue in this case appeared to be heat related rather than plugging. The replacement rate in Canada was on the same order as in the USA but appeared to be slightly lower.

4. MY2002 (and later) compact SUV
   [Note: No plugging cases were reported for this vehicle.]
   - This had a close coupled 600 cpsi (ceramic catalyst) located 9 inches downstream from the exhaust manifold.
   - This vehicle was certified to LEV1 standards and was sold in relatively low volume in Canada.
   - This vehicle exhibited a higher catalyst replacement rate in Canada compared to the USA (about double), but the main problem was a rattling noise concern. Because of the underlying rattle issue, this model was not specifically investigated for plugging. Therefore no conclusions were reached regarding whether a significant portion of the higher warranty rate in Canada was due to plugging.

5. Several other 600 cpsi catalyst applications were sold prior to MY 2004 but none had emission control systems representing tier 2 technology. Most were true under-floor designs, with the front catalyst located 30 to 48 inches downstream. One had a slightly closer mounted catalyst but its overall design was again not characteristic of tier 2 technology.

<u>Experience w/MMT Plugging</u>:

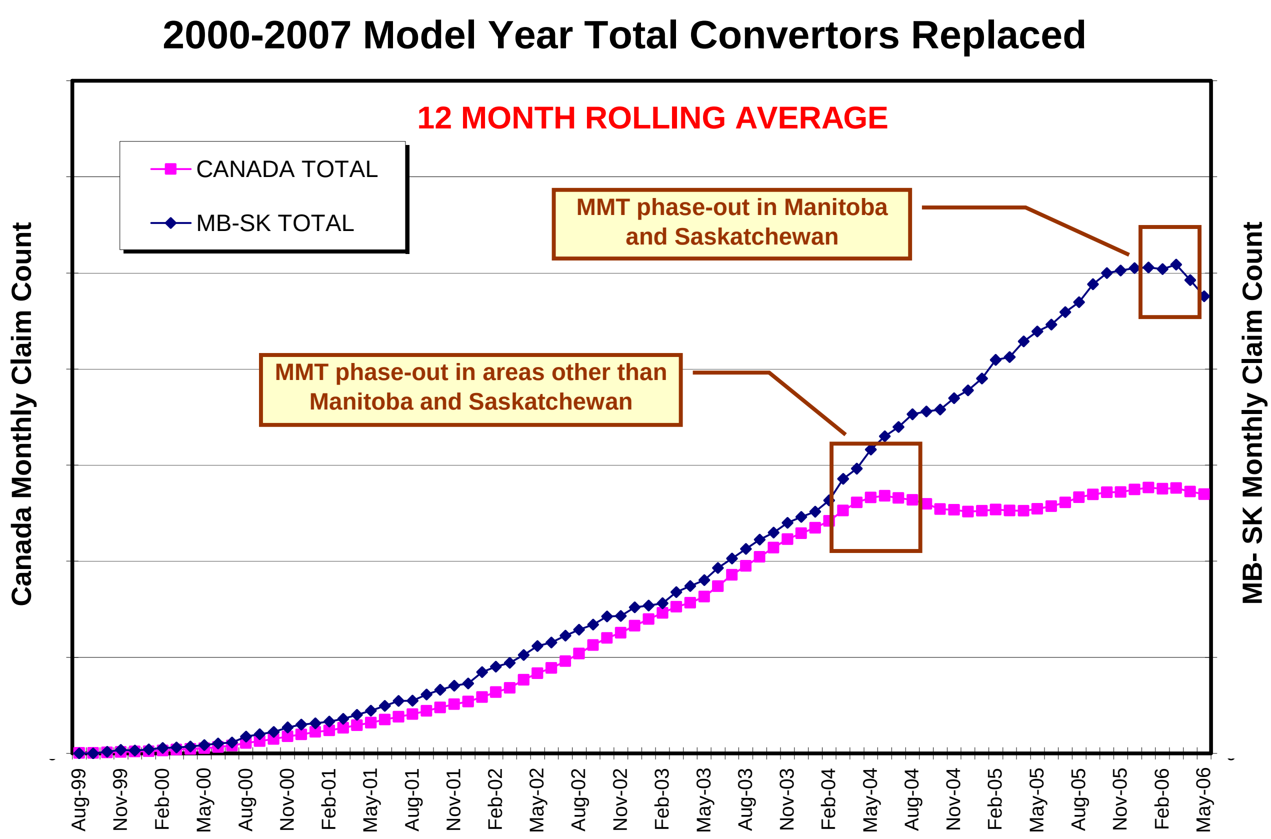
Manufacturer J observed three vehicle models where MMT related plugging was obvious. But additionally an <u>overall product analysis</u> comparing corporate wide catalyst warranty replacement rates in Canada vs. the US indicated an apparent MMT effect that reached more broadly than to just the three specifically identified cases (which are discussed below following the discussion of the overall product analysis). The data shown in Figures 1 through 8 of this report were complied as of July 2007.

- Figure 1 plots the monthly running 12 month average number of catalyst replacement claims for the **entire car and light truck product line versus time**. Use of the running average evens out the seasonal variations and best illustrates trends before and after MMT was removed from the fuel.
- Data are plotted for all of Canada excluding Manitoba and Saskatchewan and then separately for just Manitoba and Saskatchewan combined. This is because MMT remained in the fuel longer in Manitoba and Saskatchewan than in the rest of the country.

- The monthly warranty claim count for all of Canada excluding Manitoba and Saskatchewan begins to flatten corresponding to the time period when MMT was removed from most Canadian fuel (i.e., early 2004).
- However, the plot for just Manitoba and Saskatchewan continues to rise all through 2004 and does not begin to flatten until the fall of 2005 corresponding to the time period when MMT was removed from the fuel in these two provinces.
- The Canada data is plotted against the left vertical axis and the Manitoba and Saskatchewan data is plotted against the right vertical axis and these axes have different scales. The intent is to show the dependence of the replacement trend on the phase out of MMT by region.

[NOTE: To protect confidential information the numbers on the vertical scale are not shown. However, the key points can be observed from the shape of the curves.]

Figure 1



- While the overall trends shown above indicate a correlation between MMT use and the catalyst replacement rate, a direct cause and effect relationship was found in three distinct cases. For these three cases catalyst warranty repair rates were significantly higher in Canada than in the USA. Follow up inspection of replaced catalysts from

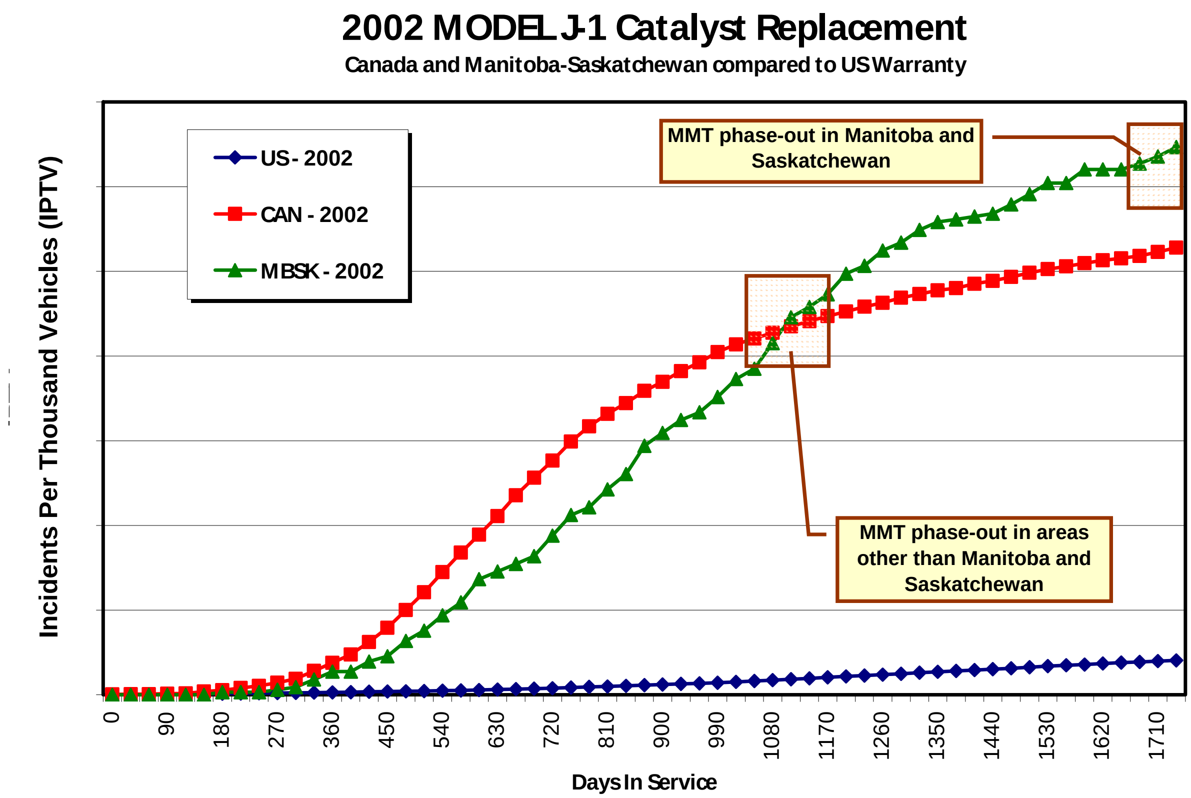
Canada confirmed that the difference between Canada and USA was attributable to manganese oxide plugging. Two of the significant plugging cases involved two of the HDCC configurations discussed above; whereas the third case actually involved a close coupled 400 cpsi catalyst.

Case #1: Vehicle J-1 (the MY 2002/3 midsize SUV described above) represents the most notable plugging case.

- For this vehicle design (Model J-1), catalyst replacements in Canada represented 70% of North American catalyst warranty replacements for this model although Canadian sales represented only 5% of the total North American sales of this model.
- Actual warranty rates are not disclosed in this report due to confidentiality of the data. Figures 2 through 5 illustrate plots of catalyst replacement warranty rate versus time in service for the 2002 and 2003 model years. The incidents per thousand vehicle (IPTV) values on the vertical scales for these graphs have been removed to protect the confidential data, but the graphs are all plotted on the same scale to allow a number of comparisons.
- Figure 2 allows two comparisons for the 2002 model year. The overall Canadian catalyst replacement warranty rate (cumulative incidents per thousand vehicles) is compared to the rate observed in the USA where MMT use has been nearly zero. Additionally it is compared to the rate observed in Manitoba and Saskatchewan where a significant portion of the fuel continued to use MMT until late in 2005.
    - Both the overall Canadian rate and the Manitoba-Saskatchewan rates were substantially higher than the USA rate which on a relative comparison basis was nearly flat.
    - The peak value of the ratio of the overall rate in Canada versus the US was 35 times for MY 2002.
    - The overall Canadian rate began to flatten as MMT was removed from most Canadian fuel beginning in early 2004, except for in Manitoba and Saskatchewan. The rate in Manitoba and Saskatchewan continued to rise and began to show signs of also flattening when MMT was finally removed from the fuel in those two provinces.

Best Viewed in Color

Figure 2

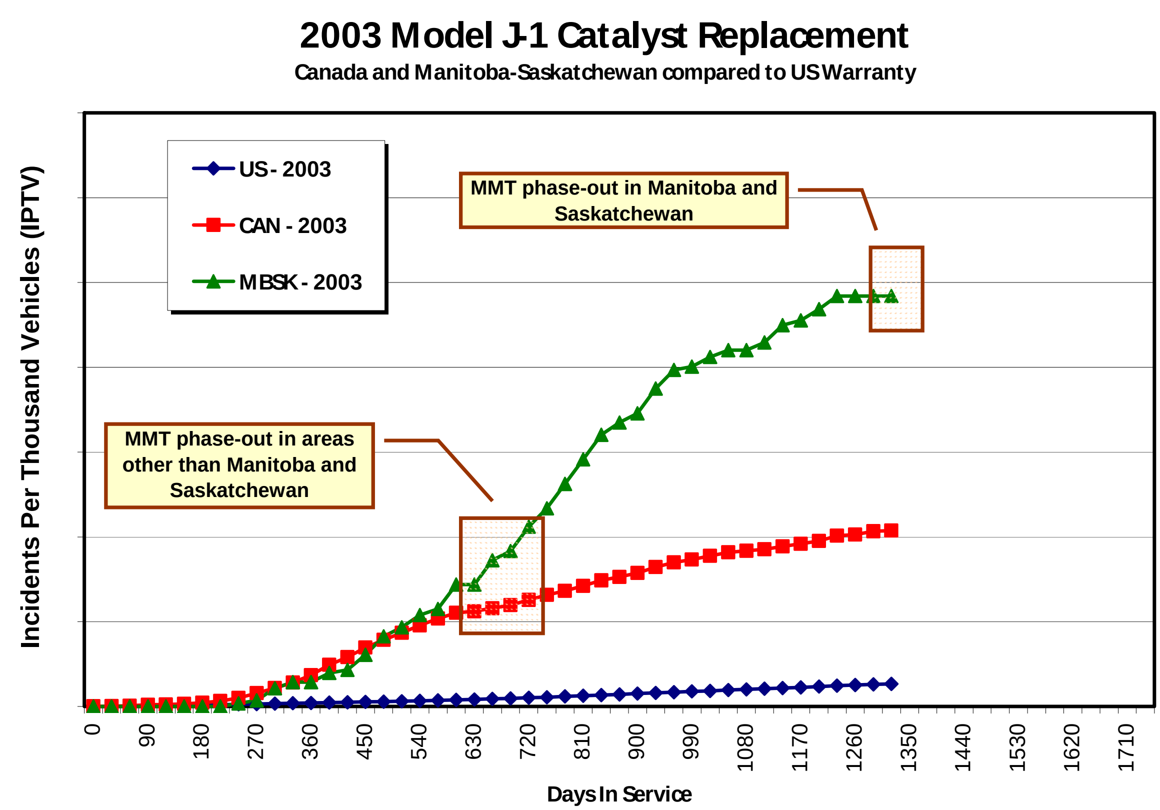


- Figure 3 shows the same information that figure 2 did for MY 2002, except figure 3 shows the 2003 MY. This is plotted on the same scale as figure 2 to allow comparisons of information given there are no numbers on the vertical scales.
  - Again the overall Canadian rate and the rate for just the two provinces that continued with MMT use substantially exceeded the rate in the USA. Up to the point where MMT began to be phased-out, the Canadian warranty experience for both the 2002 and 2003 model years is almost identical.
  - The overall Canadian rate does not continue on the same increase path as it did for MY 2002 since these newer vehicles would have accumulated less mileage before the time period when the MMT phase out began to occur. In other words, fewer of these vehicles would have reached the minimum plugging threshold before MMT was removed.

Best Viewed in Color

- While the peak value for the catalyst replacement ratio for all of Canada for 2002 J -1 model was 35 times the US rate, this dropped to 14 times for the 2003 J-1 model when the phase out of MMT began across the country.
- Conversely in Manitoba and Saskatchewan where MMT use continued unabated until the late fall of 2005, the catalyst replacement peak ratio when compared to the US rate grew to 25 times for 2002 J-1 model and stayed almost the same for 2003 J-1 model at 23 times.
- The two province rate continues to rise on a path similar to the 2002 model year as would be expected since MMT use continued there. However, the trend begins to flatten at the point when MMT was finally removed from the fuel in these two provinces

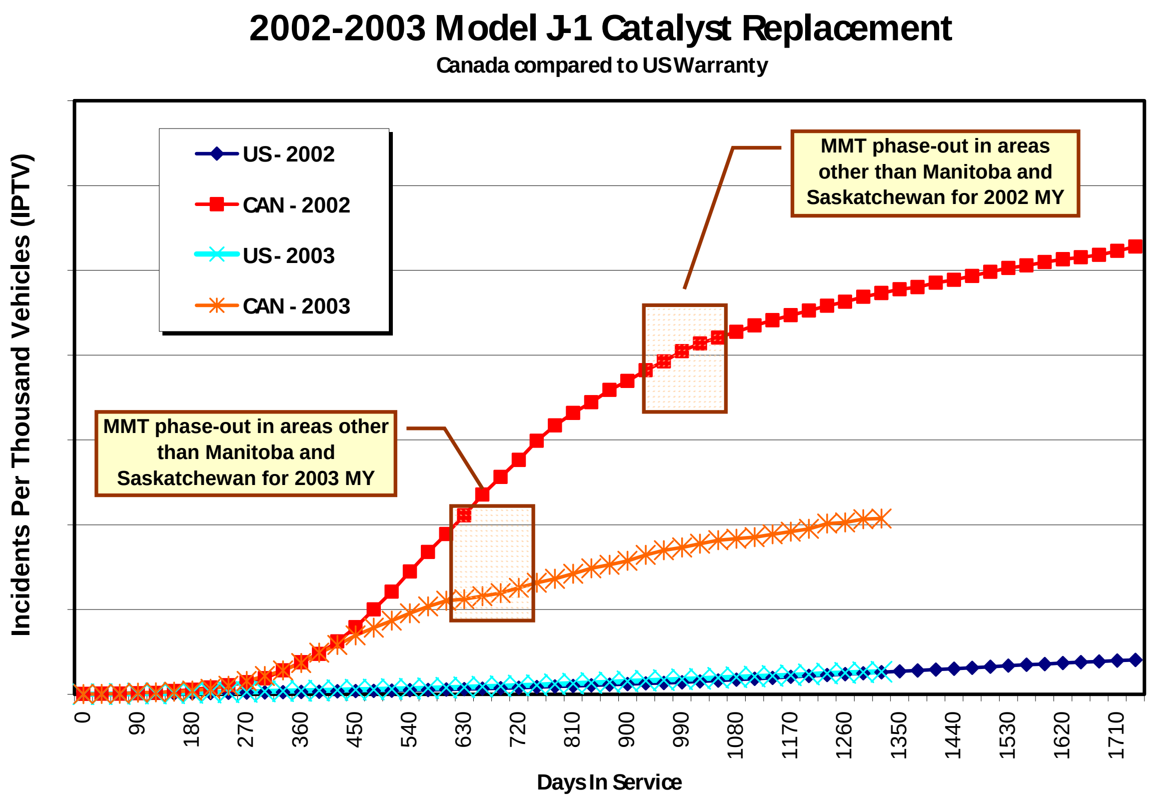
Figure 3



Best Viewed in Color

- Figure 4 simply combines the overall Canadian (except for Manitoba and Saskatchewan) and US rates from figures 2 and 3 on the same graphs to allow a more direct comparison of model years 2002 and 2003.
    - The overall Canadian rate for MY 2003 stopped tracking the 2002 path and began to flatten during early 2004 when MMT began to be phased out.
    - The USA rate for both MY 2002 and 2003 follow almost exactly the same track.

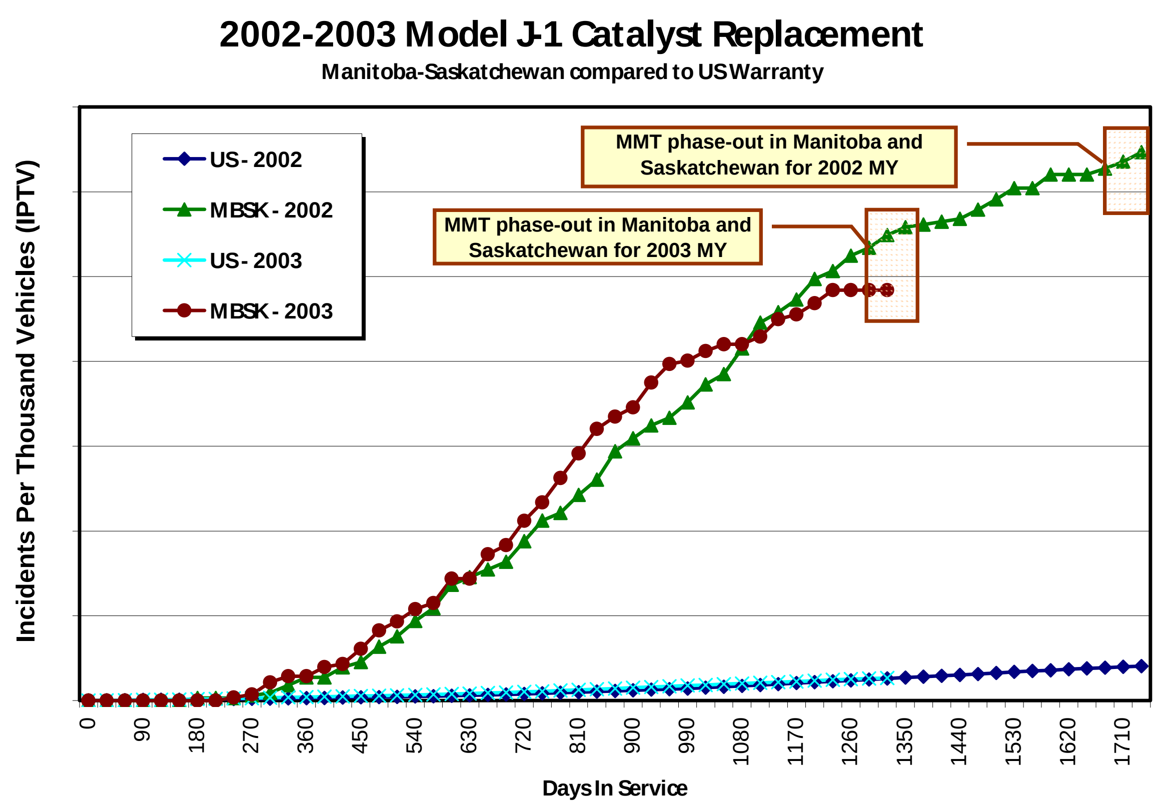
Figure 4



Best Viewed in Color

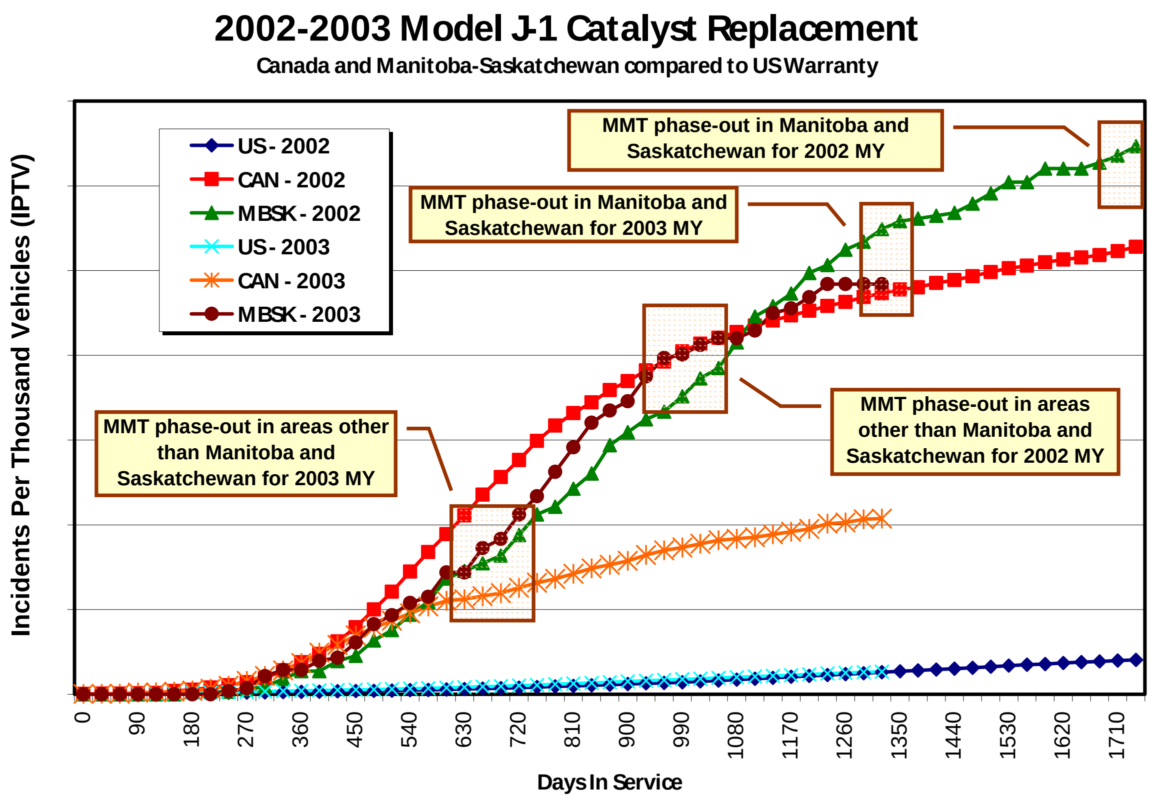
- Figure 5 combines the rates for model years 2002 and 2003 for Manitoba and Saskatchewan and compares these to the US rates.   These are the same plots that were included in figures 2 and 3. They are plotted together on the same graph to display the equivalent comparison for just Manitoba and Saskatchewan that was made for the rest of Canada in figure 4. As could be observed in figure 4 with the overall Canadian rates, the model year 2003 rate for Manitoba and Saskatchewan stopped tracking the 2002 rate around the time that MMT was phased out of these areas.

Figure 5



- Figure 5a combines everything from figures 2 through 5, including the Manitoba and Saskatchewan lines all on one graph. This creates a complex graph but hopefully the building block approach used to create it will make it understandable.
    - The main additional observation from this graph is that the Manitoba and Saskatchewan warranty rates continue to rise at the points for both MY2002 and 2003 where the remaining Canada rates begin to flatten.
    - The data for this graph ends right about at the time that MMT was removed from the fuel in Manitoba and Saskatchewan so this graph is not conclusive regarding the post MMT trend in these areas.

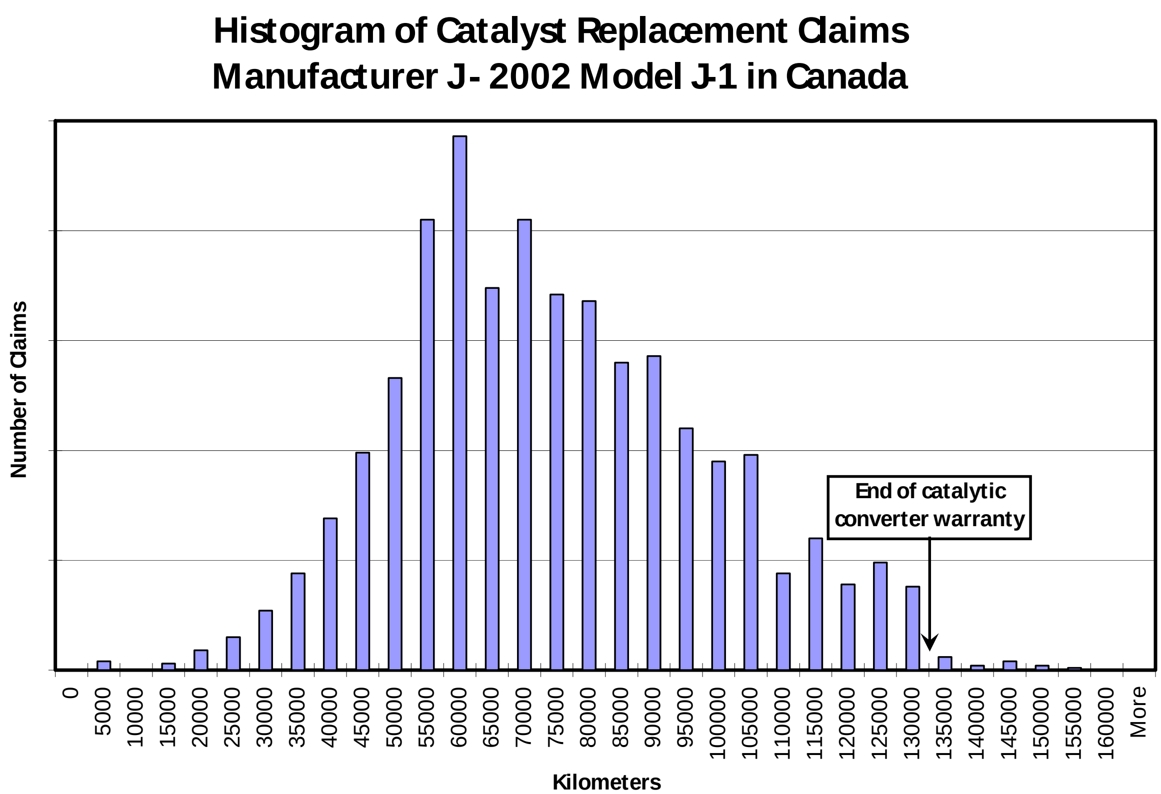
Figure 5 a



Best Viewed in Color

- Figure 6 is a histogram of all Canadian catalyst replacement claims for the 2002 MY version of model J-1. This illustrates that the minimum plugging threshold for this vehicle catalyst design occurs in the 30,000 to 50,000 kilometer (19,000 to 31,000 mile) range.

Figure 6



NOTE: This histogram does not represent what would have occurred if MMT stayed in the fuel and if one waited until all of the vehicles would have achieved their useful lives before plotting this histogram. This is not a cumulative distribution. **As more vehicles in the fleet would have accumulated more mileage with fuel containing MMT, additional vehicles would have had been expected to experience catalyst warranty claims**. Hence the shape of this distribution, especially the high mileage back side of this histogram had not had a chance to fill in. **But this early life distribution is useful in estimating where the minimum plugging threshold begins**.

Is it possible that the difference in IPTV ratio as shown in Figures 2 through 5 was a function of the difference between the Canadian and US market areas and hence, not have been related to MMT use?

- Manufacturer J's experience has been that overall the total vehicle warranty rate in IPTV tends to be slightly higher in Canada than the US. The reasons behind this market-to-market variation include the fact that the Canadian climate is colder than the US on average and the corrosion conditions in Eastern Canada are more severe than in the US.

- The IPTV ratio for Canada for catalyst replacement and for all other warranty repairs related to model J-1 were calculated separately. The peak value of the ratio of the Canadian warranty rate divided by to the US warranty rate was over 35 times for catalyst replacements for all of Canada but only 1.4 times for all other warranty repairs.

- **The answer to the above question is NO**. The ratio of catalyst replacement claims is over an order of magnitude higher in Canada than the US when compared to the baseline of all other warranty for this model of vehicle.

- Additionally, if the higher catalyst warranty rates in Canada were due to reasons other than MMT use, then there would be no reason for the Canadian rates to start to flatten out relative to the US rates as they did once MMT was removed from the fuel.

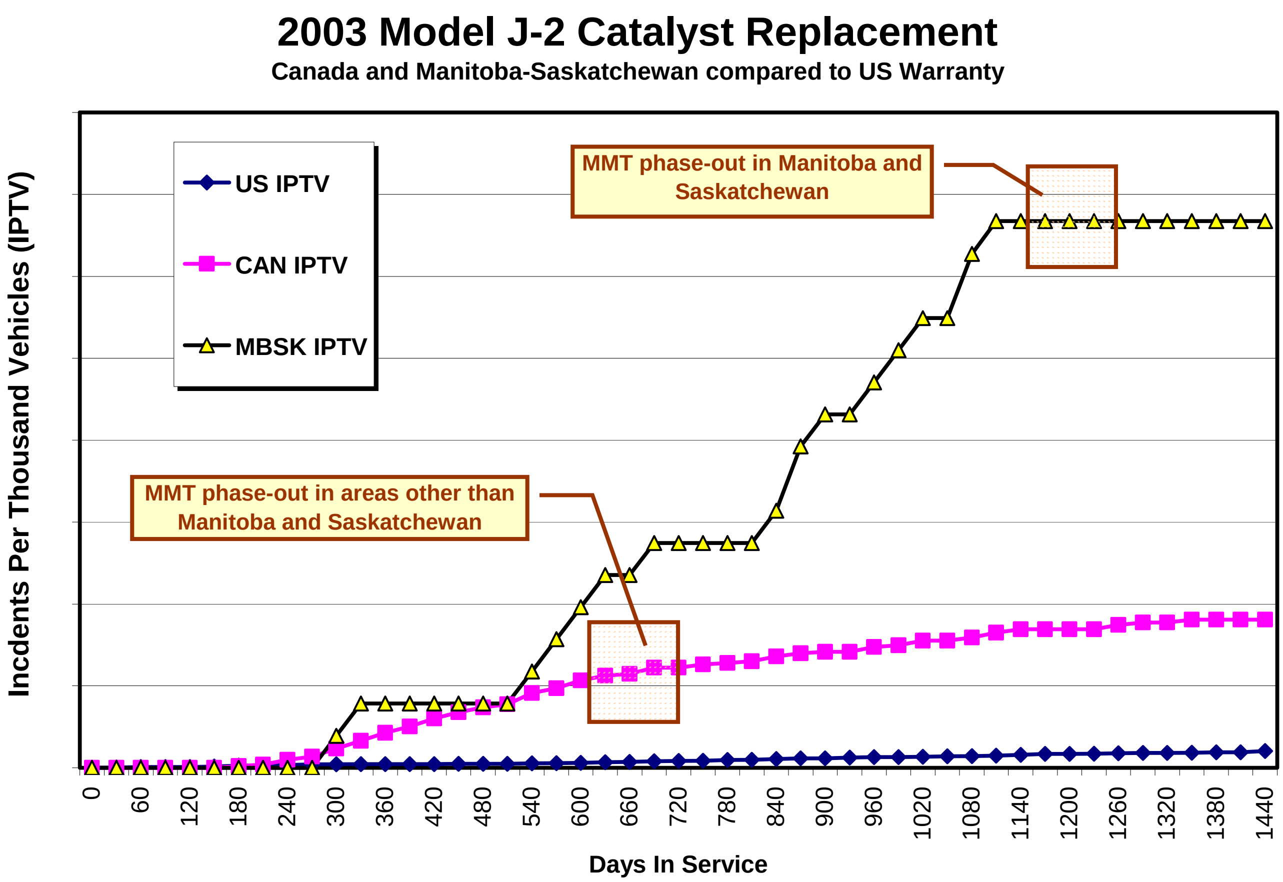
Case #2: This case involves primarily the AWD version of vehicle model J-2 (the MY 2003 small wagon).

- Isolated plugging was observed on the two non-AWD versions, but the number of occurrences identified was small and the degree of plugging was less than for the AWD version. In fact, based upon comparison between Canada and the USA, no obvious difference in warranty rates could be observed for the non-AWD versions.
- On the other hand, significant plugging was observed on the AWD version where the primary catalyst was located closer to the exhaust ports.
- Figure 7 illustrates a plot of catalyst replacement warranty rate versus time in service for the 2003 model year for model J-2. The vertical scales have been removed to protect the confidential data, but the graph allows several observations similar to what was seen on case #1 above.
  - The overall Canadian rate was substantially higher than the USA rate which on a relative comparison basis was nearly flat. The peak value

of the ratio of the rate in Canada versus the US was 37 times for MY 2003.

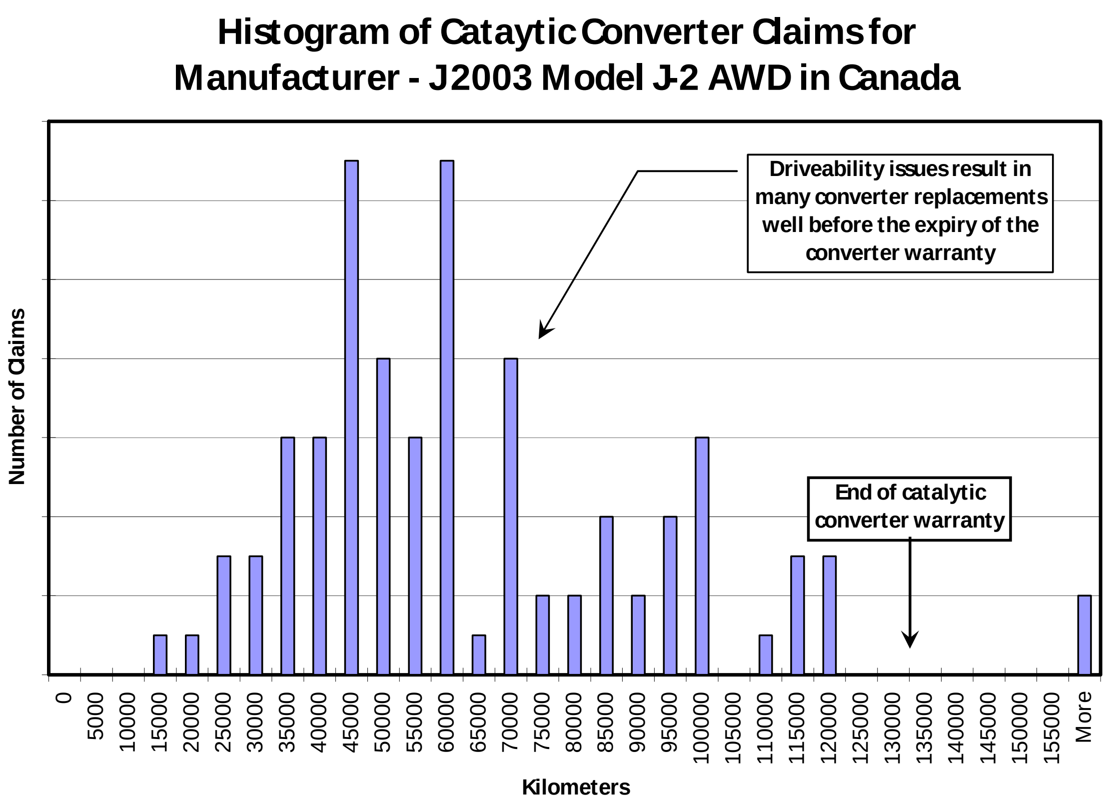
- The overall Canadian rate began to flatten as MMT was removed from most Canadian fuel beginning in early 2004.
- The rate in Manitoba and Saskatchewan continued to rise until MMT was removed later in these provinces. The MBSK IPTV ratio to the US IPTV peaked at over 57 times higher.

Figure 7



- Figure 8 is a histogram of all Canadian catalyst replacement claims for the 2003 MY AWD version of model J-2. This doesn't exhibit as sharp of a defined threshold point where plugging cases begin to rapidly increase as was observed above for model J-1 in figure 6; however this histogram still generally shows the same type of distribution. In this case the plugging threshold appears to be in the range of around 22,000 to 35,000 kilometers (14,000 to 20,000 mile).

Figure 8



Note 1: This histogram does not represent what would have occurred if MMT stayed in the fuel and if one waited until all of the vehicles would have achieved their useful lives before plotting this histogram. This is not a cumulative distribution. **As more vehicles in the fleet would have accumulated more mileage with fuel containing MMT, additional vehicles would have had been expected to experience catalyst warranty claims.** Hence the shape of this distribution, especially the high mileage back side of this histogram had not had a chance to fill in. **<u>But this early life distribution is useful in estimating where the minimum plugging threshold begins</u>**.

Note 2: The driveability of these vehicles is affected long before there is any emissions impact. This is due to the fact that these vehicles have two catalysts and therefore the second cat is doing more work to clean up the exhaust than the front cat. Customers have reported driveability (low power) problems long before the OBD light comes on and hence the lack of claims at higher kilometers (over 60,000).

As was discussed above relative to the experience with model J-1, the question regarding whether the difference in IPTV ratio as shown in Figure 7 for model J-2 could have been a function of the general difference between the Canadian and US market areas was again considered here and again the answer is "NO.".

- As in the model J-1 case, the total warranty IPTV ratio, excluding catalyst replacements was noted as tracking at about 1.4 times for Canada vs. US. The peak ratio for catalyst repairs in Canada vs. the US was 37 times. Clearly the catalyst replacement ratio is an order of magnitude higher than the general warranty IPTV ratio.

- Again, if the higher catalyst warranty rate in Canada was not due to MMT use, there would have been no reason for the difference ratio to begin to flatten after MMT was removed as it did do for model J-2 (as well as J-1).

Case #3: This case did not involve any of the vehicles described above that used HDCC catalysts. This case involved a passenger car using only a 400 cpsi catalyst. However the catalyst was close coupled to the manifold. [NOTE: The vehicle in this case will be designated as model J-3 throughout the remainder of this report.]

- This was a turbo charged vehicle that operated on premium fuel. It ran at high temperature and had a high exhaust flow relative to its catalyst size. Aside from this severe catalyst location, the emission control system did not represent tier 2 technology.
- This vehicle design dated back to MY 2000 which gave it more time in service and mileage exposure to MMT before MMT began to be removed from the fuel. [Note: MY2000 is when the first close coupled catalyst was used even though it was not a high density catalyst.]
- Due to the unique situation where the catalyst was moved from under-floor in 1999 to close coupled in subsequent model years, and the higher heat and load conditions that this engine with its turbocharged configuration experiences, this model served as an indicator of things to come with advance emission technologies.
- From 1999 through 2002, this case actually involved five different vehicle/engine versions that used 5 variants of the same catalyst systems. There was a 4 cylinder turbo charged engine that was available in a high pressure and low pressure boost. There was a 6 cylinder engine that was available in three different turbo boost or performance levels. In 2003 and beyond a new engine family was added to this mix at higher volume. This later engine did not use the same system design and the amount of potential Mn exposure began to drop as the MMT® phase-out began in early 2004.
- Because the warranty system for this vehicle group in the USA was very different from that used in Canada, manufacturer J could not provide warranty

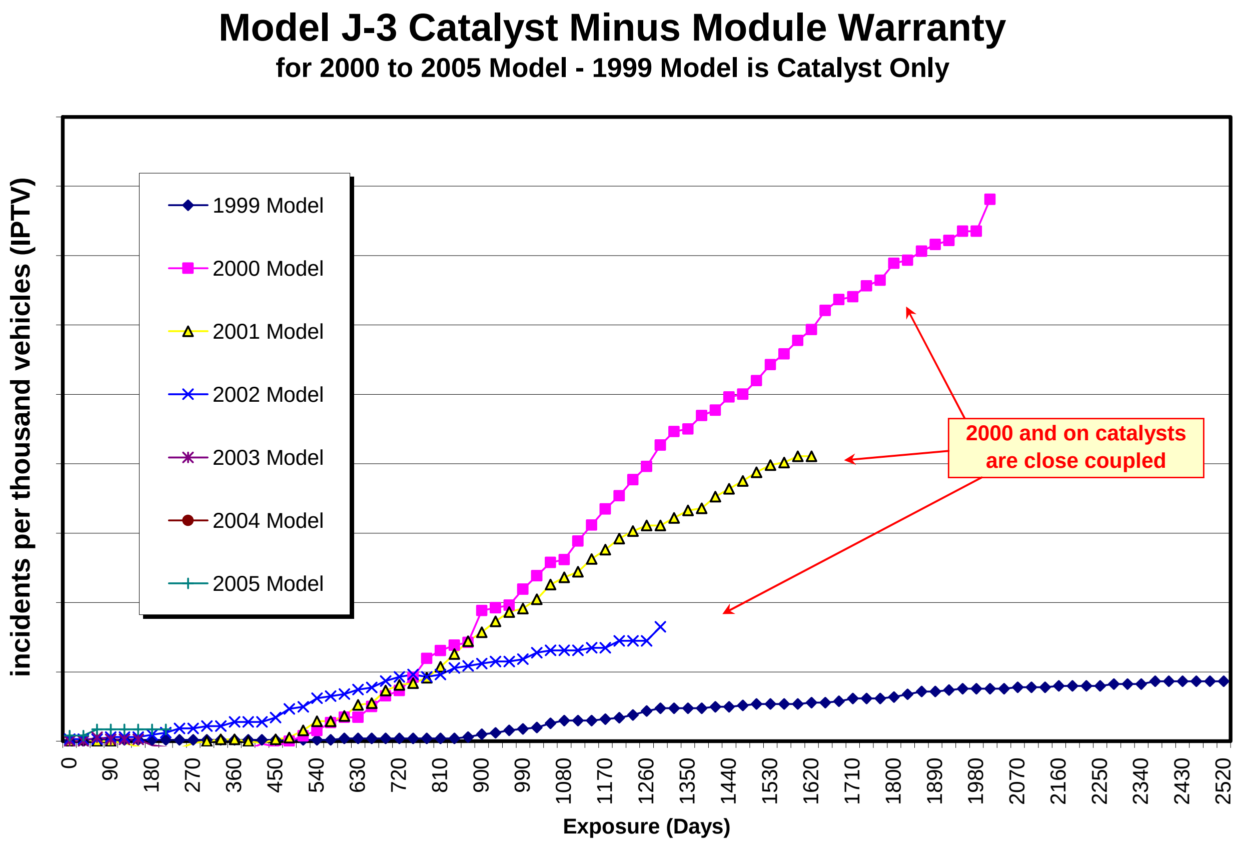
trend charts like those above for case #1 and #2 that compared US and Canadian warranty catalyst replacement rates. Hence figure 9 is plotted comparing only the various Canadian model years.

- Since MY 1999 involved a full under-floor catalyst design, it would not have been expected to show a very high MMT effect (i.e., due to the lower temperature of the exhaust flow into the catalyst face). So while a US "baseline" curve could not be generated for this case, the 1999 MY curve serves somewhat of a surrogate for the USA baseline.
- <u>The following observations can be made from figure 9.</u>
    - The MY 1999 curve is fairly flat as would have been expected.
    - The MY 2000 curve rises most dramatically as this was the earliest MY having the high temperature close coupled design. Because of the age of the vehicles from this model year, these would have had the highest mileage and hence the highest exposure to MMT before it was removed from most of the Canadian fuel.
    - The 2000 model year IPTV was found to be over 9 times higher to the 1999 IPTV.
    - The curve for each successive model year begins to track the MY 2000 curve but then starts to fall away, each at an earlier point presumably due to decreased MMT exposure as MMT was being removed from most Canadian fuel.
    - The 2003 and later MY curves appear to track the MY1999 curve, because these vehicles would have had very little MMT exposure before it was removed from the fuel.

      [NOTE: An analysis of the situation in Manitoba-Saskatchewan did not provide any valuable results since there were too few vehicles from this case group that were sold and operated in that area.]
- An analysis of the plugging case frequency vs. odometer indicated the earliest plugging occurrences were observed around 20,000 km, but the knee in the curve where the frequency began to rise quickly was in the 65,000 to 95,000 km (approximately 40, 000 to 60,000 mile) range. This higher apparent "plugging threshold" range compared to case #1 and #2 appears consistent with the expectation that this vehicle/catalyst design would not plug as quickly as those having HDCC systems.
- Figure 10 contains a sample picture of model J-3 catalysts at 70,000 km.

Best Viewed in Color

Figure 9



The data shown in Figure 9 were complied as of July 2006.

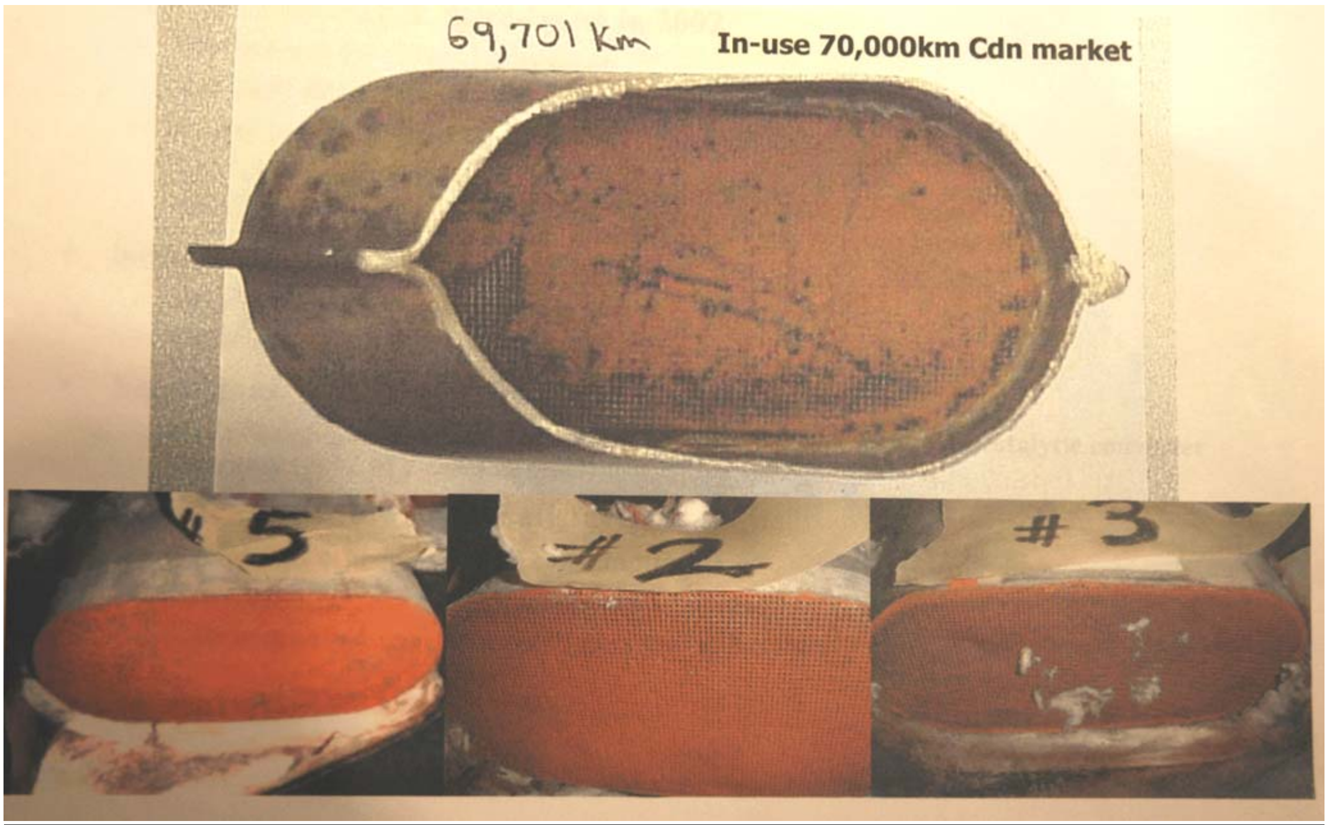
NOTE: Since the initial analysis of catalyst failures on J-3 models in Canada, a secondary issue of ignition module failure was identified on 1999 through 2002 vehicles. It is logical to assume that some of the catalyst failures during these model years could have been a result of an ignition module failure. Hence, as a worst case scenario, manufacturer J assumed that all of the 2000 through 2002 ignition module failures resulted in a catalyst failure and that none of the 1999 module failures resulted in a catalyst failure. To do this, the ignition module IPTV was subtracted from the catalyst replacement IPTV for the 2000 to 2002 data. Clearly, this worst case analysis demonstrates that the ignition module issue is not responsible for the higher rate of catalyst replacement on the 2000 through 2002 model vehicles than the 1999 models.

Best Viewed in Color

Figure 10

Typical Model J-3 Converter Failures

*** Analysis of deposits indicates 90-95%+ MN**



Future Technology Plans:

- Manufacturer J's "mainstream Tier 2 package includes high density close coupled catalysts for virtually all products." [NOTE: Here "close coupled" refers to both manifold mounted catalysts as well as catalyst located relatively short distances downstream of the manifold but still located either in the engine compartment or under the toe-board.]
- There are some exceptions, mainly due to packaging constraints, and in some cases that involve high performance (high flow and high temperature) engines; but most often such exceptions are (or will be) be certified to higher than bin 5 under Tier 2 averaging rules.
- Many systems use a second downstream catalyst. Often the downstream catalyst is a 400 cpsi (or less) design.
- Light trucks follow the same technology path.
- Trucks will likely see higher temperatures than cars in actual use, but would see about the same temperature on the FTP.
- Quick light off must be achieved even in those exception cases where packaging might force an under-floor catalyst. Hence the temperatures for even under-floor designs should have temperatures similar to close coupled designs. Other measures have to be taken to get the catalyst to the necessary temperature (e.g., insulated down pipes).

Emission Testing and Analysis:

- **In-Use Testing of the mid-size SUV (Case #1):**
  - A laboratory emission testing program was performed that involved 49 of the 2002 model-year Model J-1 vehicles for which high catalyst warranty replacement rates were observed in Canada. The test program involved 24 vehicles from Canada and 25 vehicles from the U.S. coming off lease from non-fleet owners between February 1 and June 1, 2004.
    - Customer vehicles were randomly selected from the Manufacturer's lease return fleet.
    - Vehicles are not selected based upon suspected or consumer reported MMT plugging.
    - Only properly operating vehicles with no OBD codes or major emission system repairs where included in the study.
    - Vehicles that had already plugged in-use where excluded from this testing program as they would have new and relatively fresh catalysts. Hence, this program gives a measure of the emissions effect from the "everything-else fleet" which should be an indicator of the emission effect for vehicles that have not been brought in for repair. As a result, the worst emissions case vehicles were deliberately excluded from this study.
  - All vehicles were subjected to FTP emissions testing along with catalyst flow testing to determine backpressure. With respect to flow testing results, all of the U.S. and a portion of the Canadian vehicles had normal exhaust system backpressure. However, 13 of the 24 Canadian vehicles

had high exhaust system backpressure and higher exhaust emissions than either the U.S. or Canadian vehicles with normal system backpressure.

- For the US in-use vehicle survey sample, exhaust tailpipe emissions were well within the range expected based on certification and engineering development results.
    - The 25 vehicle sample had an average in-use mileage of 64,000 km and average composite FTP tailpipe emissions of 0.076/0.645/0.169 NMHC/CO/NOx g/mile (76%/15%/42% of the LDT2 NLEV 50,000 mile certification standards).
    - All vehicles met the 50,000 mile emission certification standards for all regulated emission components.
    - The average restriction (cold flow measurement at 100 g/s) was 8.7inches of H_2O for these vehicles.
- For the Canadian in-use vehicle survey sample, exhaust tailpipe emissions were higher for all regulated emission components.
    - The full 24 vehicle sample had an average in-use mileage of 60,500 km and average composite FTP tailpipe emissions of 0.090/1.131/0.255 NMHC/CO/NOx g/mile (90%/26%/64% of the LDT2 NLEV 50,000 mile certification standards).
    - 7 vehicles exceeded the 50,000 mile NMHC certification standard, 1 vehicle exceeded the 50,000 mile CO certification standard and 3 vehicles exceeded the 50,000 mile NOx certification standard.
    - The full 24 vehicle sample average NMHC/CO/NOx emissions were 119%/175%/151% of the US sample average emissions.
- Emissions from the 24 vehicle Canadian fleet were also analyzed in separate subsets based upon high and low backpressure. The average, as well as, minimum and maximum emissions of NMHC, CO, and NOx from the US and normal backpressure Canadian fleet were comparable. In contrast, both the average, as well as, the minimum and maximum emissions of all three pollutants was higher from the high backpressure Canadian fleet.
    - In particular, average NMHC emissions from the high backpressure Canadian fleet were 40% higher than the U.S. fleet average while average NOx emissions were two times higher for the Canadian vehicles.
    - Several of the Canadian vehicles with high backpressure that had accumulated less than 50,000 miles had NMHC emission levels above the 50,000-mile emission standards to which this model was certified.
    - One high backpressure vehicle had NMHC and NOx emissions at approximately 60,000 miles that exceeded the

120,000-mile standard to which the model was certified. For vehicles with high backpressure, emissions of all three pollutants generally increased with increasing backpressure.

- Average engine-out emission levels for all pollutants were similar for the U.S., low backpressure Canadian, and high backpressure Canadian vehicles**.**
- The table designated as figure 11 below summarizes the emission test results when broken down into the high and low backpressure groups.

- The emission results plotted vs. mileage are shown below in figures 12a, 12b, and 12c for NMHC, CO, and NOx respectively. An important observation from these graphs that would not be evident by simply looking at the averages as done above was that for all pollutants, the "deterioration" rate for the Canadian fleet was higher than for the US fleet.
- The highest single emissions point shown on figures 11a through c might appear to be an outlier if these graphs were the only available information. However, this point corresponds to the vehicle that had the highest backpressure associated with plugging. Plotting the data as a function of emissions vs. backpressure as shown in the graphs in figure 13a, 13b, and 13c illustrates that the highest emissions test point appears to be logically in line with the emissions-backpressure relationship.
- The data provided in Figures 11 through 15 were complied as of December 2004.

[NOTE: An additional analysis was also performed that demonstrated that increased exhaust system backpressure and increased emission levels were positively and non-linearly correlated with the amount of Mn found on the catalyst].

Figure 11

Summary of Emission Test Program Conducted by Manufacturer J on 2002 Model Year Model J-1 Vehicles

	U.S. Vehicles	Canadian - Normal Backpressure	Canadian - High Backpressure
Number	25	11	13
Average Odometer (km)	64,000	45,000	73,000
Min/Max Odometer (km)	30,000/108,000	10,000/102,000	22,000/137,000
Average NMHC (g/mi)	0.076	0.072	0.105
Min/Max NMHC (g/mi)	0.05/0.10	0.05/0.09	0.07/0.20
Average NOx (g/mi)	0.169	0.154	0.341
Min/Max NOx (g/mi)	0.10/0.33	0.10/0.20	0.20/1.0
Average CO (g/mi)	0.645	0.580	1.598
Min/Max CO (g/mi)	0.3/1.3	0.4/0.8	0.75/5.0
Average Restriction (inches H_2O)	8.7	9.1	30.3
Min/Max Restriction (inches H_2O)	7.5/10.0	8.2/11.4	13.6/81.7

Best Viewed in Color

Figure 12a FTP Composite Tailpipe NMHC Emissions vs. Mileage

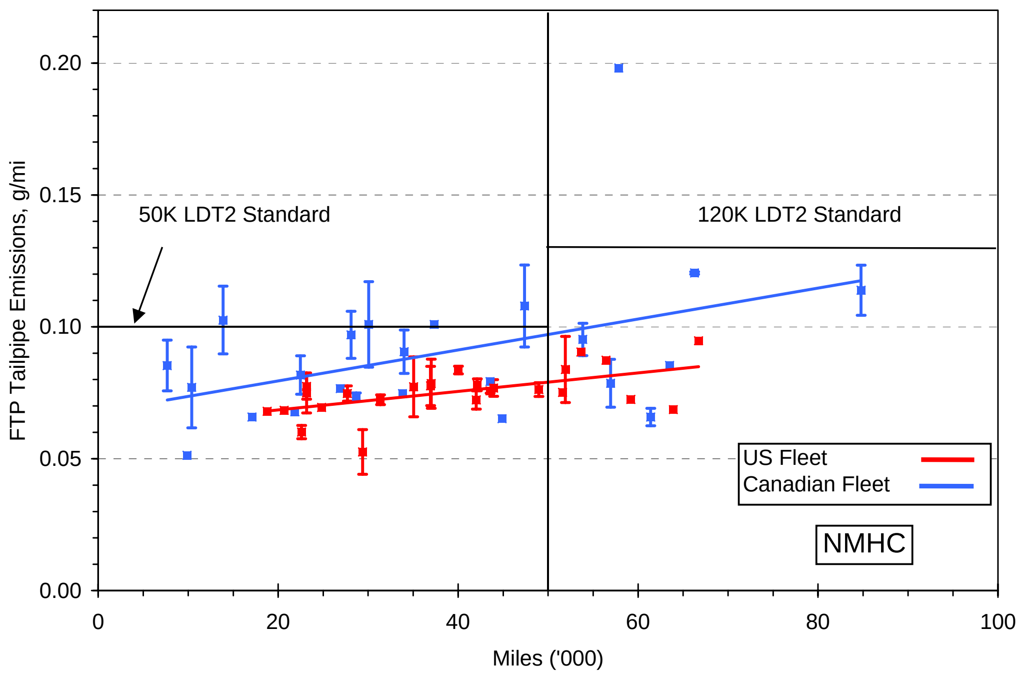
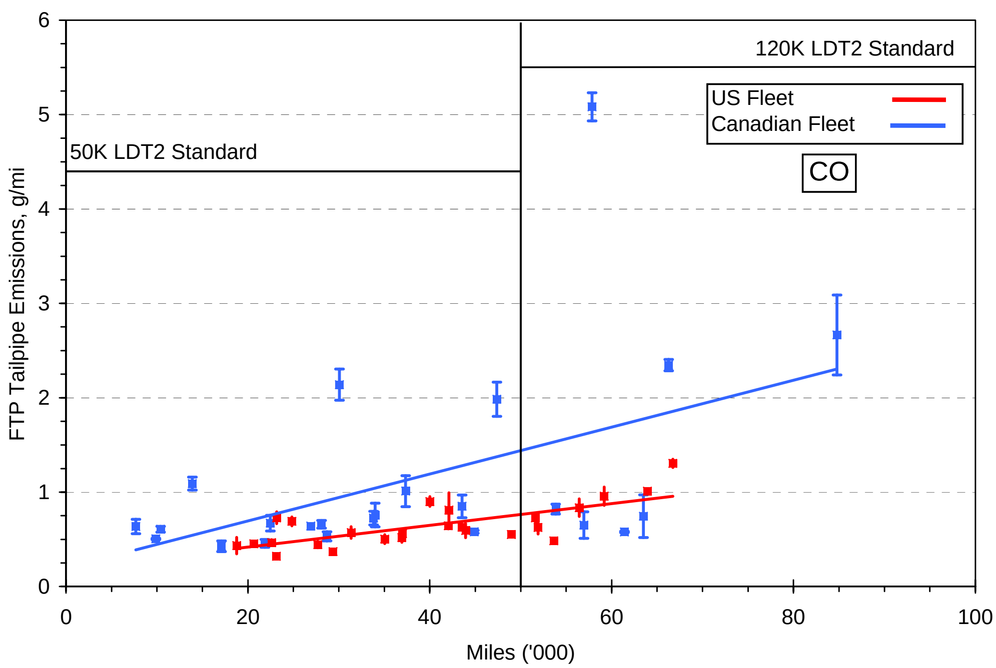


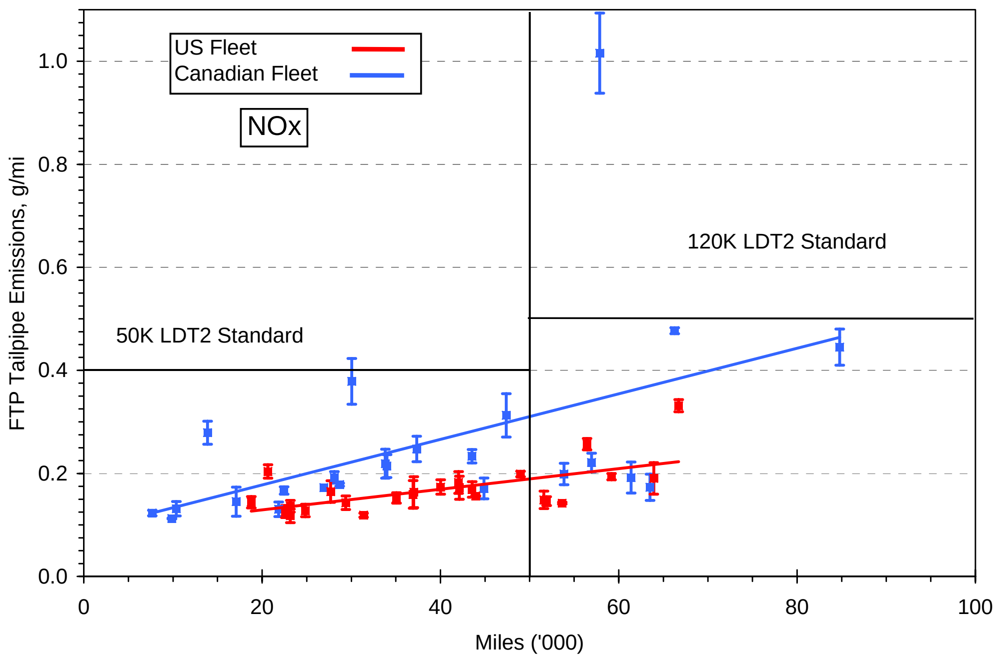
Figure 12b FTP Composite tailpipe CO Emissions vs. Mileage



Best Viewed in Color

Figure 12c

FTP Composite tailpipe NOx Emissions vs. Mileage



Best Viewed in Color

Figure 13a FTP Composite Tailpipe NMHC Emissions as a Function of Hot End Exhaust Assembly Cold Flow Restriction (@ 100 g/s)

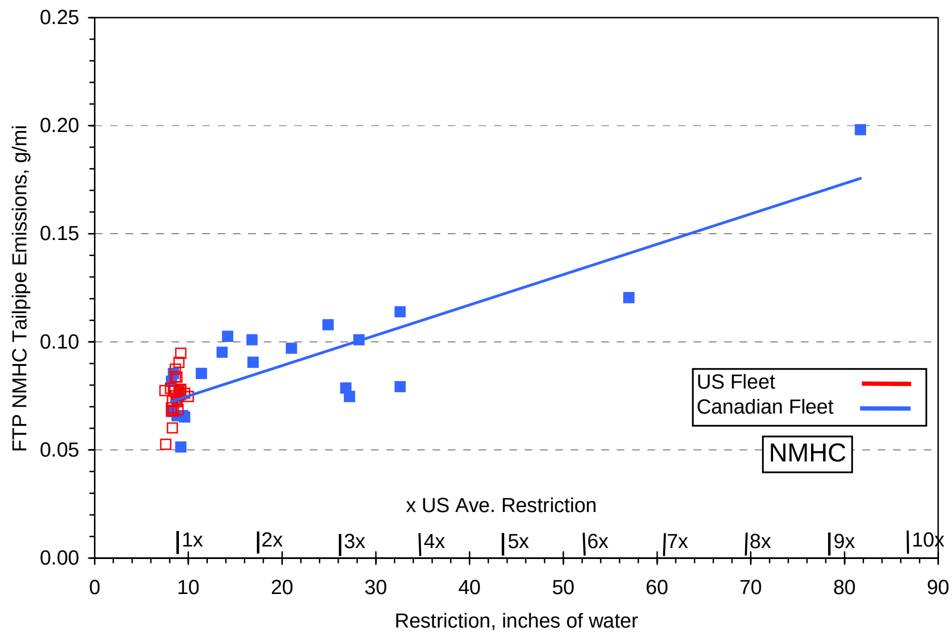


Figure 13b FTP Composite Tailpipe CO Emissions as a Function of Hot End Exhaust Assembly Cold Flow Restriction (@ 100 g/s)

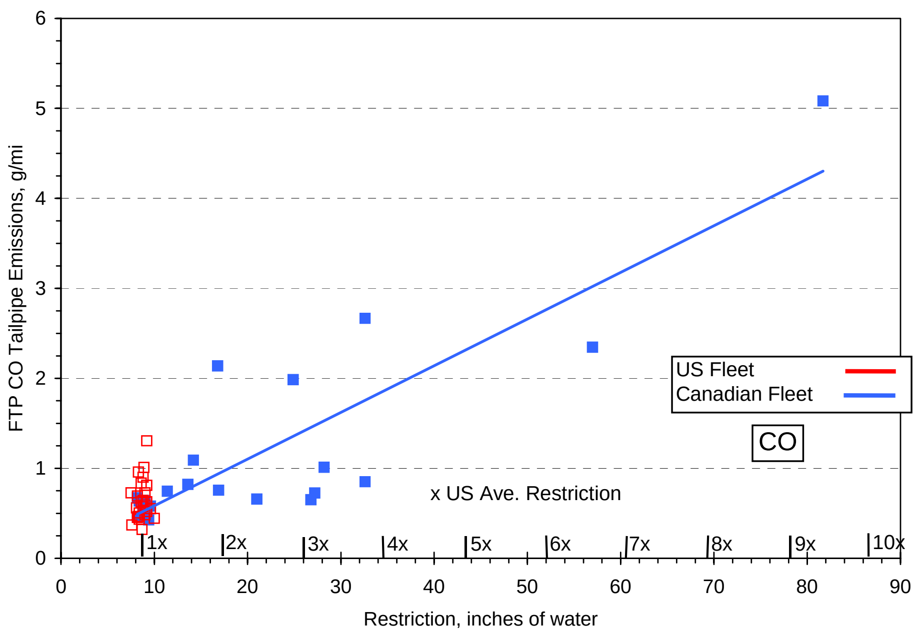
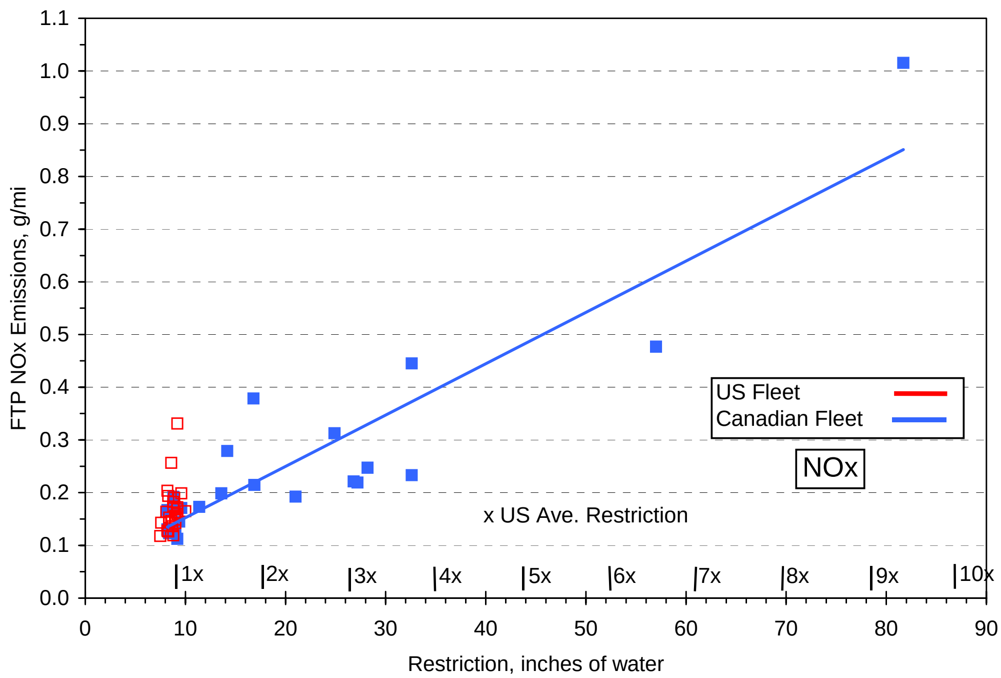


Figure 13c FTP Composite Tailpipe NOx Emissions as a Function of Hot End Exhaust Assembly Cold Flow Restriction (@ 100 g/s)



- **Analysis of Replaced Catalysts Model J-1:**

  - Findings from analysis of US warranty return catalytic converters were that primary failure modes were broken inlet catalyst elements, excessive operating temperatures and exhaust system noise with converter intact.
  - Findings from analysis of Canadian warranty return catalytic converters were the primary failure mode was partial plugging with Mn_3O_4 deposits. Other failure modes as found in the US occurred at similar rates as in the US. Figure 14 presents an analysis of failure modes for warranty returns in the USA compared to Canada for Model J-1 through September 2004
  - The Canadian catalysts had an average restriction of 212 inches of H_2O (cold flow measurement at 100 g/s) {range 13.3-852 inches of H_2O}. [NOTE: For comparison, see the table in figure 11. Here the average restriction for the US in-use test fleet was 8.7 inches of H_2O.]
  - The majority of the Canadian warranty claims occurred when the converter cold flow restriction was between approximately 75 and 375 inches of H_2O. Figure 15 presents cold flow restriction versus odometer reading for the model J-1 warranty parts that were examined.
  - The reddish-brown material was scrapped off of the inlet element face of several catalysts and subjected to analysis. The material was identified as mainly Mn_3O_4 by X-Ray Diffraction (with contamination by $Mn_3(PO_4)_2$ and cordierite support material), and elemental analysis indicated that the scrapings were 68 w% Mn. These observations support the conclusion that the reddish-brown deposit is relatively pure Mn_3O_4 (72.0 w% Mn). One additional Canadian warranty return part was analyzed in a similar fashion, with essentially the same result.
  - Figures 16a through 16d are pictures of catalyst faces illustrating a range of plugging conditions as measured by cold flow restriction. These include a typical US catalyst and three catalysts at varying cold flow measurement at 100 g/s restriction levels of 9.4, 21.0, and 81.7 inches H_2O.

Figure 14 Returned Converter Assembly Analysis for Model J-1

Failure mode	US part count	US % of failures	CAN part count	CAN % of failures
1. Over-Temperature: broken, melted or missing catalyst element(s)	96	50.53	5	2.36
2. Intact with Service Engine Soon light: catalyst elements intact, low OSC[††] or bypass	30	15.7	0	0
3. Manganese oxide Contamination: heavy red deposits on inlet catalyst element face and measured high cold-flow restriction	0	0	199	93.87
4. Mechanical Damage: external/internal damage to converter can	4	2.11	1	0.47
5. Foreign Debris: mechanical wear on inlet catalyst element face	3	1.58	2	0.94
6. Wrong Part: incorrect part returned from Dealership	4	2.11	4	1.89
7. No Trouble Found: converter/catalyst elements intact, OSC[††] OK	53	27.89	1	0.47
Totals:	190	100	212	100

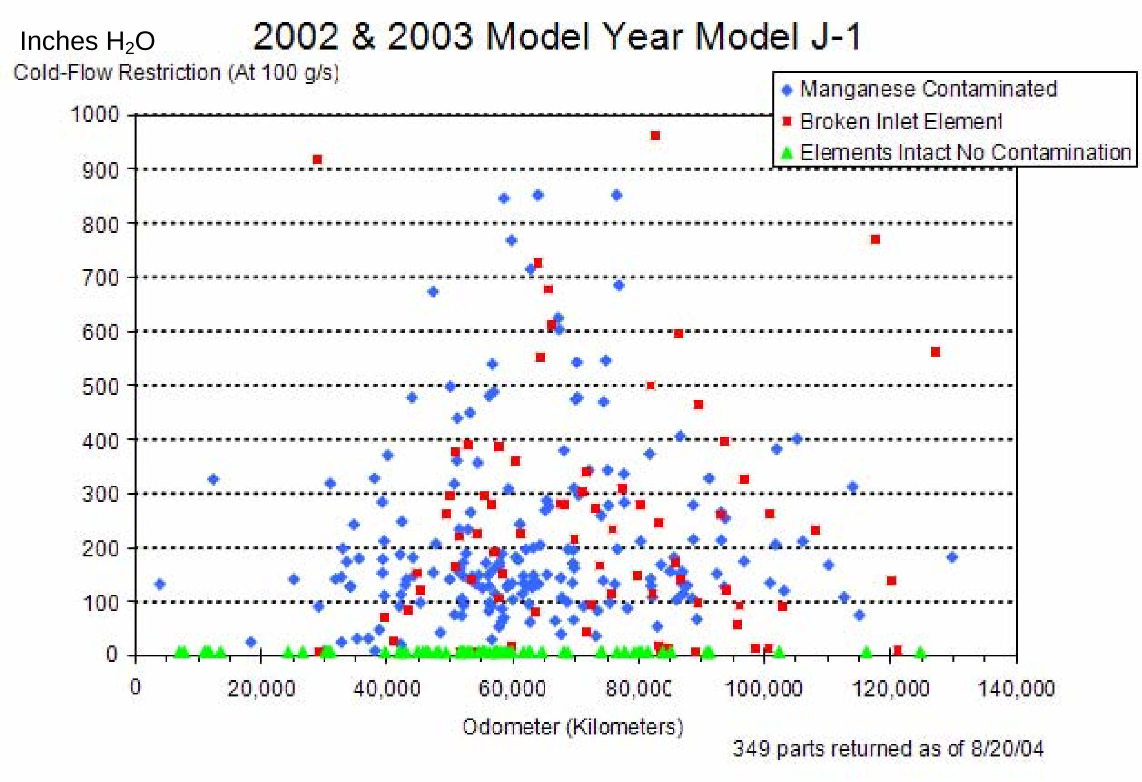
OSC[††] - Oxygen Storage Capacity

NOTE 1: Findings from analysis of US replaced and returned catalytic converters were that primary failure modes were broken inlet catalyst elements, excessive operating temperatures and exhaust system noise with converter intact.

NOTE 2: Findings from analysis of Canadian replaced and returned catalytic converters were the primary failure mode was partial plugging with Mn_3O_4 deposits. Other failure modes as found in the US occurred at similar overall repair rates as in the US.

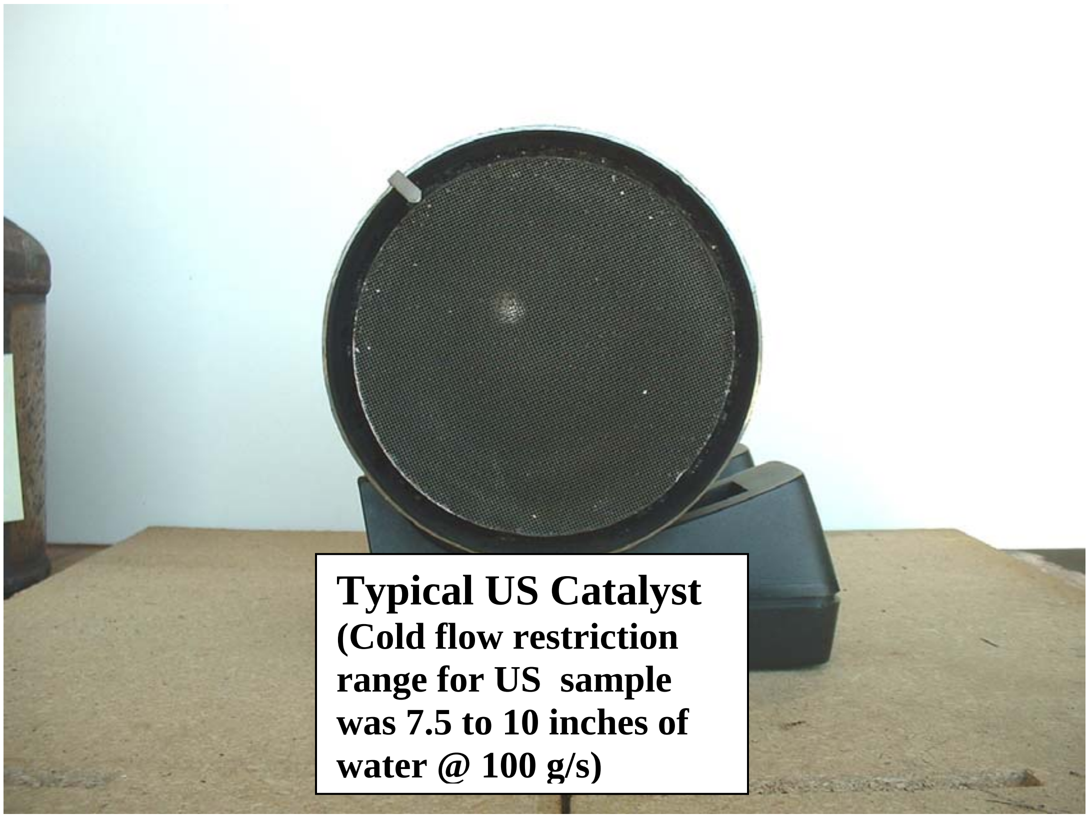
Best Viewed in Color

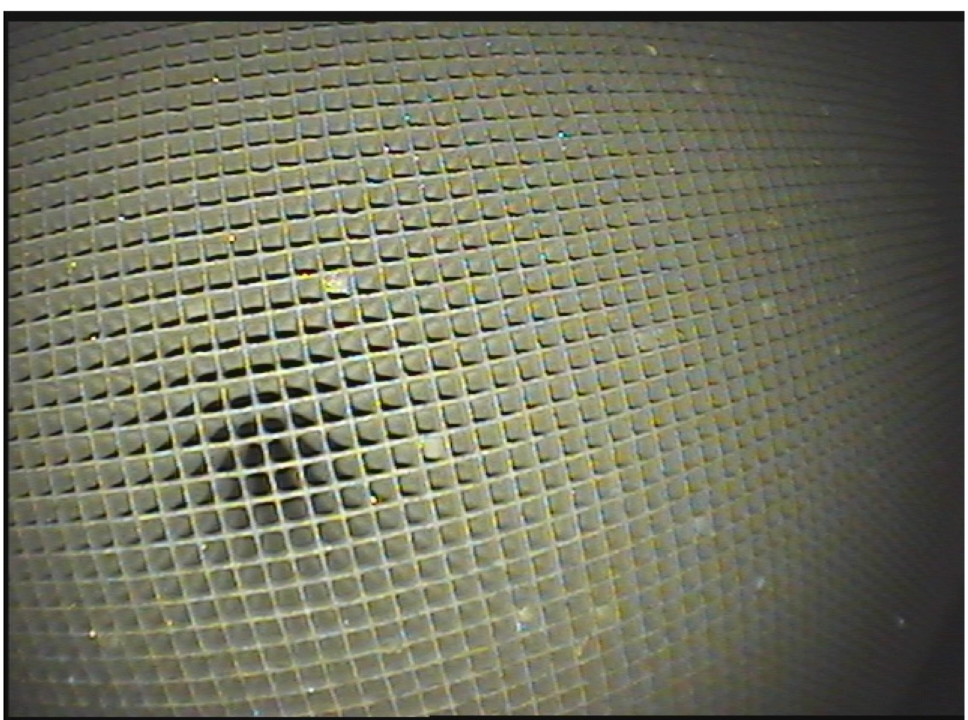
Figure 15 Cold Flow Restriction Model J-1 Warranty Parts



Best Viewed in Color

Figure 16a Photographs of a Typical US vehicle Inlet Element Inlet Face





Best Viewed in Color

Figure 16b Photographs of a Low Restriction (9.4 inches of water @ 100 g/s) Canadian Vehicle Inlet Element Inlet Face

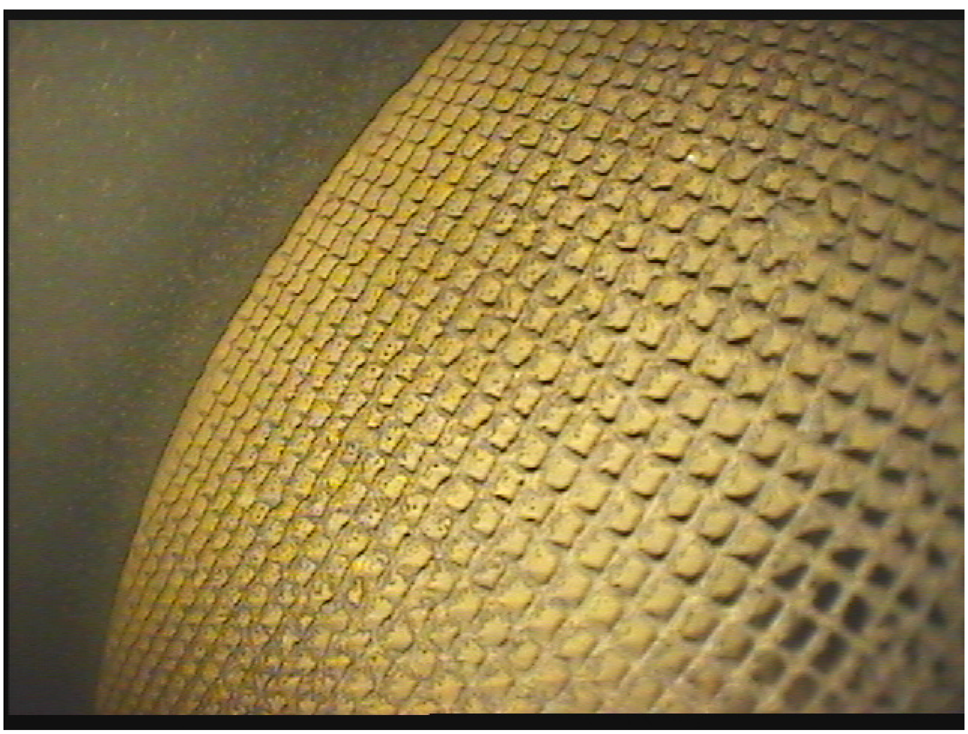
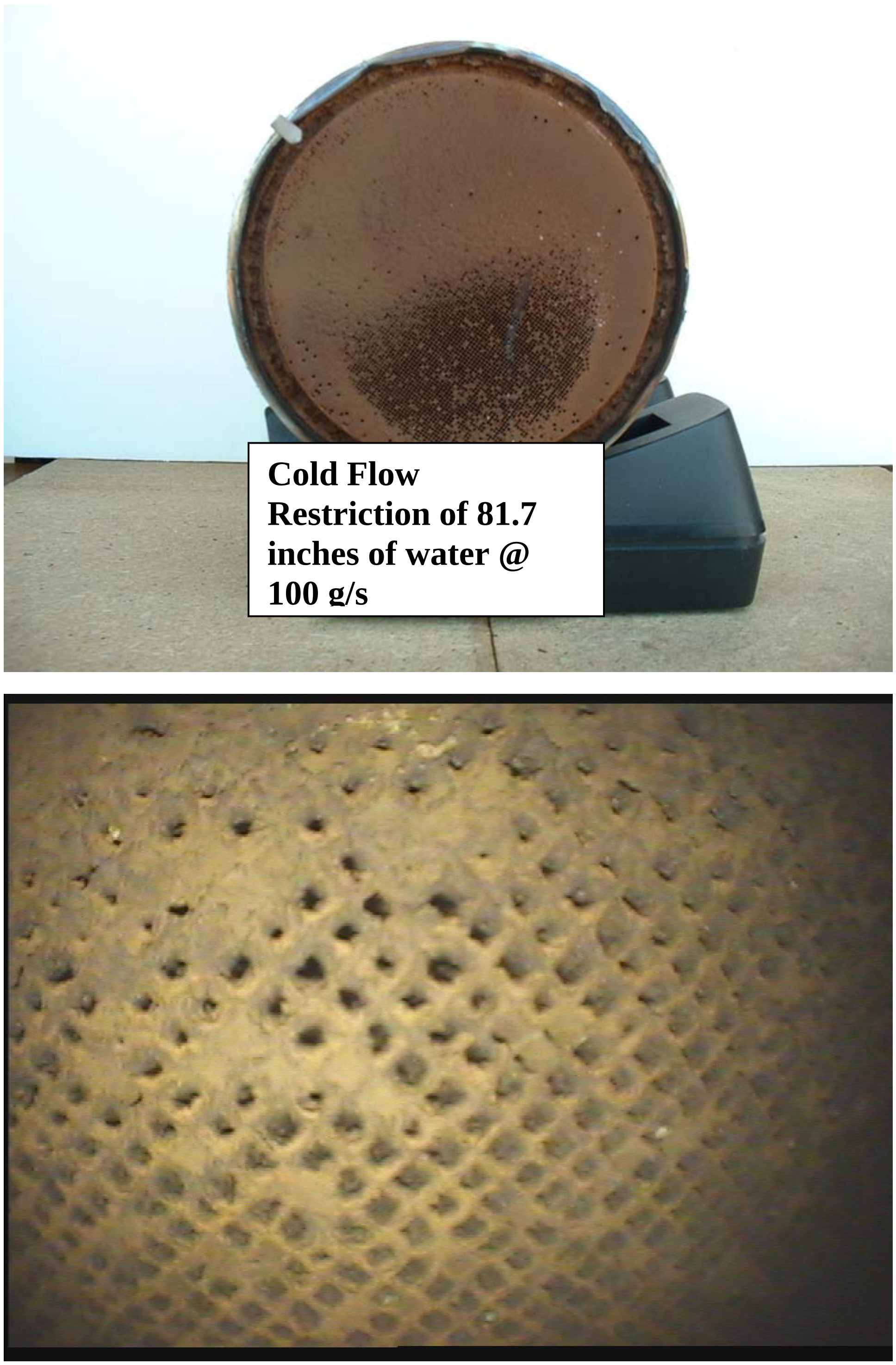


Figure 16c **Photographs of an Average Restriction (21 inches of water @ 100 g/s) Canadian Vehicle Inlet Element Inlet Face**

Best Viewed in Color

Figure 16d Photographs of a High Restriction (81.7 inches of water @ 100 g/s) Canadian Vehicle Inlet Element Inlet Face



- **Analysis of Catalysts from Test Vehicles from the In-Use Test Program for the mid-size SUV (Case #1):**
    - Following the completion of testing, and based on visual examination of the catalyst elements from the US in-use vehicle survey sample, none were contaminated with Mn_3O_4 deposits. Six of the US survey sample converters were analyzed by the supplier for contaminants. The average inlet brick Mn content was found to be a trace amount of 0.04 g Mn / part, and Mn was not found on the outlet elements.
    - Each of the Canadian survey sample converters inlet elements were analyzed for contaminants and the average inlet brick Mn content was found to be 8.6 g Mn / part. 14 of the 24 Canadian outlet elements were also analyzed, and the average outlet brick Mn content was found to be 2.99 g Mn / part. Mn was detected in varying amounts on the face of all catalysts, but in all Canadian cases much greater amounts were found on the faces of any of a sample of catalysts from the U.S. fleet.
    - Canadian converter restriction was correlated with converter Mn content.
    - The other material contaminants that were found in the deposits contained phosphorus (P), calcium (Ca) and zinc (Zn) which are all normal constituents of engine oil. On the inlet element, the amount of P was found to be about 3 times higher on average on the US samples than the Canadian samples and the amounts of Ca, Zn on the inlet and outlet elements and P on the outlet element were found to be nearly identical in quantity on US and Canadian cases. The amount of manganese on Canadian catalysts was found to be significantly higher than the amount of phosphorous on the US samples. Despite the higher amount of P found on the US sample catalysts, no evidence of plugging was found on the US catalysts. In order to limit the potential impact of phosphorous on catalyst performance, the new GF4 engine oil specifications issued in 2005 require that the content of P be maintained between 0.06% and 0.08% by wt.

- **Catalyst Temperatures for Model J-1:**
    - Measurements were made of Catalyst face temperatures experienced by the 2002/2003 version of Model J-1 for which high Canadian warranty catalyst replacement rates were observed.
    - On the US06 driving cycle, peak inlet <u>substrate catalyst bed temperatures</u> observed were about 875ºC. Peak inlet <u>gas temperatures</u> observed were 850 ºC and inlet gas temperatures remained above 700 ºC for the majority of the time on the driving cycle.

- **In-Use Testing of the AWD version of the MY 2003 small wagon (Case #2):**
  - A laboratory emission testing program that involved testing of several in-use Canadian and US model J-2 vehicles was also performed. The program design was similar to but smaller in scale than the program reported above that was run with model J-1. Seven (7) model J-2 vehicles from Ontario Canada and for (4) from the US were tested.
    - The intent was to randomly select customer vehicles being returned from leasing as was done for the model J-1 test program.
    - This approach was successful for the procurement of the 4 US vehicles.
    - But after waiting 3 to 4 months without seeing any off-lease Canadian vehicles, the procurement approach was changed.
    - The changed procurement program involved acquiring employee owned vehicles. An advertisement was published in employee news letters. From this exercise, 12 vehicles from Ontario were identified. Five of these were eliminated due to prior catalytic converter replacement or other reasons including the vehicle owner did not want to participate.
    - As with the model J-1 program, the intent was to look at vehicles that had not yet developed sufficient problems to cause the operator to seek a catalyst or catalyst plugging type repair. Only properly operating vehicles with no OBD codes or major emission system repairs where included in the study; in particular vehicles that had already had a catalyst replacement were excluded from the study.
  - All vehicles were subjected to FTP emissions testing along with catalyst flow testing to determine backpressure. The manifold mounted catalysts from all of the Canadian test vehicles and one of the US test vehicles were examined for elemental analysis of deposits.
  - This vehicle had a manifold mounted front catalyst and a second under-floor down stream catalyst. One downstream catalyst from each group (i.e., Canadian and US) was also examined for deposits.
  - <u>The major conclusions of this work were</u>:
    - For these "no complaint" vehicles, there was no discernable difference in tailpipe-out emissions between the Canadian and US vehicles. [NOTE: Because there was no discernable emissions difference, plots of emissions vs. mileage of the type included above for the model J-1 case are NOT included in this report.]
    - Mn deposits were found on the inlet faces of the manifold catalysts from all of the Canadian vehicles. No Mn was observed on the manifold catalysts from the US vehicles.
    - Mn deposits were also found on the one downstream Canadian catalyst that was analyzed, however the amount was substantially less than what was found on the front catalyst. No Mn was observed on the downstream US catalyst.

        - The average flow restriction on Canada units was 4 times higher than the US vehicles.
        - The Canadian samples clearly demonstrated an increasing restriction with distance traveled while the US samples did not.
        - Analysis of the deposition on the catalyst elements demonstrated that the amount of restriction co-relates with the amount of manganese found on the catalyst substrate.
        - Some mechanical damage was observed on three of the manifold catalysts from the Canadian vehicles. This damage might have been related to the increase in restriction caused by the Mn deposits. The elevated restriction apparently creates enough pressure on the catalyst to cause partial deformation/damage of the substrate as it is forced down the exhaust pipe.

- **In-Use Cat Survey**
    - In an effort to understand the magnitude of the problem with catalyst plugging with manganese oxide, an effort was made to analyze so-called "no apparent problem vehicles" (i.e., vehicles with no known obvious pattern of catalyst plugging exhibited by warranty data) by visually inspecting the frontal face of a number of catalytic converters on five different vehicle models .
        - The vehicles were in-use vehicles located at an off-lease marshalling yard.
        - The inspections were performed in November 2004.
        - Photos were taken using a boroscope inserted through the front oxygen sensor port.
        - Once the photos were taken, four samples were selected as representative of four different ranks of deposit accumulation: no deposits, light deposits, medium deposits and heavy deposits. Using a jury system, a qualitative judgment was then made of the amount deposits on the frontal surface of each catalyst against the reference rankings.
        - Most of the vehicle models selected for the survey did not use HDCC systems. Manufacturer J had limited applications during these model years that employed full HDCC systems. The models selected for this survey represented transitional (i.e., transition from tier 1/NLEV to tier 2 standards) technology where either the catalyst was located in a closer (and hotter) location than the historical under-floor locations and/or a higher than historically normal catalysts density was employed. The point of the survey was to look at supposedly non-problem vehicles. The survey models are described in figure 17 below.
        - Survey models J-4 thru J-7 ended up having sample sizes judged to be large enough to make a reasonable qualitative assessment of the amount of visual plugging evident on the frontal face of the

catalysts. For the fifth case, survey model J-8, only two samples were found during the survey period and one of those was subsequently found to have had its catalytic converter replaced four months prior to the inspection.

- The data provided in Figures 17 and 18 was compiled as of December 2004.

Figure 17 Description of Models Surveyed in the In-Use Catalyst Inspection Project

Survey model	Model Year(s)	Engine/Vehicle Description	Description of Catalyst Configuration
J-4	2001-2	~2 liter I- engine small car	NLEV Certification – Manifold mounted 350 cpsi catalyst
J-5	2001-2	~4 liter V-engine standard SUV	NLEV Certification – 400 cpsi warm-up catalyst located ~30 inches from manifold
J-6	2001-3	~5 liter V-engine truck	Tier 1 Certification – Dual close coupled 400 cpsi catalysts located ~16 inches from manifold
J-7	2001 only	~2.5 liter I-engine medium size car	NLEV Certification – 600 cpsi (i.e., "high density" catalyst located ~24 inches from the manifold. [See note #1.]
J-8	2002-3	~ 2 liter I-engine compact SUV	NLEV Certification – HDCC 600 cpsi catalyst located ~9 inches from the manifold [See note #2.]

NOTE 1: This vehicle could be considered to be one that employed an HDCC system given the high density catalyst was located in a mid-under floor location rather than in a "full under-floor position. However Manufacturer J did not report this in the first section of this report as one of their HDCC designs because it was an old design that was dropped after MY2001 and did not use calibration and light off strategies characteristic of the newer technology need for tier 2 emissions compliance.

NOTE 2: Survey model J-8 used an HDCC system and in fact is the same model that is described in paragraph number 4 in the first section of this report that identifies HDCC vehicles that manufacturer J sold prior to MY2004.

- Figure 18 summarizes the findings of this survey. While there had not been a significant increase in catalytic converter warranty in Canada relative to the US on these specific powertrain configurations, there still was a demonstrable tendency towards visual converter plugging in Canada. Manufacturer J concludes that this visual plugging would, with the continued use of MMT® in the Canadian market, result in increased back pressure to the point where vehicle performance and/or emissions would be impacted to the level that cause customer complaints and require replacement of the converter. Whether this will happen under the 8 year 130,000 km emissions warranty or after that as a customer pay repair is unknown.

Figure 18 Results of In-Use Catalyst Inspection Project

	Observations				
Survey Model	**No deposits**	**Light deposits**	**Medium deposits**	**Heavy deposits**	**Total Samples**
J-4	2	7	8	3	20
	10%	35%	40%	15%	100%
J-5	10	8	2	0	20
	50%	40%	10%	0%	100%
J-6	5	8	0	1	14
	37%	57%	0%	7%	100%
J-7	0	4	10	2	16
	0%	25%	63%	13%	100%
J-8	2	0	0	0	2
	100%	0%	0%	0%	100%

NOTE 3: Odometer data was collected for every vehicle surveyed however there was no apparent pattern to the amount of deposits relative to distance travelled. As it was not possible to determine what concentration or amount of MMT the vehicle was exposed to, the duty cycle the vehicle experienced, nor the servicing the vehicle had received prior to the inspection , Manufacturer J deemed that only qualitative analysis was appropriate for this in-use study.

Summary

In Canada, Manufacturer J experienced significantly higher catalytic converter warranty claims per capita (based on vehicle population) than in the US. This pattern was observed to begin in the years of 2000 to 2002 when Manufacturer J's deployment of Tier 2 like catalyst systems began.

Manufacturer J identified three (3) vehicle configurations where plugging with manganese oxides (primarily Mn_3O_4) has been confirmed. In each these cases, significantly catalysts replacement higher warranty rates were observed. Additionally, when MMT use was phased out in Canada the catalyst warranty replacement rate began to reduce but ratio still remained significantly higher than the US where MMT was not used. In the provinces of Manitoba and Saskatchewan where the use of MMT continued until late 2005, the catalyst warranty replacement rate continued to rise until the MMT phase out began.

Model J-1: The ratio of warranty claims compared to the US where MMT was not used was over 35 times higher at the peak. Random sampling of off-lease vehicles showed that MMT use causes increased exhaust system backpressure due to plugging and increased tailpipe emissions. The phase out of MMT use in Canada resulted in model J-1 warranty rates that began to reduce. Subsequent model years of model J-1 had catalyst warranty experiences that were consistent with model J-1 in the US where MMT is not used.

Model J-2: The ratio of warranty claims compared to the US where MMT was not used was over 37 times higher at the peak. Testing of selected "no reported problem" vehicles which had been operating in Canada demonstrated that the vehicles had increased exhaust system backpressure which resulted in poor vehicle driveability performance. Emissions testing revealed that the Canadian vehicles did not exhibit increases tailpipe emissions but this is due to the unique exhaust system design with two catalysts in series. The reason for the high warranty experience on this vehicle is poor performance due to plugging of the front catalyst with manganese oxides.

Model J-3: Comparison of the 2000 model year with a close coupled catalyst arrangement against the 1999 model with an under-floor design showed an approximately nine (9) times higher catalyst replacement rate. Analysis of replacement catalysts showed high levels of plugging with manganese oxides on the close coupled catalysts.

Other Models: A qualitative evaluation of catalyst plugging was done on five (5) more models sold by Manufacturer J. The visual inspection revealed significant levels of deposits on four of the five models and while there was no demonstrable increase in catalyst warranty relative to the US where MMT was not used,

Manufacturer J concluded that if the use of MMT had continued in Canada, significant numbers of plugging cases would soon be in evidence.

Manufacturer J believes that if the use of MMT continued in Canadian gasoline that the failure rate of the three subject models would increase to levels where most if not all catalysts would require replacement either under warranty or by the customer during the operational life of these vehicles. In addition, Manufacturer J also believes that other "Tier 2 like" technology vehicles would begin to develop symptoms which would require catalyst replacement and that as the deployment of full Tier 2 technology continues from 2004 model year through 2009 model year, other vehicles would also begin to demonstrate catalyst deterioration and plugging due directly to the use of MMT in gasoline.

Best Viewed in Color

Manufacturer K

Use and Experience with High Density Close Coupled (HDCC) Catalyst Systems in the Canadian Market with Exposure to MMT®

Manufacturer "K" Information

High Density Close Coupled (HDCC) Catalysts Used Prior to MY2004:

- Manufacturer K sold several HDCC catalyst equipped vehicle models in Canada prior to MY2004.
    - But for one exception, vehicles sold after MY2002 are not discussed in this report because the experience with these was not pertinent to the MMT exposure issue. These were too new to have accumulated enough mileage before MMT was voluntarily removed from Canadian fuel to have given any meaningful indication whether they would have been affected by exposure to MMT.
    - One notable exception is discussed below for a MY 2003 vehicle that began sales ahead of the normal 2003 MY period. Sales of this vehicle began in January 2002 whereas sales of typical MY 2003 vehicles began in the fall of 2002. Hence these vehicles had a potential exposure to MMT use closer to that of a 2002 MY vehicle than that of a typical 2003 MY vehicle.

- The table in Figure1 below describes the vehicles that were sold prior to MY2003 that used close coupled catalysts having high density (600 cpsi or greater) ceramic catalysts.

  [NOTE: The table does not include two additional models that used HDCC metallic catalysts as these were designs that were being phased out.]

Best Viewed in Color

Figure 1

MY	Vehicle Type	Engine (Rounded To nearest Whole Liter)	Cat Location	Cat Substrate	Wall thickness (micro-meter)	cpsi	Engine Displacement Divided by Total "front" Catalyst volume (liter per liter)	Cat Diameter (mm)
01	SUV	~2 L I4	CC (dual)	Ceramic	75	600	1.18	93
01	SUV	~2 L I4	CC (dual)	Ceramic	75	600	1.41	93
01	Passenger Car	~4 L V*	CC (dual)	Ceramic	50	900	2.46	103
02	Passenger Car	~2 L I4	CC	Ceramic	75	600	2.22	103

- The early introduction MY2003 vehicle mentioned above was sold in both a front wheel drive (FWD) and four-wheel drive (4WD) model. It is described below as two different models because addition of the 4WD system created packaging constraints that required a different catalyst design and exhaust pipe routing that appeared to affect the sensitivity of the system to catalyst plugging when exposed to MMT. Both Models used an ~2 liter I4 engine and close coupled 600 cpsi ceramic catalyst having a 75 micrometer wall thickness; however there were differences in the catalyst size and location. Both models were certified to the NLEV-LEV emissions standards.
    - The 4WD model will be referred to as Model K-1 throughout the remainder of this report. Because of the packaging constraints this model used a smaller catalyst located closer to the engine than the FWD model.
        - The catalyst inlet face was located 17 cm downstream of the exhaust port.
        - The ratio of the engine displacement divided by the catalyst volume was 3.77 liters per liter.
        - The catalyst diameter was 80 mm.
        - The exhaust flow passage in the catalyst for this model had a sharper bend causing the flow to impact the catalyst face at a greater angle than the FWD model.
    - The FWD model will be referred to as Model K-2 throughout the remainder of this report.
        - The catalyst inlet face was located 44 cm downstream of the exhaust port.
        - The ratio of the engine displacement divided by the catalyst volume was 2.06 liters per liter.
        - The catalyst diameter was 103 mm.

<u>Experience w/MMT Plugging</u>:

- There was no obvious elevation in catalyst warranty claims on any of the vehicle models listed in figure 1. As a result, no investigations or inspection of catalysts were performed with these vehicles to determine if there were any signs of manganese oxide deposits beginning to occur. Hence, there is no information about the potential long term sensitivity of any of these vehicles to manganese oxide plugging. All that is known is that no significant pattern of plugging began with any of these vehicles during the limited time and mileage that they were exposed to fuel containing MMT.

- Elevated catalyst warranty claims were observed on model K-1. For this model, all catalysts replaced under warranty regardless of reason or customer complaint were inspected. Visual inspection confirmed that the primary reason for higher warranty rates in Canada where MMT had been used compared to the USA where MMT had generally not been used was due to plugging with manganese oxide.

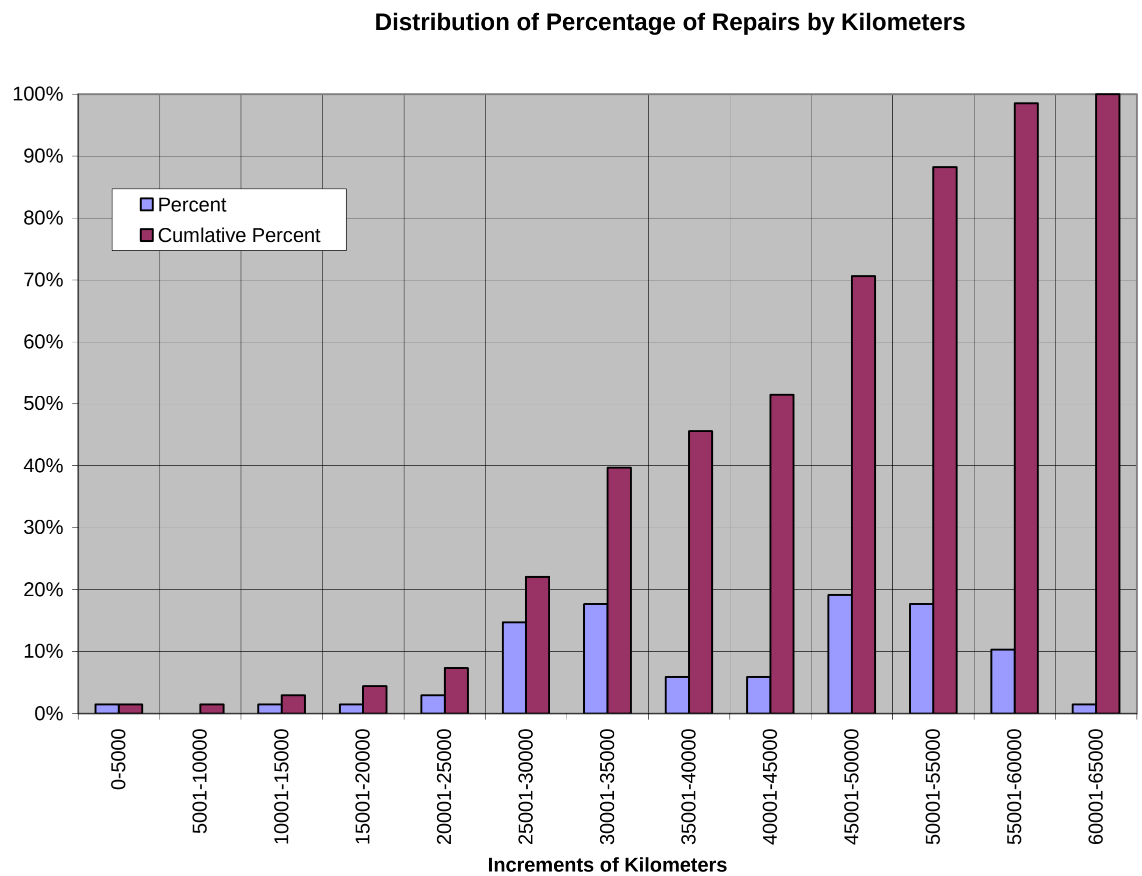
.

  - Manufacturer K chose a conservative measure to determine which catalysts were clearly replaced due to MMT related plugging and which might have been replaced due other failure mechanisms
  - A catalyst was recorded as being plugged if it was plugged at least 70% based on visual inspection. Catalysts plugged to a lesser degree where considered as <u>possibly</u> having been replaced due to reasons other than MMT related plugging.
  - The mileage range for 70% plugging was observed to occur roughly between 20,000 and 60,000 km. There were a few cases that occurred earlier but the frequency of failure increased noticeably at and beyond the 20,000 km range.
  - A distribution of plugging (at the 70% level or greater) versus kilometers appears below as Figure 2.

Best Viewed in Color

Figure 2

Catalyst Repair Analysis for Model K-1



NOTE: Only catalysts that were plugged 70% or more were counted in this analysis. Of this data set, over 80% of the catalysts had more than 90% of the inlet surface area plugged (based upon visual inspection) with deposits verified to be predominantly manganese oxide. Catalyst repairs included in this analysis occurred between November 2002 and October 2003.

NOTE: The analysis in Figure 2 applies only to Canadian warranty repairs. However, there were no plugging cases observed in the USA during this analysis period.

- Sample pictures of a catalyst from the Canadian market and from the US market at comparable mileages are shown below in Figure 3.   The picture of the Canadian catalyst was selected to illustrate the appearance of an approximately 70% plugged catalyst.
- Deposits on the plugged Canadian catalyst in Figure 3 were determined via XRD analysis:
  - Mn: 52-59wt%, P: 1-3wt%.
  - Composition mainly Mn_3O_4 but partly $Mn_3(PO_4)_2$.
- Warranty records indicated that the Canadian market catalyst shown in Figure 3 was replaced on a vehicle brought in for service with a customer complaint of "low power." The customer's fuel usage practices were recorded as "regular, any brand."

Figure 3 - Model K-1 HDCC Catalyst

Future Technology Plans:

- All vehicles certified to Tier 2 Bin 5 or more stringent standards will be equipped with high density (600 or 900 cpsi) close coupled catalysts in the foreseeable future.
- Lower cpsi leads to lower catalytic performance, are less cost effective, and result in larger catalysts which are difficult to use due to packaging design constraints.
- Metallic catalysts have been used on a small number of vehicles but this is not being done for new vehicles because new technology ceramic catalysts are more durable.

Emission Testing and Mechanism Analysis:

- **Track Testing:**
    - Three test vehicles were run on a track using gasoline with MMT added at a concentration of 18mg/L. One test vehicle was run from each of the following models:
        1. Model K-1 - the 4WD version where plugging had been observed in the market.
        2. Model K-2 - the FWD version of this same vehicle body style.
        3. Another FWD vehicle model that used the same power train and catalyst configuration as the above FWD version but which had a different body style configuration.
    - The vehicles were driven at essentially constant speed at 150Km/hr for most of each day stopping only for the night shift and for fueling stops.
    - Test vehicle #1 (Model K-1) above plugged @16,000 Km.
    - Test vehicles #2 and #3 (the FWD configurations) were run to 100,000 Km. At the end of the test, the catalysts were observed to be coated with Mn oxide but no individual cells were completely plugged.
    - Emissions were not measured on these track test vehicles - only degree of plugging was monitored.
    - See figure 4 for a picture of the plugged catalyst for test vehicle #1.

Best Viewed in Color

Figure 4

Model K-1 Track Test

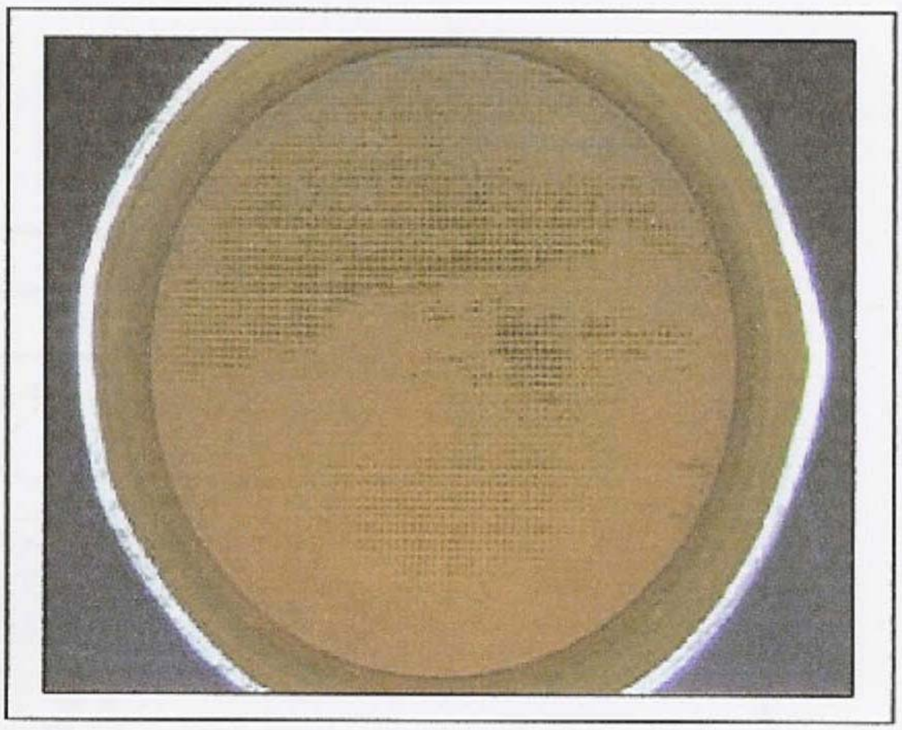
Vehicle test
Mileage: 16,000 km
Fuel : MMT(Mn:18mg/L)

Best Viewed in Color

- **Engine Dynamometer Testing**
  - A model K-1 engine with a production configuration 600 cpsi close coupled catalysts was subjected to dynamometer testing at high, constant load with throttle changing mode.
  - MMT concentration: 36 mg/L
  - The catalyst plugged after 17 hours of operation.
  - Analysis of deposits: Mn: 70wt%
  - Mn_3O_4 was the cause of plugging
  - See figure 5 for a picture of the plugged catalyst from this test.

Figure 5

Model K-1 Dynamometer Test



Engine dynamometer test
Aging : 17hrs
Fuel : MMT(Mn:36mg/L)

- **Emissions Testing**

  - Only very limited emissions testing was performed.
  - Emission testing was done using one plugged Canadian warranty return catalyst. The catalyst was approximately 90% plugged based upon visual inspection.
  - CO emissions were approximately six times the standard whereas HC and NOx levels were still under the standards.

- **Plugging Mechanism**

  - Temperature Considerations
    - Based upon unpublished internal research and supported by work published by others, Manufacture K believes it is critical to keep the temperature below 790 to 810°C "brick temperature" (i.e., the temperature measured in the middle of the catalyst brick). At temperatures above this threshold manganese oxide accumulation accelerates. [NOTE: Brick temperature tends to run higher than catalyst face temperature. Hence, this 790 to 810°C brick temperature range is generally consistent with the threshold reported by others suggesting this critical threshold occurs around 700°C just ahead of the catalyst face.]
    - Only peak temperatures were available for LA#4, US06, and SC03 cycle testing. These did not show significant operating temperature differences between models K-1 and K-2. However, model K-1 was confirmed to run hotter during cruise conditions. See Figure 6 for the peak temperatures and Figure 7 for cruise temperatures.

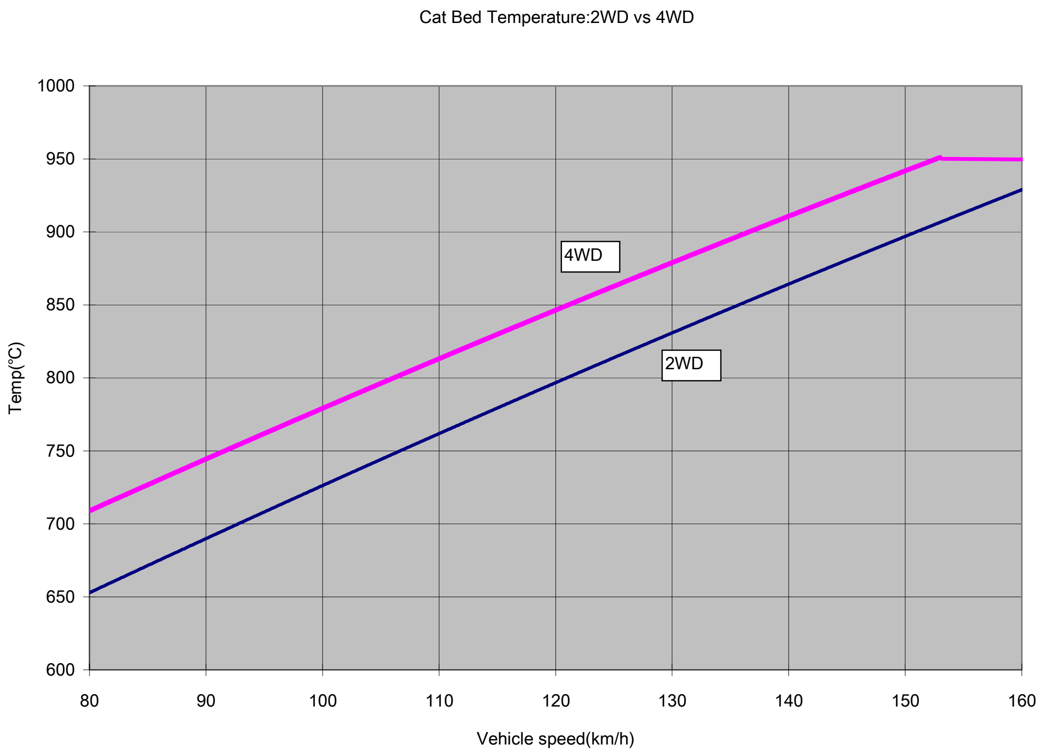
Figure 6

Peak Catalyst Brick Temperatures on Various Test Cycles for Models K-1 and K-2

	Model K-2 (FWD)	**Model K-1 4WD**
LA#4	839°C	828°C
US06	930°C	945°C
SC03	810°C	818°C

Figure 7

Difference in Catalyst Bed Temperature for the Model K-1 (4WD) and Model K-2 (FWD) at Cruise Conditions.



- Manufacturer K believes that plugging that was observed in the market with model K-1 had a higher tendency to plug than Model K-2 because of a compound set of conditions:
  - Higher temperatures during some in-use operations that are inherent to the 4WD design.
  - Smaller catalyst (had to be smaller due to packaging constraints).
  - Sharper angle of incidence of the exhaust flow at the catalyst face (also due to packaging constraints).
  - Catalyst located closer to the engine exhaust ports (also due to packaging constraints).

- Summary comments regarding the plugging mechanism:

  - The critical parameters are:
    1. Temperature: higher temperature encourages plugging.
    2. Exhaust gas flow: slant flow to the wall of the catalyst helps plugging.

3. Cell density: higher cpsi boosts plugging, although plugging can occur with 400 cpsi catalyst.

- Plugging mechanism is:
  1. Physical (adhesion of Mn-compounds).
  2. Still investigating the possibility of chemical mechanisms (chemical reaction of MN-compound) - however, to date it appears the process involves predominantly physical adhesion.

Best Viewed in Color

Manufacturer L

Use and Experience with High Density Close Coupled (HDCC) Catalyst Systems in the Canadian Market with Exposure to MMT®

Best Viewed in Color

Manufacturer "L" Information

High Density Close Coupled (HDCC) Catalysts Used Prior to MY2004:

- In MY 2001, two HDCC packages were sold in Canada as well as in the USA. These were:
  - Model L-1:
    - ~2 liter I4 engine
    - Single 600 cpsi close coupled catalyst with 4.3 mil wall thickness.
    - Certified to NLEV/LEV standards.
    - The catalyst was mounted to the manifold as shown in figure 1.

Figure 1
Catalyst Mounting Configuration for Model L-1 (I4 engine)

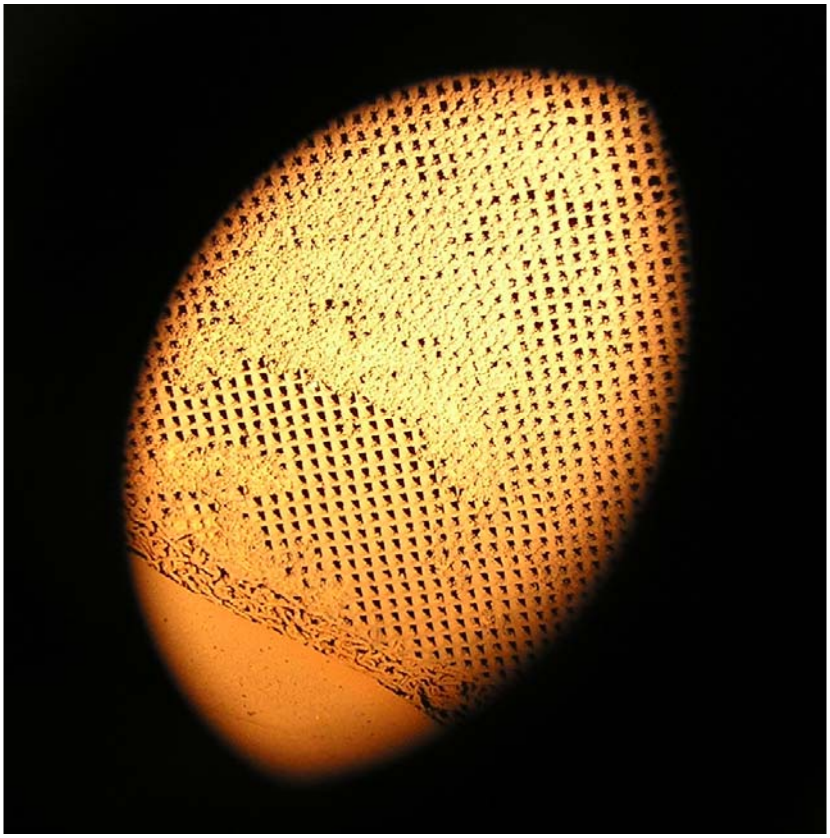
- Model L-2:
  - ~3 liter V6 engine
  - Close coupled 600 cpsi catalysts with 4.3 mil wall thickness on each side of the V engine. There was no down stream catalyst.
  - Certified to NLEV/LEV standards.
  - One catalyst was mounted on each side of the V engine as shown in figure 2.

Figure 2
Catalyst Mounting Configuration for
One Bank of Model L-2 (V6 engine)

Experience with Catalyst Plugging:

- Manufacturer L did not observe any plugged catalysts identified by customer complaint warranty cases.
- Several Canadian In-Use Catalysts from MY 2001 vehicles were inspected by arranging to locate the vehicles through cooperating dealers.
- Four vehicles were inspected as described below:
    - One 2001 Model L-1 with the I4 engine was inspected.
        - This vehicle had accumulated about 35,000 miles.
        - It was procured from St. Albert, Alberta, Canada.
        - The catalyst showed significant beginnings of plugging, but not yet enough plugging to cause driveability issues.
        - A photograph of the partially plugged catalyst is shown in figure 3.

Figure 3
Partially plugged catalyst found on Model L-1



- Three Model L-2 vehicles with the V6 engine were inspected.
  - Two of these were coated with manganese oxide. Significant plugging was not observed but there were signs that plugging was beginning as a few cells were plugged with other cells being partially blocked.
  - These vehicles had accumulated 30,000 and 38,000 miles respectively.
  - Pictures of these two catalysts are shown in figure 4a and 4b.

Figure 4a
In-use Catalysts from Model L-2 with V6 engine
Sample from East St. Paul, Manitoba with 30,000 accumulated miles

Figure 4b
In-use Catalysts from Model L-2 with V6 engine
Sample from Edmonton, Alberta with 38,000 accumulated miles

Best Viewed in Color

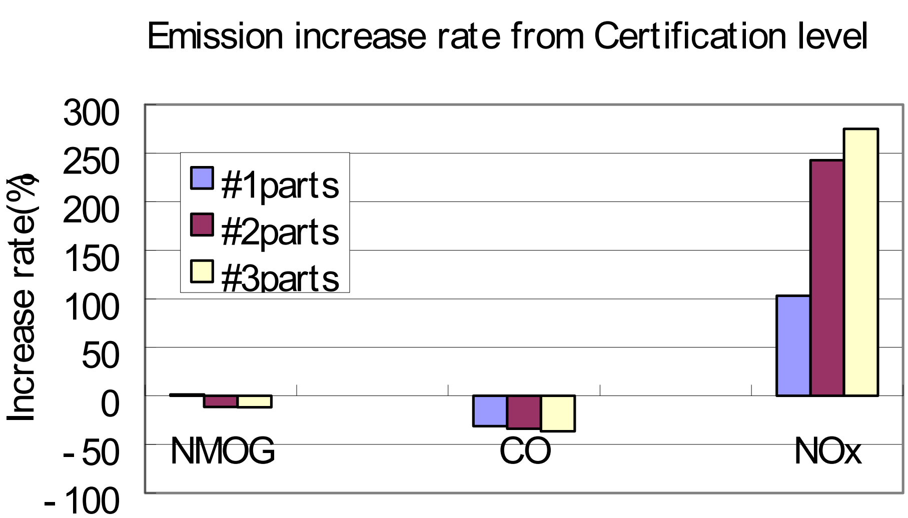
Future Technology Plans:

- All Tier 2-Bin 5 certified vehicles use and will continue in the foreseeable future to use high density close-coupled (HDCC) catalysts.

Emission Testing and Mechanism Analysis:

- Figure 5a and 5b summarize the results of emission testing performed on three different in-use catalysts procured from Model L-2 V6 discussed above (none of which had yet become significantly plugged). Figure 5a compares the emissions to certification values. Figure 5b provides the actual emission data.
    - o Catalytic converter performance was close to certification levels for NMOG and CO emissions, but not NOx emissions.
    - o NOx emissions were significantly higher than their certification levels, although still within the standards.

Figure 5a
Comparison of Emission Test Results with Certification Levels on 3 In-Use Model L-2 Catalysts from the Canadian Market



NOTES: All emission tests were single tests (i.e., not averages of multiple tests.)

Figure 5b
Emission Test Data on 3 In-Use Model L-2 Catalysts from the Canadian Market

Converter	#1	#2	#3	
Mileage	48042	38000	61213	Km
	30026	23760	38268	Miles
Emission Results in grams per mile				Standard 50K/100K
NMOG	0.041	0.034	0.038	0.075/.090
CO	0.537	0.47	0.557	3.4/4.2
NO	0.05	0.077	0.103	0.2/0.3

- A vehicle was driven on the road in a durability style test. Emissions were measured at 30,000 and 50,000 miles.
  - The test vehicle was a MY 2004 vehicle with a ~4 liter V6 engine. This was a different vehicle and engine than model L-2 but it had a similar catalyst layout. This vehicle was certified to Tier 2 Bin 5 standards whereas model L-2 was certified to NLEV/LEV standards. (For reference purposes the model represented by this test vehicle is designated as model L-3.)
  - Mileage was accumulated on real roads using gasoline containing 17mg/L MMT.
  - A single vehicle was driven on a predetermined driving route. This route consisted of a combination of high/medium/low speeds in city/suburban/highway conditions. Multiple routes were driven per day, 6 days a week.
  - At 50,000 miles both catalysts were significantly plugged, although not yet plugged enough to cause a drivability issue. Pictures of the two catalysts at the end of the test are shown in figures 6a and 6b.

- Deposits were confirmed to be manganese oxide.
- Figure 7 shows the result of emissions testing at 30,000 and 50,000 miles.

Figure 6a

Picture of the Back (or Right*) Catalyst from the MY 2004 Road Test Vehicle (Model L-3) with V6 Engine after 50,000 Mile Road Test.

*[NOTE: The engine is transverse mounted by rotating it clockwise. Therefore the "back" catalyst is the one on the side of the engine next to the firewall, which is also the right side of the engine.]

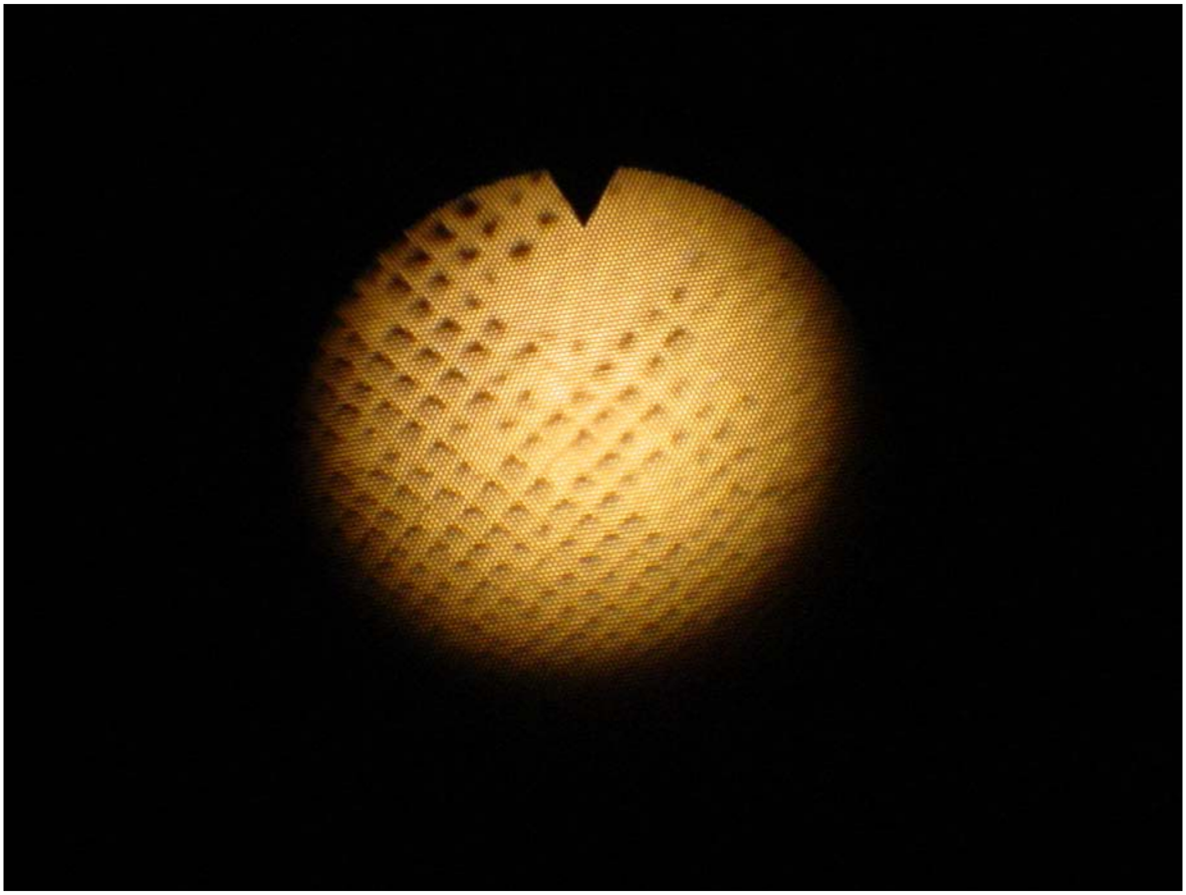


Figure 6b

Picture of the Front (or Left*) Catalyst from the MY 2004 Road Test Vehicle (Model L-3) with V6 Engine after 50,000 Mile Road Test.

*[NOTE: The engine is transverse mounted by rotating it clockwise. Therefore the "front" catalyst is the one on the side of the engine closest to the front of the vehicle, which is also the left side of the engine.]

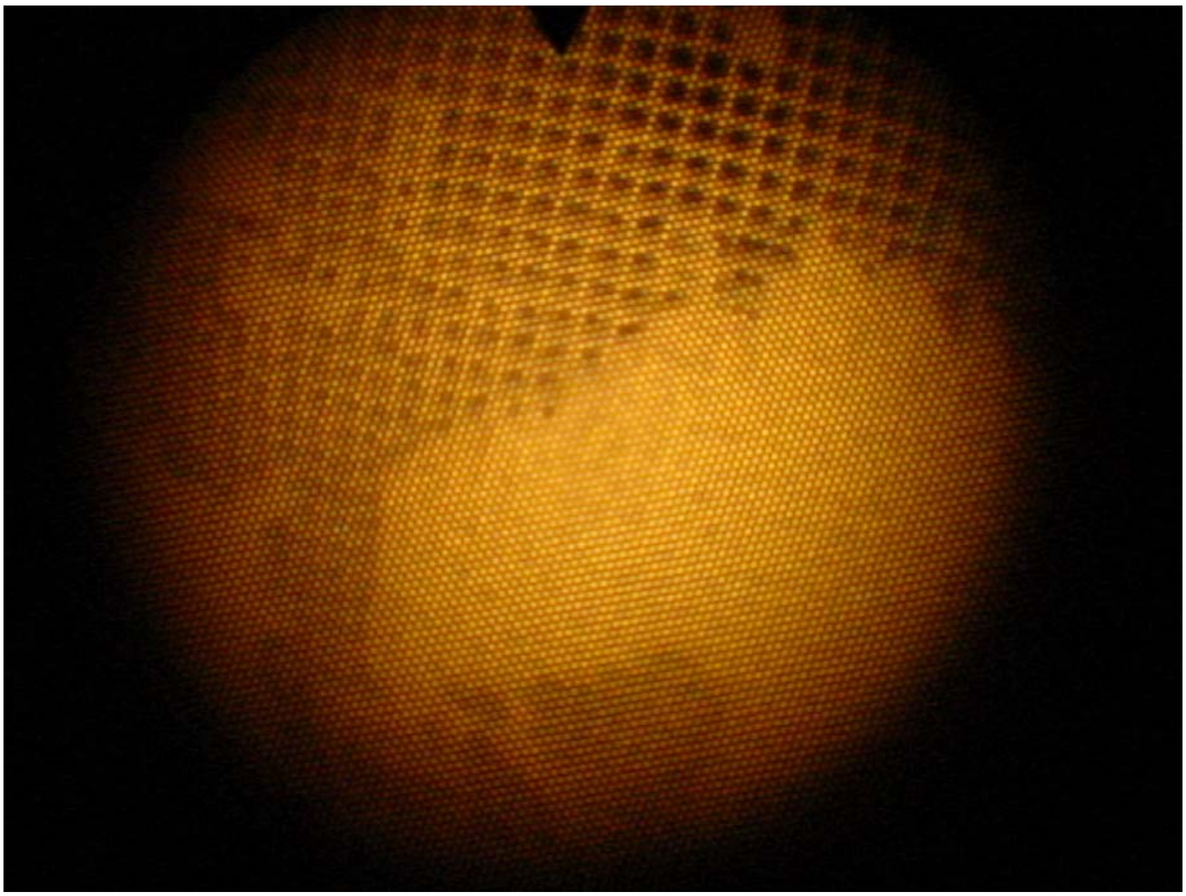
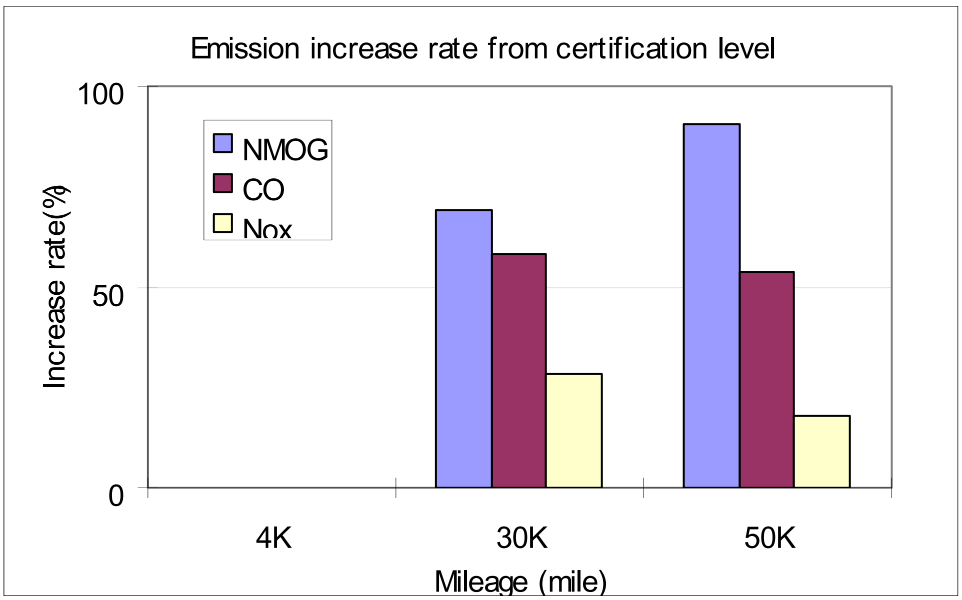


Figure 7
Emissions from Road Durability Test (Model L-3)
Compared to Certification Levels*

*** [NOTE: Emissions are expressed as % change from interpolated emission levels at the 30,000 and 50,000 miles derived from certification durability testing.]**



NOTE: All emission tests were single tests (i.e., not averages of multiple tests.)

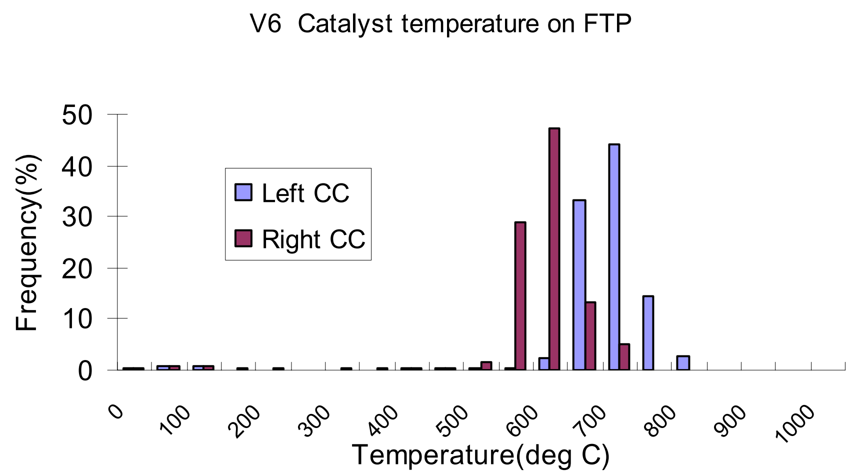
- Note that emissions trends differed from the in-use catalysts removed from MY 2001 model L-2 NLEV/LEV certified vehicles (see figure 5a) compared to that observed with the MY 2004 model L-3 on-road test vehicle (see figure 7). The in-use catalysts were coated with only a few cells plugged. These exhibited elevated NOx and no effect on NHMC or CO. Whereas the 50K mile road tested catalyst, which had appreciable plugging, exhibited a greater increase in NMHC and CO with a much lower affect on NOx. Again, as noted on the graph, the emissions increases are expressed as the percentage change compared to interpolated emissions levels derived from official certification durability testing.

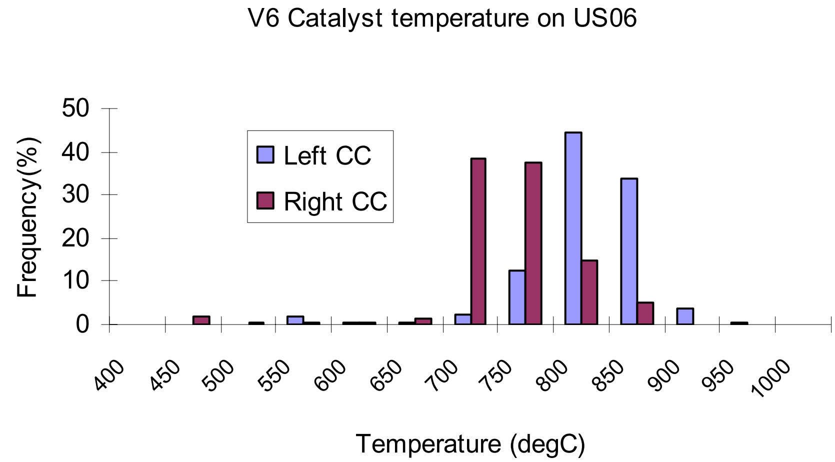
- FTP and US06 "pre-catalyst" temperature profiles for the MY 2004 road test vehicle with the V6 engine are shown in figure 8. [Note: The temperatures shown in figure 8 were measured using a physically different vehicle but of the same model year and configuration as the road test vehicle.] Other manufacturers have identified 700°C as the approximate threshold

Best Viewed in Color

where manganese oxide accumulation begins to accelerate. Figure 8 shows that the US06 temperatures substantially exceed this threshold whereas the FTP distribution is more centered on this threshold.

Figure 8
FTP and US06 "Pre-Catalyst" Temperature Distributions
For Model L-3





[Note: The "right" catalyst, also described in figure 6b as the "back" catalyst is the one on the side of the engine facing the vehicle firewall. The "left" catalyst is then the catalyst on the side of the vehicle closest to the front of the vehicle. The right catalyst was located 191 mm from the manifold and the left catalyst was 105 mm from manifold. As would be expected, the closer of the two catalysts exhibited the higher temperatures.]

Best Viewed in Color

Manufacturer M

Use and Experience with
High Density Close Coupled (HDCC)
Catalyst Systems in the Canadian Market
With Exposure to MMT®

Best Viewed in Color

Manufacturer "M" Information

High Density Close Coupled (HDCC) Catalysts Used Prior to Model Year (MY) 2004:

The following summarizes which products Manufacturer M sold in Canada for MY 2001 thru 2003 with either close coupled or mid-under floor catalysts.

- Manufacturer M's first high density close coupled configuration was on a MY 2001 passenger car with a 4 cylinder engine under 2 liters. **Subsequent references to this model in this report will refer to it as model M-1.** This was certified to ULEV standards. The catalyst was a very close coupled 600 cpsi (0.110mm or 4.3 MIL wall thickness) ceramic catalyst directly coupled to the exhaust manifold. This close coupled configuration was very similar to what was used in prior model years, however, before MY 2001, a 400 cpsi catalyst was used and the shape and material of the manifold was different even though the distance from the exhaust ports to the catalyst face was about the same.

- All other Manufacturer M packages for MY 2001 using high density (600 cpsi) catalysts had the catalyst in a full under floor location. [NOTE: Manufacturer M had used 600 cpsi catalysts on a number of vehicles prior to MY 2001 dating back as far as MY 1998; however all of these also used full under-floor designs.]

- In MY 2002, Manufacturer M sold a SUV with a 4 cylinder engine in 2 to 3 liter range. It used a dual bed catalyst mounted in an "under toe board" or "mid-under floor" location. **Subsequent references to this model in this report will refer to it as model M-2.** Both beds were high density catalysts (600 cpsi). Wall thickness of the front brick was 0.110mm (or 4.3 MIL). This vehicle was certified to tier 2 bin 5 standards. For this vehicle, the catalyst was as close to the engine as some larger vehicles that used "close coupled" catalysts located in their correspondingly larger engine compartments. Hence, for all practical purposes, this application is considered to be a HDCC system, even though the catalyst is not located in the engine compartment. Manufacturer M sold several other vehicles that also used mid-under floor catalysts similar in design to this vehicle. However, the main distinguishing factor was that the exhaust stream was directed into the catalyst for this vehicle at a relatively sharp angle (because of packaging constraints) whereas the other mid-under floor designs (discussed below) had the exhaust inlet tube oriented relatively perpendicular to the catalyst face.

- Manufacturer M sold two additional vehicle models in MY 2002 with high density catalysts located in the mid-under floor location. Both had approximate 2 liter 4 cylinder engines and used a dual brick catalyst. The cell densities for the one vehicle were 600 cpsi for the front and 600 cpsi for the rear brick (with the wall thickness of the front brick being 0.110mm or 4.3 MIL). **Subsequent references to this model in this report will refer to it as model M-3.** The cell densities for the other were 900/400 (with the wall thickness of the front brick being 0.064mm or 2.5 MIL). **Subsequent references to this model in this report will refer to it as model M-4.** Both of these were certified to tier 2 bin 5 standards in MY 2002. As discussed above, the catalyst general location was similar to the above small SUV2002, however the exhaust inlet tube was oriented relatively perpendicular to the catalyst face.

- In MY 2003, Manufacturer M had a number of HDCC equipped vehicles certified to tier 2 bin 5. [NOTE: Certification to tier 2 bin 5 was voluntary for MY2003. Certification to this level was not required by regulation until MY2004.] These early tier 2 bin 5 vehicles were:
  - Model M-2 which was tier 2 bin 5 certified in MY 2002 continued essentially unchanged into MY 2003.
  - Models M-3 and M-4 which were tier 2 bin 5 certified in MY 2002 continued essentially unchanged into MY 2003.
  - A second small SUV with a 4 cylinder engine in the 2 to 3 liter range was certified to tier 2 bin 5 using a 900/600 mid under floor catalyst (wall thickness 0.064mm for front brick). **(Refer to this as model M-5.)**
  - An intermediate size passenger car using a 4 cylinder engine in the 2 to 3 liter range also used a 900/600 mid under floor catalyst (wall thickness 0.064mm for front brick). **(Refer to this as model M-6.)**
  - The same intermediate size passenger car powered by a V6 engine used a 900 close coupled catalyst on each exhaust bank followed by a 350 single catalyst under the floor (wall thickness 0.064mm for front brick). **(Refer to this as model M-7.)**
  - A larger size SUV with a V6 engine used similar catalyst architecture as the above passenger car. It used a 900 close coupled catalyst on each exhaust bank followed by a 350 single under floor catalysts (wall thickness 0.064mm for front brick). **(Refer to this as model M-8.)**
  - Additionally, model M-1 was continued into MY 2003 but at a less stringent standard than tier 2 bin 5.

Experience w/MMT Plugging:

Manufacturer M has had two models exhibit a significant frequency of MMT plugged catalysts.

[NOTE: Here "significant frequency" means having enough warranty repairs that were confirmed to be related to MMT plugging to identify a pattern of plugging rather than simply observing a few isolated plugged catalysts.]

- **Manufacturer M's first model that exhibited plugging was model M-1**, the MY 2001 through 2003 passenger car that used a manifold mounted high density catalyst.

  - This vehicle was a high sales volume vehicle, so even a relatively low initial catalyst failure rate became quite noticeable early.
  - Higher catalyst warranty replacement rates were noted in Canada compared to the USA especially for the automatic transmission version of model M-1. Follow up inspection of catalysts replaced under warranty confirmed that a major portion of the difference in Canadian and USA warranty repair rates was due to MMT caused plugging of Canadian catalysts. Such plugging was not observed in the virtually MMT-free USA, except in one isolated region of the U.S. where MMT

continues to be evident (Four Corners area of the U.S.; Northwest New Mexico, fuel stations supplied by Giant Industries). However, the analysis of the catalyst warranty replacement history for this vehicle was complicated because there was another failure mechanism that also contributed to the higher Canadian warranty rate that was not MMT related.

- This other failure mechanism was due to a cracking of the cast iron exhaust manifold that resulted in noticeable noise complaints from vehicle operators. The catalytic converter and the exhaust manifold were integrated together as one unit in the exhaust system, so to remedy the noise problem and the cracked manifold, the catalyst was also replaced when servicing the manifold.
- Varying levels of manganese oxide deposits were often evident on catalysts replaced as a result of the manifold failure; however, there is no known specific relationship between the cracking in the manifold and formation of manganese oxide deposits.
- Manufacturer M established a program where all replaced catalysts were returned by dealers to the manufacturer for inspection. Analysis of this inspection data clearly shows that MMT related plugging was a major contributor to the higher overall catalyst warranty repair rate observed in Canada. More details on the scope and approach for the catalyst inspection program are discussed later in this report.

[NOTE: Because there was more than one reason for the higher Canadian warranty rate for this case, it would not be appropriate to simply divide the Canadian warranty rate by the USA rate and claim that the "X-times" ratio was completely attributable to MMT related plugging.]

- The manual transmission version of this vehicle did not appear to have as high a warranty repair rate attributable to MMT. Inspection of warranty return catalysts confirmed this difference. Plugged catalysts were found on the manual transmission version. But the warranty repair rate was not high enough to allow a conclusive analysis.

    - The lower plugging sensitivity with the manual transmission vehicle could be a temperature effect. A manual transmission vehicle would be expected to operate at lower temperature than a comparable automatic transmission vehicle. There are at least two reasons for this. One is that with the manual transmission, the driver tends to seek a lower gear under higher load situations causing the engine to work less hard. The other is on decelerations the manual does not return to idle unless the clutch is depressed. This can lead to an engine pumping situation that could contribute to catalyst cooling. It has been noted in literature published elsewhere that high exhaust temperature is one of the critical parameters that can aggravate MMT related plugging.
    - The analysis of warranty rate information that follows concentrates on the automatic transmission vehicle. Comparable warranty rate charts are

not included for the manual transmission because the results are less conclusive.

[NOTE: The focus on only the automatic transmission version does not mean there wasn't an MMT related problem on the manual transmission vehicle. Keep in mind that MMT was removed from the bulk of the Canadian fuel supplies by the spring of 2004. Many vehicles in this 2001 MY fleet simply did not have enough mileage exposure to reach their plugging mileage threshold. The greater plugging sensitivity of the automatic version caused its warranty trends to start to show up at lower mileages, before MMT was removed from the fuel. Had MMT stayed in the fuel longer, the manual transmission vehicles would have been expected to exhibit increased plugging rates at higher mileages.]

- An analysis of plots of warranty occurrence ratio* versus time in service for the automatic transmission vehicle version illustrate several important trends. Because of the highly confidential nature of warranty rates, these plots are shown with the vertical scale removed.

  *[NOTE: **Occurrence ratio** is the total cumulative warranty occurrences divided by the cumulative model year sales for each month since production began. After the model year sales are complete (somewhere shortly after about 12 months) the cumulative annual sales remain constant for each subsequent month. Hence from this point on, occurrence ratio becomes the "simple percentage" of total warranty claims divided by total model year sales.]

  - Figure 1a plots Canadian vs. US warranty occurrence ratio for all warranty cases involving catalyst replacement for the **automatic transmission** version of the 2001 model M-1. The Canadian replacement rate was considerably higher than the rate occurring in the USA where the fuel was essentially MMT free. However, figure 1a alone is not conclusive regarding the MMT effect since it does not provide a basis for separating out the incremental portion of Canadian catalyst replacements that might have been associated with the separate manifold cracking problem.
  - Figure 1b clearly illustrates the MMT effect on Canadian warranty occurrence ratios. This figure compares the catalyst replacement occurrence ratios for model M-1 for each of the MYs 2001 through 2003. The MY 2001 line in figure 1b is the same line that is shown for Canada in figure 1a. Even though figure 1b plots the occurrence ratio for all catalyst replacements regardless of causes (as does figure 1a), comparison of the occurrence ratios for these three model years illustrates an effect that can only be attributed to MMT plugging.
    - The vehicle design was not changed during this 3 model year period. Hence there is no reason why the catalyst replacement occurrence ratio plotted versus time in service for each model year should not track each other for each successive year unless some external condition changed over time.
    - Note on figure 1b that the occurrence ratio for MY 2002 tracks MY 2001 very well until about the 32nd month. Around this time, the MY 2002 occurrence ratio begins to fall short of the MY 2001

rate. This time period would have been in the spring of 2004, when MMT was disappearing from Canadian fuel.

- Likewise the occurrence ratio for 2003 appears to start falling short of the earlier trends at about the 20th month zone, which again would have been in the spring of 2004 for MY 2003.
- The removal of MMT was the only known change in external conditions during this time period, hence the lower occurrence ratio for each successive model year had to be due to the lower MMT exposure to vehicle in each newer model year.

- Figure 1c includes plots of the occurrence ratio for only confirmed plugged catalysts for model M-1 for MYs 2001 through 2003. This graph shows the same general pattern as figure 1b, namely that each successive model year stops tracking the prior year around the spring of 2004. However, since these graphs only include confirmed plugged catalyst repairs, it can be seen that the occurrence ratio becomes fairly flat (i.e., little additional increase) after the MMT removal time period.

[NOTE: Inspection of replaced catalysts of from 2001MY and later model M-1 vehicles began in early 2002. The warranty "call-in," which required dealers to return catalysts of certain part numbers to the warranty department in return for payment on the claim, began in September of 2002. At that time, the average 2001MY M-1 vehicle had about 20,000km accumulated. Hence only a few vehicles, which were high-mileage, exhibited MMT plugging before the inspection program began. It should be noted that while the call-in officially applied to every warranty repair catalyst, and every received catalyst was inspected, there was a small proportion that never arrived from the dealers. This was estimated to be about 5 to 10% of the returns. These parts may have been accidentally disposed of by technicians, misplaced, or otherwise discarded. But every catalyst that was received by the manufacturer was then subjected to the following:

⇒ Catalyst brick faces were visually inspected using a boroscope (microscopic camera). Pictures were taken of the faces of bricks showing heavy accumulation and/or minor or severe plugging.

⇒ Back pressure was measured using a water manometer with a scale graduated in millimeters. A constant volume flow in the direction of exhaust flow was induced by generating a vacuum at the catalyst exit; the static pressure drop across the brick of a converter was then measured using the manometer. In the case of a two brick converter, the pressure drop across the front brick was measured as the second brick was never visibly affected by accumulation.

Catalysts were NOT selectively sampled. Every one that was received was subsequently inspected. The 100% inspection program ran until late summer 2004, following the removal of MMT from the majority of gasoline. After that the number of MMT plugged catalysts being received on a month-to-month basis declined dramatically and a visual inspection revealed a greatly diminished occurrence of plugging and accumulation in the catalysts that were returned. At that point in time a less comprehensive inspection protocol was adopted and only those catalysts exhibiting any kind of accumulation or plugging (approximately 10% or less) were photographed and flow tested. Catalysts that appeared to be affected by MMT were selectively retained for evidentiary and demonstration purposes.

- Figure 2 and 3 summarize the observations resulting from the inspection of catalysts from the warranty return program. Figure 2 shows on a quarterly basis beginning with 2003 the percent of the returned catalysts that were determined to be plugged rather than exhibiting other problems. Figure 3 shows the warranty claim contention split into two categories. The red bar indicates those claim contentions that would be expected to be associated with catalyst plugging, namely, restricted flow, low power, or MIL illumination. Whereas the green part of the bars represent catalysts replaced due to cracked manifolds, noise, and other miscellaneous issues.

- Note that the percentage of plugged catalysts in figure 2 hovered around 70 to75% of all inspected catalysts up until the time the MMT was removed (i.e., after the first quarter of 2004). After MMT removal, the plugging percentage dropped dramatically.
- The warranty contention code information in figure 3 shows a consistent pattern when compared to figure 2. The red bars showing the collection of reported warranty contention codes that would be associated with plugging exhibit almost the same pattern as the red bars in figure 2 representing catalysts that were verified to be plugged.

- Figure 4 is a distribution plot of total catalyst warranty claims vs. mileage. From this it can be observed that the mileage threshold where plugging incidents appeared to begin to increase significantly was in the 40,000 to 60,000 km range (or about 25,000 to 37,000 miles). The peak was in the 80,000 to 100,000 km range (or about 50,000 to 62,000 miles).
  - The distribution in figure 4 includes all catalyst replacements. Hence, from it alone one can't conclude exactly where the MMT plugging threshold actually occurs. However, it gives an indication of the minimum threshold. In other words, it might be possible that the initial increase in the distribution could be due to other failure mechanisms. But one can conclude from the distribution that the earliest the plugging threshold can be for this particular vehicle would be in the range cited above.
  - It is not important to try to analyze this in further detail here. The point to be made here is that MMT plugging would not be expected to be seen at lower mileage. In fact this distribution may have been somewhat truncated given MMT was removed from most fuel in early 2004. Had it remained in the fuel there probably would have been appreciably more catalysts that would have exhibited plugging at significantly higher mileages.
  - Given MMT was removed from the fuel when even the MY 2001 vehicles were still relatively new from a mileage accumulation standpoint, the distribution in figure 4 indicates a significant percentage of the fleet never got a chance to reach the plugging threshold before MMT was removed. Hence, the total number of warranty claims manufacturer M observed for this vehicle likely only represented a small percentage of what might have happened should MMT have been left in the fuel indefinitely.
  - This minimum threshold effect also explains why the occurrence ratio graphs for MYs 2002 and 2003 in figures 1b and 1c start to exhibit significantly lower occurrence ratios compared to MY 2001 after the point in time that MMT was removed. Simply put, each successive model year fleet would have had a smaller percentage of vehicles that

would have accumulated enough mileage to reach the plugging threshold before MMT was removed from most of the fuel.

- Analysis of returned catalysts in the USA showed the normal array of other catalyst failure problems, e.g., cracking and thermal degradation, but no indications of MMT related failures. See figure 5a through 5d for sample pictures of warranty return parts from the US market.

[NOTE: In figure 5a, these are all catalysts that were replaced by dealers under warranty at higher mileage levels in the U.S. In these particular cases, the ceramic substrate was cracked which led to noticeable noise from vibration in the converter canister. The large portions noticeably missing from some of the substrates are cutouts for the benefit of post-replacement inspection. These failures are rare and are believed to be caused by severe mechanical or thermal shock. None of these catalysts from the U.S. showed any signs of any deposit formation on the face or outer perimeters of the substrate, relative to the type and amount of deposits seen on replaced catalysts from the Canadian market.]

- Manufacturer M inspected four (4) MY 2001 model M-1 vehicles in the "Four Corners" region of the U.S. (i.e., where the states of Colorado, Utah, Arizona, and New Mexico all join each other) where MMT was evident in a small portion of market fuel samples from gasoline sold in that area. The catalysts from two of these vehicles were deposit free and had no orange coloration on the catalyst face prevalent in cars exposed to gasoline containing MMT. The spark plugs and oxygen sensor also did not have the traditional orange deposits or coloration associated with MMT exposure. The fuel sampled from the tanks of these vehicles did not contain MMT. The other two vehicle catalysts did have the obvious signs of MMT exposure and significant deposit formation on the catalyst face. The analysis of the fuel sampled from the tanks of these vehicles revealed the presence of manganese associated with the MMT additive.
  - This was a limited survey designed only to give an indication of whether any plugging was occurring in this area of the US. The vehicles were not randomly selected, but rather represented what could be accessed quickly via solicitation of vehicles at a cooperating dealer.
  - The owners were chosen based on two criteria:
    - Their vehicle had accumulated at least 40,000 miles.
    - They used one of the brand name fuels identified as potentially containing MMT.
  - Figure 6 contains a picture of one of the plugged catalysts from this survey.

- **Manufacturer M's second significant plugging case was with Model M-2,** the MY 2002 through 2003 SUV that used a mid-under floor high density catalyst.
  - Model M-2 clearly has exhibited higher warranty rates in Canada compared to the US for MY 2002. Figure 7a plots the 2002 occurrence ratios for all catalyst repairs in both countries. Again the vertical scales are blinded but the trends are observable.

  - Observe that the Canadian occurrence ratio begins to climb almost exponentially until the time period when MMT was removed from most Canadian fuel. After this time period, the curve bends flatter and begins to almost parallel the US rate.
  - Observe that at its maximum, the **Canadian rate was about 3 times the US rate**.

  [Note: Unlike the model M-1 case, there was no indication of any other failure mechanism that would have caused the Canadian occurrence ratio to exceed the US level. The full incremental increase of the Canadian warranty rate beyond the US rate can be attributed almost entirely to MMT effects. Hence in this case it is appropriate to attribute the 3 times multiplicative effect to MMT caused catalyst warranty claims.]

  - As with model M-1, this observation pertains to the automatic transmission version. The warranty rate for the manual transmission version of model M-2, like model M-1, was not as clearly distinguishable from the US baseline.

- Also, as was observed with model M-1, figure 7b shows the Canadian occurrence ratios for model M-2 for MYs 2002 and 2003 track each other well until the spring of 2004 where the 2003 curve appears to stop tracking the 2002 rate. Again, this was the time period when MMT was disappearing from Canadian fuel.
  - In fact the MY 2003 curve looks very much like the US baseline (non-MMT use) curve plotted in figure 7a. [NOTE: Figures 7a and 7b are plotted on the same scale. So even though the vertical scales have been removed, the curves from the two figures can be compared directly to each other.]
  - This indicates that the 2003 MY vehicles were too new to have accumulated enough miles to have reached the plugging threshold before the time that MMT was removed.

- Figure 7c includes plots of the occurrence ratio for only confirmed plugged catalysts for model M-2 for MYs 2002 and 2003. This graph shows the same general pattern as figure 7b, namely that the 2003 MY stops tracking the prior year around the spring of 2004. Since these graphs only include confirmed plugged catalysts, it can be seen that the occurrence ratio becomes fairly flat (i.e., little additional increase) after the MMT removal time period

[NOTE: The same warranty return inspection program that was instituted for model M-1 was performed for model M-2. Hence all catalysts that were replaced under warranty by dealers were returned for inspection under the same conditions as described above for model M-1.]

- Figure 8 summarizes the observations resulting from the inspection of warranty return catalysts from model M-2. As with model M-1 as shown on figure 2a, figure 8 shows a marked drop in the quarterly percentage of catalysts found to be plugged after the first quarter of 2004. At the peak just before the MMT removal period, the quarterly percentage of plugged catalyst reached about 75% of all warranty return catalysts for that quarter.

- Figure 9 is a distribution of catalyst repairs vs. mileage. While this is the distribution for all catalyst repairs, one can deduce from this distribution that the minimum plugging threshold would be in the 20,000 to 40,000 kilometer range (i.e., in the 12,000 to 25,000 mile range).
  - This threshold appears to be lower than the one for model M-1.
  - However the threshold for model M-2 is not as clearly defined as the one for model M-1. The M-1 catalysts experienced a very low failure rate until a distinct increase began in the 40,000 to 60,000 km range. Whereas the failure rate for M-2 began to increase earlier but more gradually.
  - Additionally the catalyst repair rate appears to reach its peak for model M-2 at a lower mileage than for model M-1. This could be an artifact resulting from the fact the model M-2 was newer than model M-1 meaning fewer vehicles would have accumulated enough miles to reach a possible higher and later peak if MMT had remained in the fuel.
  - However, in general it does appear that model M-2 might have been slightly more sensitive to plugging than model M-1 which caused some catalysts on model M-2 to plug more quickly (i.e., at lower mileage).

- At first this potentially greater sensitivity to plugging for model M-2 may seem counter intuitive given the catalyst is located in a mid-under floor position that is not as closely coupled as for model M-1, which had a manifold mounted catalyst. However, the catalyst on model M-2 sees higher inlet gas temperatures, largely because of the relatively higher loads that are experienced by this 4 wheel drive SUV. Additionally, the exhaust inlet pipe to the catalyst housing is at a slanted angle relative to the catalyst face. High temperature and flow at an angle to the catalyst face have been reported in publicly available literature as accelerators of the MMT plugging phenomenon.

- Figure 10 contains sample pictures of model M-2 Canadian market catalysts.

- Manufacturer M did not observe an MMT plugging problem that could be detected via warranty data with the MY 2002 model M-3 or M-4 even though they both used a high density catalyst located in a mid-under floor position. As discussed above, the exhaust flow for both of these vehicles approaches the catalyst face in a near perpendicular manner. Additionally, based upon limited available temperature information both of these models appear to operate at lower temperature than either model M-1 or M-2. These parameters indicate that models M-3 and M-4 would be less sensitive to MMT plugging. This does not mean that none of these would have plugged had MMT stayed in the fuel longer.

- Manufacturer M added HDCC designs to models M-5 thru M-8 beginning with MY 2003. No significant plugging problem has been observed on any of these vehicles in the field. This is not surprising. For even with models M-1 and M-2 which exhibited plugging in the field, very low plugging incidences were observed for MY 2003 simply because the vehicles were too new to have accumulated enough miles to reach their plugging threshold before MMT was removed from the fuel supply.

Future Technology Plans:

Manufacturer M will employ in the future, in general, three after-treatment system architectures to achieve compliance with Tier-2 exhaust emission standards. In the majority of these applications, catalytic converters with 600 or greater cpsi ceramic substrates will be specified for at least the first catalyst in the exhaust stream. These three system architectures are:

- A single close coupled, manifold mounted, high density catalyst will be used on the smaller 4 cylinder passenger cars (as used on model M-1).
- A dual brick catalyst located in the mid-under floor locations will be used on the larger 4 cylinder engine models (as used on model M-2).
- V6 engines will use two HDCC catalysts, one on each bank of the exhaust plus a single or double brick under floor catalyst (as used on models M-7 & 8). [Note: The downstream under-floor catalyst will not necessarily be a high density catalyst.]

Emission Testing and Mechanism Analysis:

Manufacturer M performed a variety of testing. The following gives an overview. **More detailed technical reports are available for two of the more significant testing efforts. These are noted below under topics #5 and #6**.

1. MY 2001 Model M-1 Durability Testing: This involved accumulating mileage on production vehicles on an actual road course, monitoring performance, and conducting emissions testing at scheduled mileage intervals. One vehicle was run on clear fuel and one on fuel containing 8.3 mg/L MMT. Both vehicles were driven using the same mileage accumulation courses, however they were not driven at the same time. The clear-fueled vehicle was run a few months before the MMT-fueled vehicle. Drivers were instructed to obey state and local speed limits. Mileage was accumulated by driving the vehicles on local roads consisting of normal city and highway conditions and some minor elevation changes. The vehicles were driven essentially all day long seven days a week with a rest or soak period overnight. An engine dynamometer durability test was also performed, which corroborated the catalyst plugging experienced during the road test. The dynamometer test used the same MMT containing fuel that was used in the road test. Figure 11a provides pictures of the plugged catalysts from both the road and dynamometer tests. Figures 11b and 11c show the emissions versus mileage results from the road durability test for NMOG and NOx respectively.

Highlights of results for the road durability test (see figure11b & c for actual results):

- Emissions did not change significantly through the 30k mile test point.
- Loss of power for the MMT vehicle was reported at about 37k miles.
- OBD catalyst MIL illumination occurred slightly above 40k miles.

- Rough running was reported just before the emission test was performed at about 42k miles.
- Both NMOG and NOx increased significantly at the next test point at about 42k miles. Emissions measured at this point were about 4 times higher than the prior test (i.e., at 30,000 miles) for NMOG and about ten times higher for NOx.
- Figure 12 summarizes the analysis of deposits that was performed. This analysis confirmed that manganese oxide was the primary material.

2. First Canadian Market Sampling: Five consumer catalysts from the 2001 Model M-1 were examined early on, during August and September 2002, when Manufacturer M first began to realize the plugging situation was occurring. This was not a random survey. The purpose was simply to get an initial look at what might be happening in the field. Sample catalysts obtained from vehicles operated in Canada and representing a range of mileages were obtained from various sources including warranty returns and where voluntary arrangements could be made through a dealer to trade catalysts on a consumer vehicle. Mileages were 38k, 49k, 86k, 103k, and 131k miles.
   - Pictures are included in figure 13 for 4 of the 5 catalysts. A picture of the 5th was not available.
   - The catalyst with 38k miles was well coated with deposits but not severely plugged. All of the other catalysts (including the one not pictured) were significantly plugged.
   - Analysis of deposits confirmed that manganese oxide was the primary material.

3. Canadian Vehicle Early Emission Performance Market Test: Catalysts from six in-use 2001 model M-1 vehicles were tested for emissions using a single slave test vehicle. Catalysts were procured from vehicles whose mileages were high enough to be within the expected plugging range (i.e., not by random selection from owner registration lists as would be done of IUVP or recall testing, but by seeking voluntary participants through cooperating Manufacturer M dealers).
   - The source vehicle mileages ranged from 35 to 81k miles.
   - The results of this testing are shown in figure 14a.
   - 3 of the 6 catalysts exhibited emission levels higher than what is permitted under federal in-use exhaust emission standards applicable to vehicles within those mileages.
   - More importantly, emissions from 5 of the catalysts exceeded baseline* (non-MMT fleet) emissions shown in figure 14b by 3.5 to 11 times for NOx and by 2 to 6 times for THC.

   [*Note: The "baseline" emissions shown in figure 14b are from a randomly procured non-MMT in-use fleet in the U.S. market. The vehicles were procured and tested according to mandatory "in-use verification program" (IUVP) testing requirements under EPA's "CAP2000" certification regulations. This data was the required four year old "high mileage" IUVP test data applicable to the MY2001 model M-1. Vehicles 1 through 4 were procured and tested in Ann Arbor, Michigan and vehicle number 5 was procured and tested in Denver.]

4. Canadian Vehicle Emissions and Fuel Economy vs. Plugging Ratio: Manufacturer M performed a preliminary study of the relationship between emissions and fuel economy vs.

plugging ratio for the 2001 model M-1. This initial study utilized various sources of testing that had been done in various early testing programs. [NOTE: A more comprehensive study of emissions vs. plugging was conducted later. It is referred to as the "Large Canadian Survey" and is discussed under topic #6 below. The results from the preliminary study of emissions vs. plugging were fairly closely corroborated by the more scientifically and statistically designed program discussed under topic #6.]

- For the preliminary study, all available emissions data (i.e., from the above two test projects - see topics #1 and #3) as well as results from additional catalysts obtained from warranty returns selected to represent a full range of percent plugging were plotted vs. percent plugging.
- The results appear in figure 15. Emissions were observed to begin to rapidly increase when the catalysts were 50 to 60% plugged. Fuel economy started dropping after a plugging ratio of about 60% had occurred. With catalysts plugged in the 60 to 80% range, NMOG emissions were 3 to 7 times higher than for an unplugged catalyst, NOx emissions were 5 to 10 times higher than for an unplugged catalyst, and CO emissions were 3 to 9 times higher than for an unplugged catalyst.

[NOTE: For comparative purposes, the 100K Master catalyst was installed on the emission test vehicle to determine baseline emissions with a thermally aged catalyst to simulate in-use operation to 100,000 miles on RFG with no MMT additive. It was free of manganese deposits on the substrate surface.]

5. <u>On-Road Mileage Accumulation Test Results</u>: Manufacturer M performed testing of emissions vs. mileage for 7 vehicle types using the same on-road mileage accumulation procedure as discussed above under topic #1 of this section of this report. The focus was testing vehicles that were popular in the Canadian market. A separate report has been prepared for this test program titled "Effect of MMT upon Vehicles in a Test Program." One of these 7 vehicle types was model M-1. This vehicle was not retested, but rather for completeness, the results from the earlier testing discussed above under topic #1 was included in the report. The remaining vehicle types tested were model M-2, M-3, M-4, M-6, M-7, and M-8. A matched pair of model M-7 vehicles, one with clear and one on MMT fuel, were run together (i.e., at the same time on the same road courses that were used for the testing of model M-1). For the remaining vehicles, the clear fuel vehicle was run at an earlier date as part of final development testing. This testing was accomplished by removing the catalyst and oxygen sensors and subjecting them to a rapid aging cycle using an engine dynamometer. This cycle has been demonstrated to produce emissions results that very closely match those from vehicles that have undergone conventional mileage accumulation when no abnormal fuel related deposit issues are concerned. In all cases, the MMT fueled vehicle was run on fuel containing 8.3mg/L MMT and was run on the same on road courses as for the vehicle pairs discussed above for models M-1 and M-7.

[NOTE: The testing history of two of the MMT fueled vehicles, model M-3 and M4, was problematic. The data is included in the report for completeness. These vehicles were run early in the program when the focus was still on potential exhaust valve problems. As a result, some special testing to evaluate valve issues was conducted which took the test vehicles out from the quality control auspices of the durability program for a period of time. These deviations are discussed in the technical report.]

Overall conclusions presented in the technical report were:

- All vehicles operating on MMT fuel in this program developed MMT-related deposits on the surface of their primary catalysts, despite the fact that a wide variety of engine/catalyst configurations were tested.
- The catalyst deposit material was confirmed to consist of MMT combustion products. Elemental analysis by XRF indicated that a significant percentage of the material was manganese. Mineral analysis by XRD revealed that Mn_3O_4 was virtually the only crystalline material present.
- In some cases, the deposit covered virtually the entire face of the catalyst, causing a substantial backpressure increase and drivability problems.
- The NO_X and NMHC tailpipe emissions of most of the vehicles running on MMT fuels increased over their clear-fueled counterparts. CO emissions remained relatively unaffected. In no case was a net decrease observed in the emissions of the MMT-fueled vehicles.
- The MIL (Malfunction Indicator Lamp) illuminated on four of the vehicles, with a code corresponding to a catalyst efficiency problem. In some cases, this occurred after relatively low mileage accumulations. All of these vehicles were operated on MMT fuel.
- Vehicles retrieved from the Canadian market, where MMT fuel was common, exhibited catalyst deposits identical in composition to those from the test vehicles in this program.
- In all cases, spark plugs from the MMT-fueled vehicles in this program were also heavily coated with manganese oxide.
- The vehicles accumulated mileage on real-world courses. These were the same road courses historically used by manufacturer M for vehicle durability testing.
- This research confirmed that emission systems designed to meet the stringent Tier 2 emission standards are clearly less tolerant of MMT.
- However, the results from this test program do not necessarily reflect average market experience in Canada, because of fluctuations in MMT concentrations in Canadian gasoline and variability in vehicle operational patterns.

6. <u>"Large Canadian Survey" -- Random Survey of In-Use Catalysts</u>: A separate technical report is available for this program titled "Evaluation of Catalytic Converters Retrieved from the Canadian Market." The following is an overview:

- Catalytic converters were retrieved from in-use model M-1 vehicles in Canada.
    - The vehicles were randomly selected by a third party contractor.
    - Vehicles were excluded if the vehicle's catalyst had been replaced. This eliminated vehicles from the survey that had experienced sufficient plugging to result in a warranty claim. But the objective of this survey was to get a look at the vehicle population that had not been reported as having a problem at the point in time when the survey was conducted.

  - A group of 63 catalysts were selected the met the selection criteria.
- Catalysts were sent to a third party contractor for evaluation.
  - Flow measurement
  - Emission testing on a chassis dynamometer using a slave vehicle
  - Photography of the catalyst surface
  - Analysis of catalyst deposit material
- A few catalysts were found to be substantially plugged (80%) with MMT combustion products and caused drivability problems and high emissions. These were vehicles that likely could have had a catalyst replacement had the driver sought repair of the driveability problems.
- This first random selection process resulted in a "data gap," in which no catalysts were found with a measured plugging percentage between 30% and 80%.
  - One potential reason for this was the severity of the criteria. Vehicles that had enough plugging to have caused the catalyst to be replaced were inherently screened out of the program.
  - Emissions testing conducted with this first set of catalysts showed a substantial increase in emissions for the catalysts that were plugged more than 80% compared to the group below 30%. But with no catalysts represented in the middle range, it was not possible to draw a statistically conclusive trend of emissions versus percent plugging across the full percent plugging range.
- A second catalyst retrieval program was conducted. The starting pool consisted of all warranty-returned catalysts in the Ontario province. A pool of 25 catalysts was randomly selected from this much larger set.
- These catalysts were tested by the same third party contractor in groups of four. Flow testing was performed on all 25 units, however. After the second set of four catalysts completed the emission test sequence, it was determined that the data gap had been sufficiently addressed, thereby confirming the emission trends observed in the original data set.

[NOTE: The technical report discusses the entire program methodology in greater detail, including explaining how and why the second program was run to fill the "gap" in the percent plugging range.]

The following is a summary of the results:

- Catalyst plugging percentages ranged from 2% to 82% for the initial 63 catalyst sample. Catalysts from the follow up program filled in gaps in mid-range percentage plugging and extended the range up to 92%.
- Catalyst deposits were determined to be primarily manganese in the form of Mn_3O_4.
- Driveability problems were noted for some of the highly plugged catalysts.
- THC, NOx, and CO emissions all began to increase at the 30% plugging point.
- At plugging levels above 50% the emissions increases were substantial.
  - THC increased to about double the baseline at the 50% plugging.
  - THC increased by 4 to 10 times the baseline in the 80 to 90% plugging range.

- CO showed a similar multiplicative effect as THC across the plugging range.
- NOx increased to about 4 times the baseline at 50% plugging.
- NOx increased by 6 to 14 times the baseline in the 80 to 90% plugging range.

- The measured plugging percentage was generally greater for catalysts with higher mileage accumulation, but the correlation was not strong. Severely plugged catalysts with high emissions were found as low as 55,000 km (~34,000 miles). However, none of the catalysts below 55,000 km were plugged any more than about 12%.

[See the technical report for graphical representations of the data supporting the above conclusions.]

7. Emissions Recovery Testing: Tailpipe emissions testing was performed with a 2001 Model M-1 with a plugged catalyst. Emissions were measured before and after removal of deposits. Emissions prior to the cleaning were above the emissions from an in-use catalyst procured from the US market where MMT had not been used. Emissions from the plugged catalyst exceeded the emissions of the baseline US catalyst by about 14 times for NOx, 6 times for HC, and significantly for CO. [NOTE: CO emissions are not expressed here as a multiple of the baseline since the baseline was so close to zero.] The emissions measured from the plugged catalyst after it was cleaned lowered to within about 1.25 to 1.30 times the emissions from the baseline US catalyst. See figure 16a for results of this testing and see figure 16b for a description of the deposit removal process.

[NOTE: This process of attempting to remove the manganese oxide deposits from a contaminated catalyst's face would be impractical for anywhere outside of a controlled laboratory due to health exposure concerns and variability of results. It would not be practical in a service or warranty repair environment.]

8. Analysis of Deposits: Manufacturer M analyzed the deposits found on the face of various catalysts retrieved from the Canadian in-use market. Such analyses have shown consistent results as reported by other manufacturers:
   - Manganese Oxide makes up the major portion of the deposits.
   - Electron microprobe analysis shows evidence of physical and not chemical deposition.
   - There is nothing that would indicate deposits are caused by or accelerated by presents of engine oil components. P and Ca were detected in very low concentration. Engine dynamometer testing using engine oil containing no P and Ca was performed. The engine failed due to the insufficient oil properties, but the MMT deposits accumulated on the catalyst had the same composition and characteristics as engines run using normal engine oil.
   - Figure 12 illustrates results of analyses of deposits from both the road and dynamometer (bench) durability tests.
   - Figures 17 and 18 demonstrate that deposits are formed by physical mechanisms rather than chemical interactions. In Figure 17, a stainless steel probe was placed in front of the catalyst and exposed to the exhaust gas flow. There was no washcoat or

other catalytic agent on the probe, yet deposits were still formed. Moreover, the morphology of those deposits bears a close resemblance to the morphology of deposits that formed on the catalyst surface. This strongly suggests that deposits are formed by agglomeration rather than by any chemical interactions with the catalyst washcoat. Figure 18 provides further evidence of a physical deposit mechanism. The cross-section picture of the catalyst inlet shows that there is a gap between the cell wall and the deposit, which demonstrates that no chemical bond has been formed. Moreover, the manganese from the exhaust gas is found only in the deposit, while none is found in the substrate, which again shows that there is no chemical reaction between the manganese and the catalyst washcoat.

9. <u>Temperature Information</u>: Manufacturer M has temperature information for a variety of its vehicles under cruise speed conditions ranging from 60 to 180 km per hour and temperature profiles for their internal road mileage accumulation road route. Several manufacturers have noted that Mn_3O_4 accumulation appears to accelerate at temperatures above about 700°C (temperature at the catalyst face) or around 800°C (temperature of the catalyst brick measured about 1 inch behind the face). In light of this possible critical temperature, a few observations can be made regarding the operating temperatures of several of Manufacturer M's vehicles. See figures 19 through 21 for the temperature data.

- The Model M-1 and M-2 reached catalyst gas temperatures significantly above 700°C between 100 and 120 km/hr cruise and approached 800°C at 130 km/hr. A version of model M-1 that was equipped with an under-floor catalyst stayed below 700° within most of this same speed range. Model M-4 also reached temperatures above 700° within this same speed range, although not as high as models M-1 and M-2. Model M-4 didn't exhibit significant plugging in the field as did models M-1 and M-2. This may have been in part related to its somewhat lower temperature, but also compared to models M-1 and M-2, model M-4 had a fairly straight in or perpendicular flow to the catalyst face.
- The 2003 model M-8 reached even higher gas temperatures in the same speed range. This vehicle exhibited a slight increase in emissions and back pressure during "durability" type testing. [See the technical report referenced under topic #5 above for this durability test.] While this vehicle was too new for there to be sufficient field experience data from vehicles with mileages high enough to be in the suspected plugging range, the durability testing indicates this vehicle may not plug as rapidly as models M-1 and M-2. [Again see the report under topic #5.] This could in part be due to the fact that the flow angle involved with model M-8 is not as severe as with models M-1 and M-2.
- Models M-6 and M-7 reached significantly lower gas temperatures (in the lower 600's). Durability type testing of these vehicles [Again see the technical report under topic #5.] resulted in deposit formation on the catalyst but not enough to produce an obvious emissions increase on the test. Manufacturer M's analysis is that the lower temperatures for these products make these vehicles less susceptible to plugging, although they could plug under severe driving conditions.

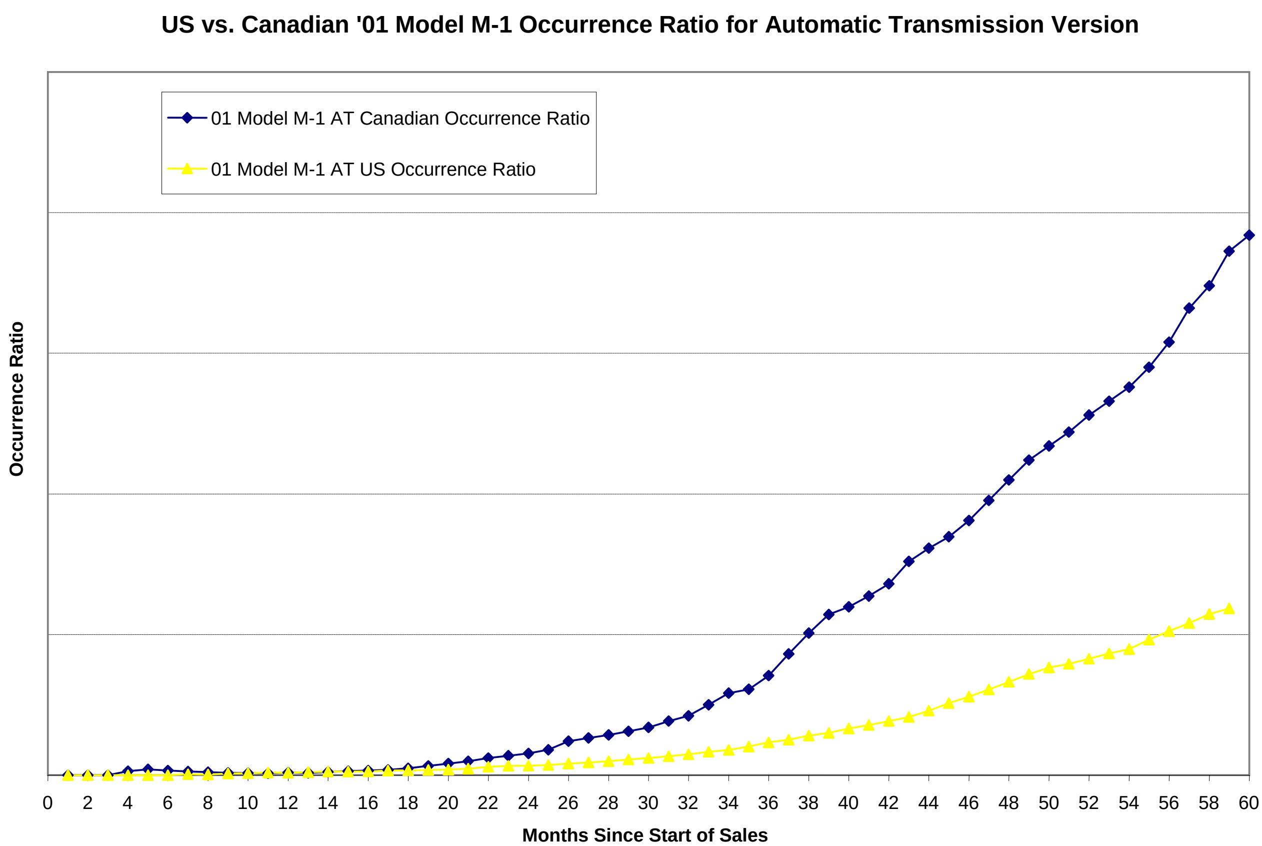
- Figure 20 provides temperature frequency distribution plots for the automatic and manual transmission versions of the MY 2001 model M-1. As noted above, the manual transmission vehicle has shown less susceptibility to plugging. This is consistent with the temperature frequency plots that demonstrate that the manual transmission version runs substantially cooler by about 100 degrees or so (based upon visual and not digital analysis of the plots).
- Finally, observe figure 21 which gives catalyst temperature distributions for several models. Note that models M-1 and M-2 (i.e., the two most significant plugging cases) have the temperature distributions that extend to the highest levels.

All figures referenced above are attached below:

Best Viewed in Color

Figure 1a Warranty Claim Occurrence Ratio for Canada vs. USA for Auto Transmission MY 2001 Model M-1

(All Warranty Claims for Catalytic Converter Replacement Regardless of Repair Reason)

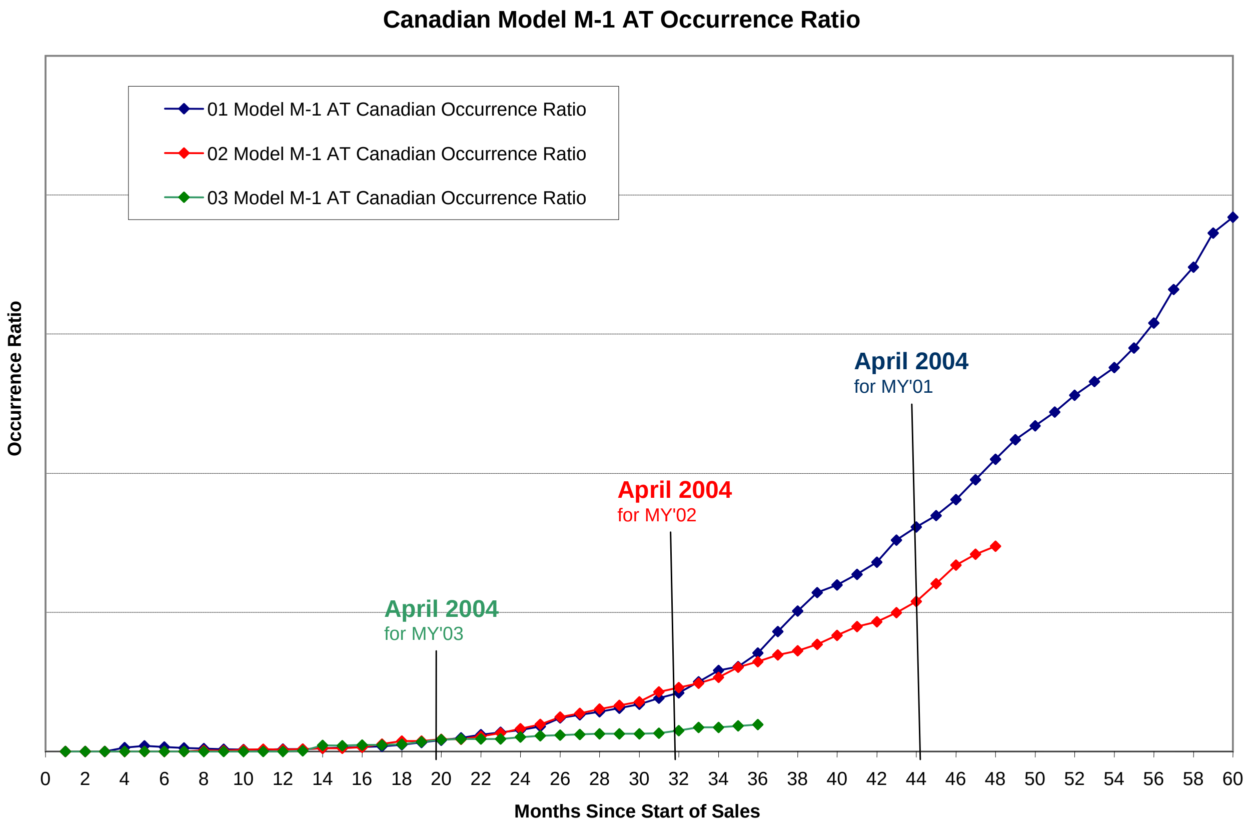


<u>NOTE</u>: Occurrence ratio is the total cumulative warranty occurrences divided by the cumulative model year sales for each month since production began. After the model year sales are complete (somewhere shortly after about 12 months) the cumulative annual sales remain constant for each subsequent month. Hence from this point on, occurrence ratio becomes the "simple percentage" of total warranty claims divided by total model year sales.

Best Viewed in Color

Figure 1b Warranty Claim Occurrence Ratios for Canada for the Automatic Transmission Version for MYs 2001 thru 2003 Model M-1

(All Warranty Claims for Catalytic Converter Replacement Regardless of Repair Reason)



NOTE: The occurrence ratio for MY 2002 tracks MY 2001 very well until about 32 months where it appears that it is beginning to fall away. This fall away zone would have been in the spring of 2004, when MMT was rapidly disappearing from Canadian fuel. MMT was removed from the majority of fuel between January and April 2004. Likewise the occurrence ratio for MY 2003 appears to start falling short of the earlier trends at about the 20th month which again would have been in the spring of 2004.

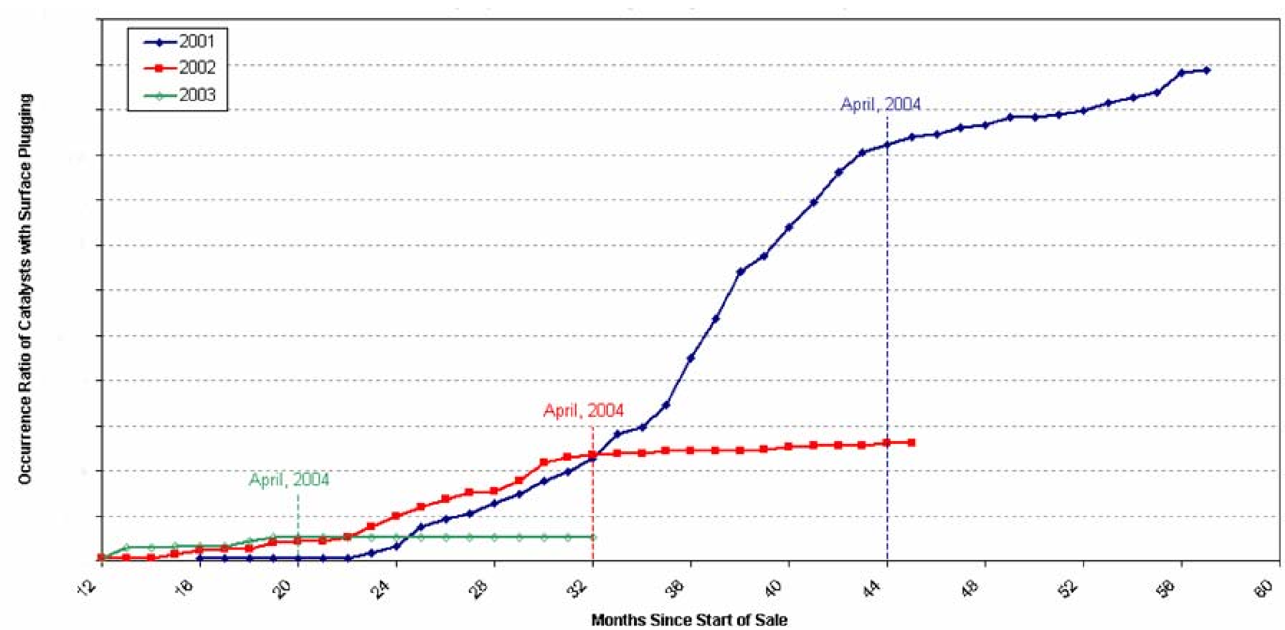
Best Viewed in Color

Figure 1c

Plugging Occurrence Ratios for the Model M-1 Automatic Transmission Version for MYs 2001 - 2003

(Inspected Warranty Catalysts thru June 30, 2005)

Plugging Occurrence Ratio = (Total plugged catalysts verified via inspection of all replaced catalysts) divided by (model year sales to date)



NOTE 1: All catalysts replaced under warranty were returned from dealers for inspection by the manufacturer. This graph shows the occurrence ratio for only those catalysts that were found to have surface plugging or flow restriction. The 100% inspection program ran until late summer 2004, following the removal of MMT from the majority of gasoline. After that the number of MMT plugged catalysts being received on a month-to-month basis declined dramatically and a visual inspection revealed a greatly diminished occurrence of plugging and accumulation in the catalysts that were returned. At that point in time a less comprehensive inspection protocol was adopted and only those catalysts exhibiting any kind of accumulation or plugging (approximately 10% or less) were photographed and flow tested. Catalysts that appeared to be affected by MMT were selectively retained for evidentiary and demonstration purposes.

NOTE 2: This graph removes the confounding effect of the manifold failure related catalyst replacements. Now the flattening trends for each model year can be seen to begin occurring in the April 2004 time frame when MMT had been removed from the majority of fuel. Again as in figure 1b, each respective model year stops tracking the prior year around April 2004 relative to each model year.

Figure 2

Catalytic Converters observed to have Surface Plugging and/or Restricted Flow
2001-2003 MYs Combined for Model M-1 w/Automatic Transmission
(Inspected Warranty Catalysts thru June 30, 2005)

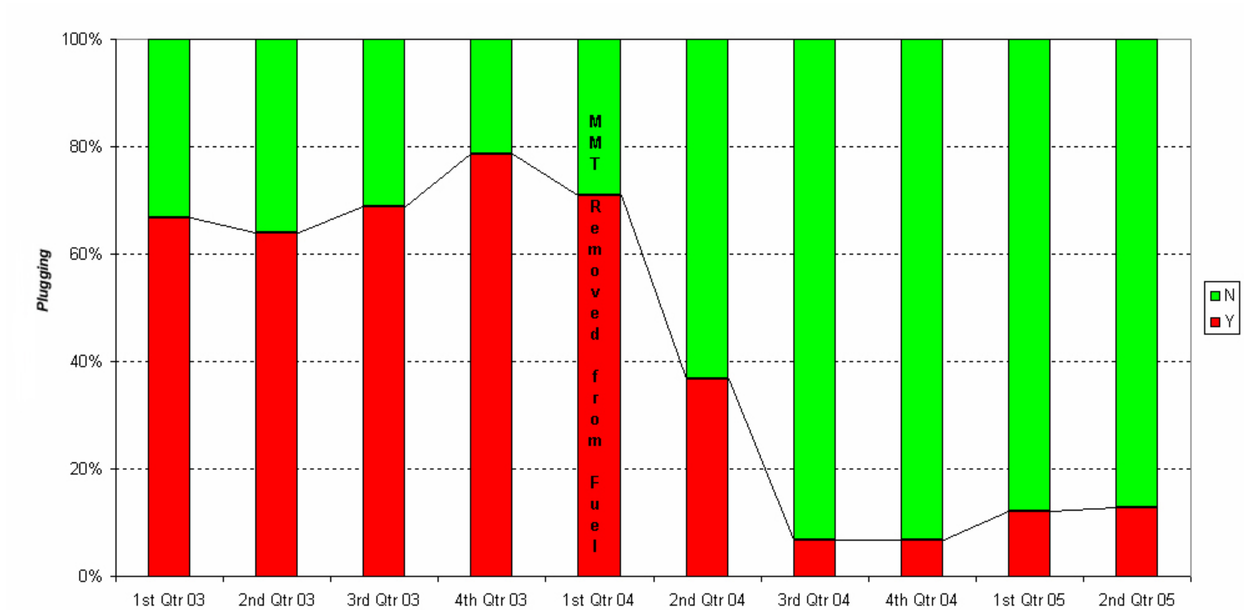
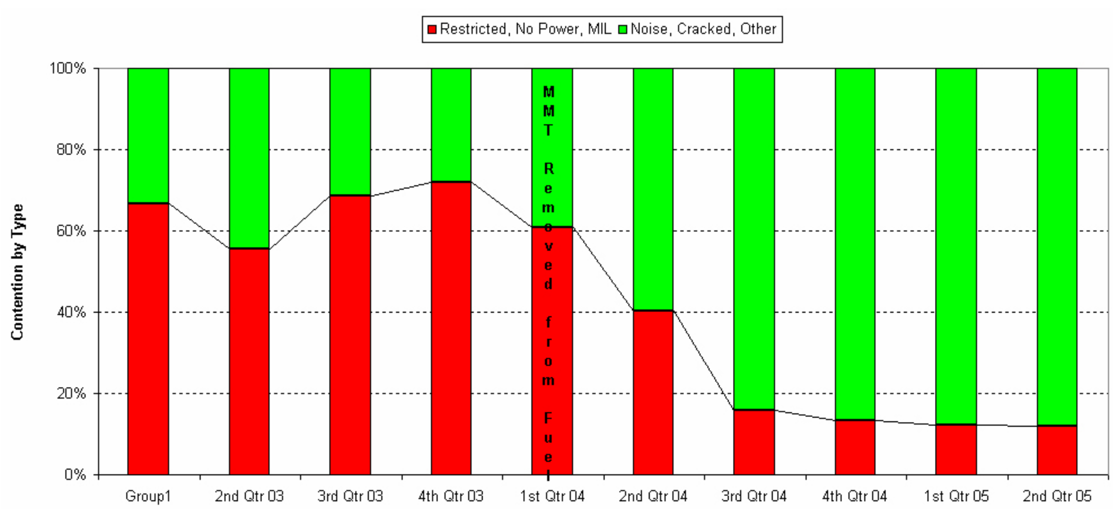


Figure 3

Warranty Claim Contention
2001-2003 MYs Combined for Model M-1 w/Automatic Transmission
(Inspected Warranty Catalysts thru June 30, 2005)



Best Viewed in Color

Figure 4

Distribution of Catalyst Warranty Claims vs. Mileage For Model M-1 for MYs 2001-2003

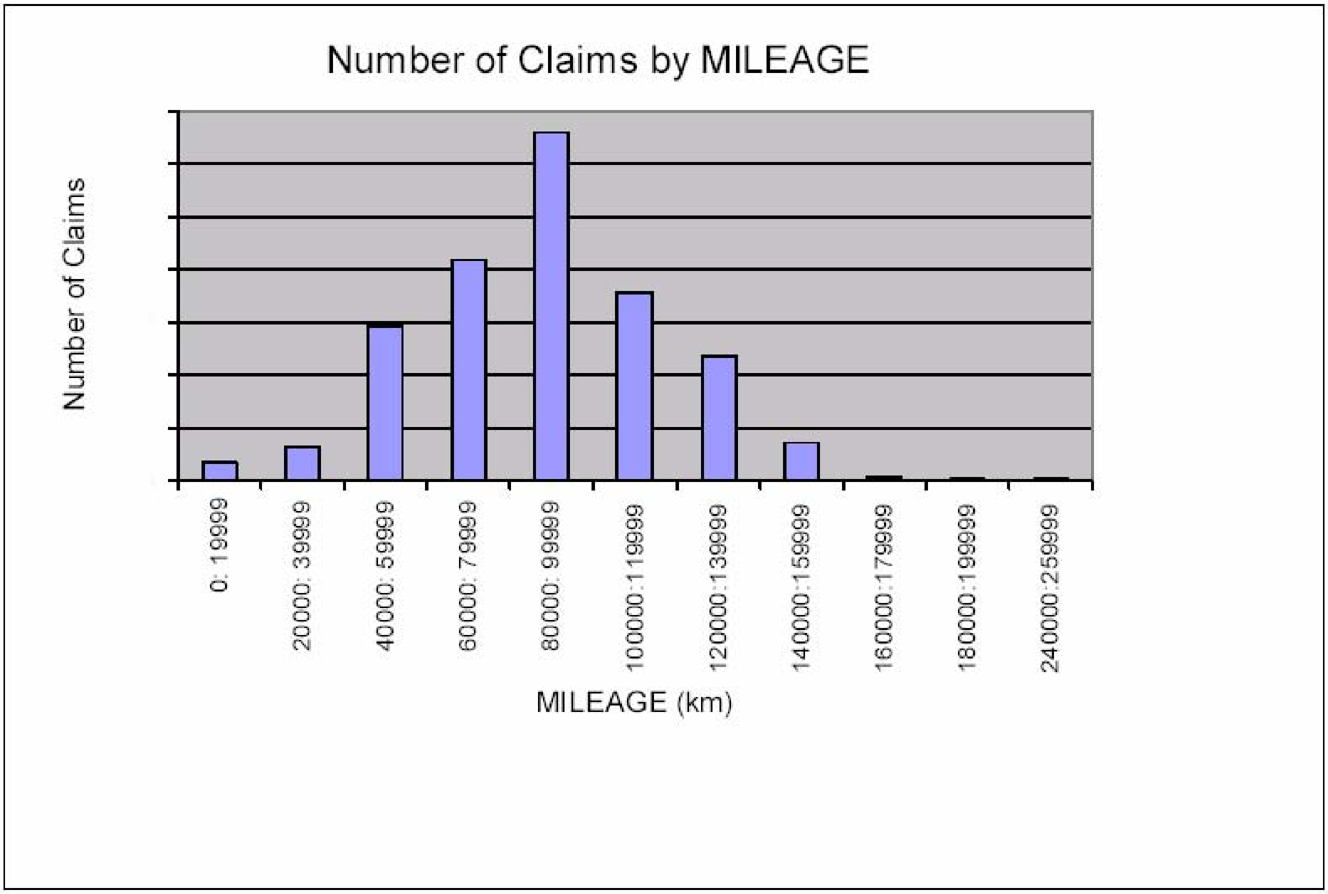


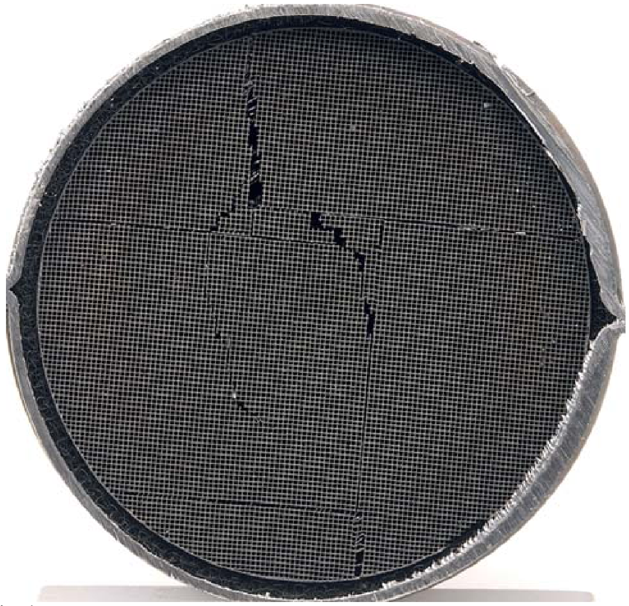
Figure 5a Pictures of Warranty Return Parts from the US Market

Best Viewed in Color

Figures 5b, c & d

Additional Pictures of Warranty Return Parts from US Market

Figure 5b



Mileage: 46284 mi.
State: Texas
Reason for Warranty Return: MIL on

Figure 5c

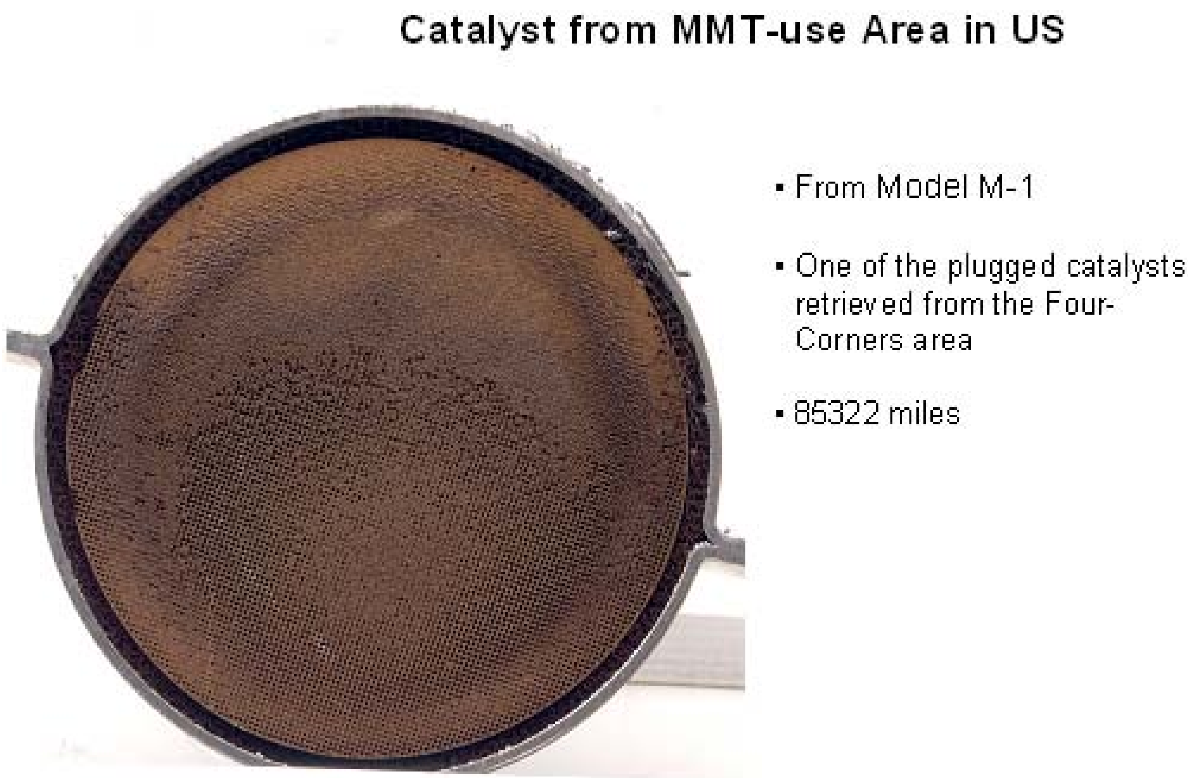
Mileage: 68970 mi.
State: Alabama
Reason for Warranty Return: Noise during acceleration

Best Viewed in Color

Figure 5d

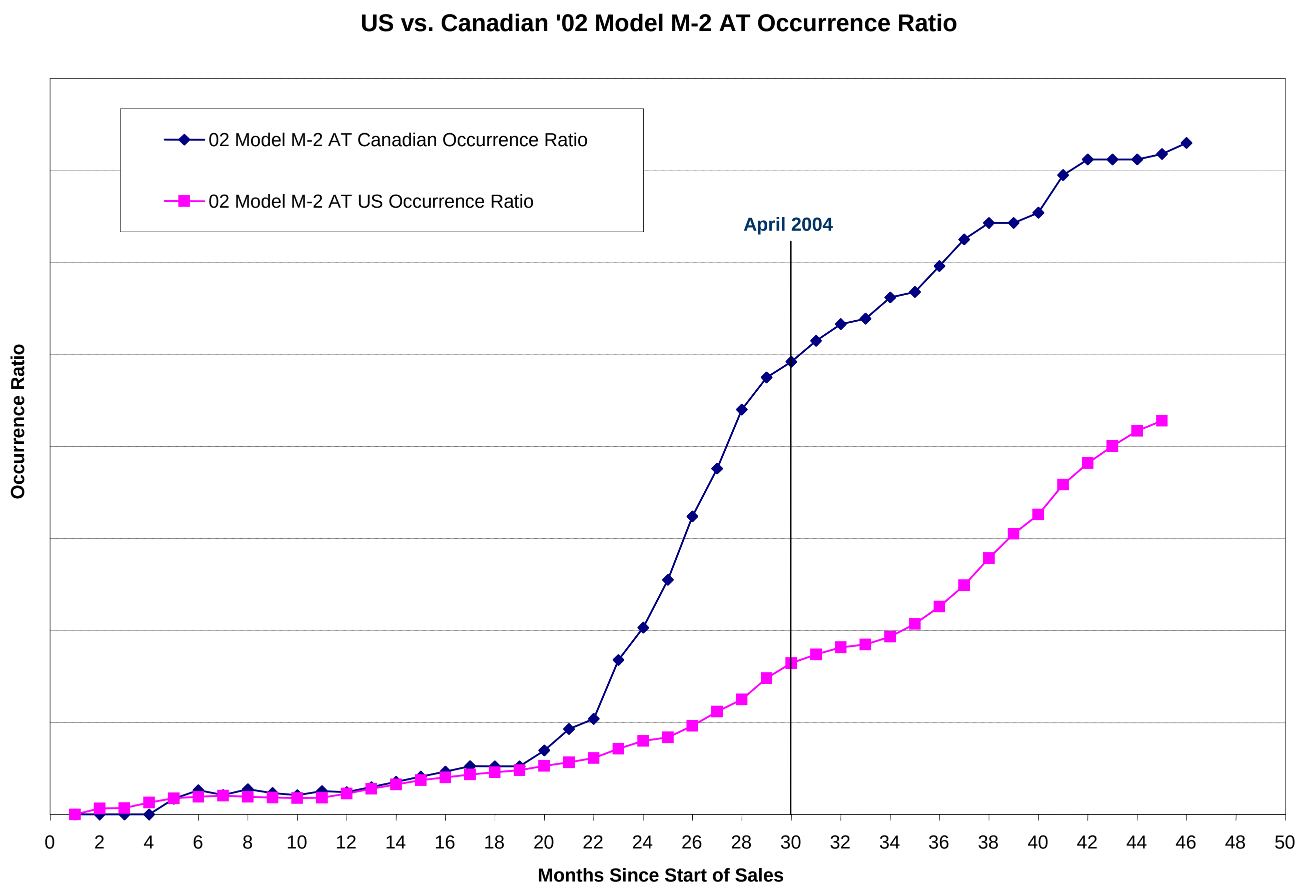
Mileage: 74270 mi.
State: California
Reason for Warranty Return: Cracked exhaust manifold

Figure 6 Picture of a catalyst sampled from the "Four Corners" area of the USA where MMT was sold in limited amounts



Best Viewed in Color

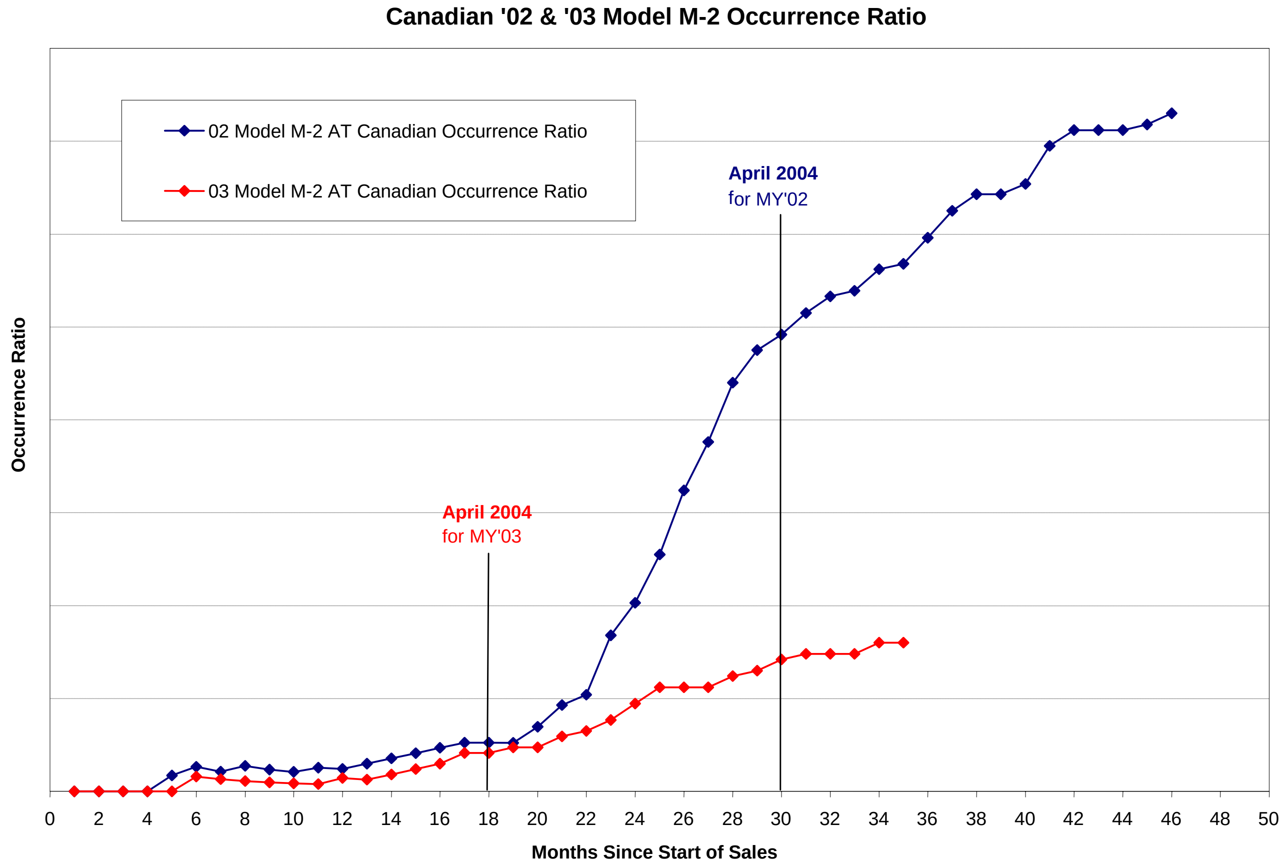
Figure 7a Warranty Claim Occurrence Ratio for Canada vs. USA for Model M-2 Auto Transmission Version for MY 2002



<u>NOTE 1:</u> This plot is for total catalyst warranty repairs regardless of repair reason.

<u>NOTE 2</u>: The Canadian curve stops its rapid rise and bends over to a slope similar to the USA curve after the spring of 2004. MMT was removed from the majority of fuel between January and April 2004.

Figure 7b **Warranty Claim Occurrence Ratios for Canada for the Model M-2 Automatic Transmission Version for MYs 2002 thru 2003**



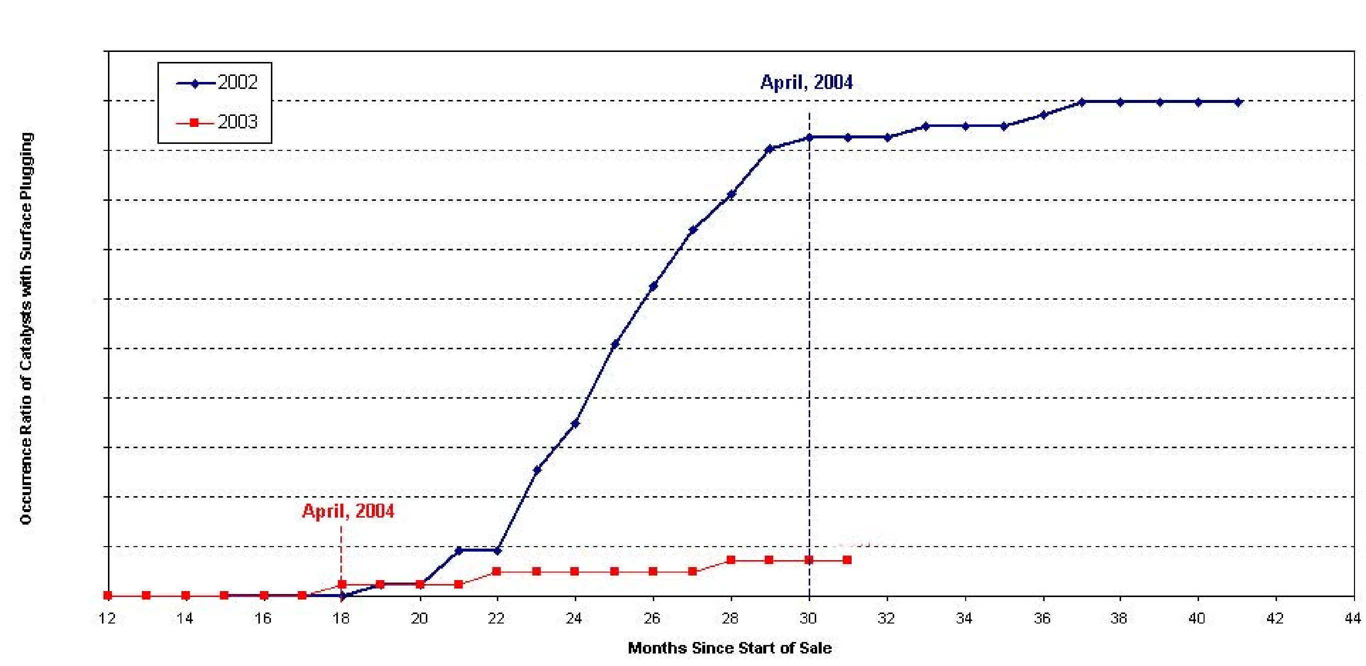
<u>NOTE 1</u> : As was observed in figure 1b for model M-1, this plot for model M-2 shows the same trend where the MY 2003 Canadian occurrence ratio stops tracking the prior model year in the spring of 2004 when MMT was rapidly disappearing from Canadian fuel. MMT was removed from the majority of fuel between January and April 2004.

<u>NOTE 2</u>: This plot is for total catalyst warranty repairs regardless of repair reason.

Best Viewed in Color

Figure 7c Plugging Occurrence Ratios for the Model M-2 Automatic Transmission Version for MYs 2002-2003

Plugging Occurrence Ratio = (Total plugged catalysts verified via inspection of all replaced catalysts) divided by (model year sales to date)



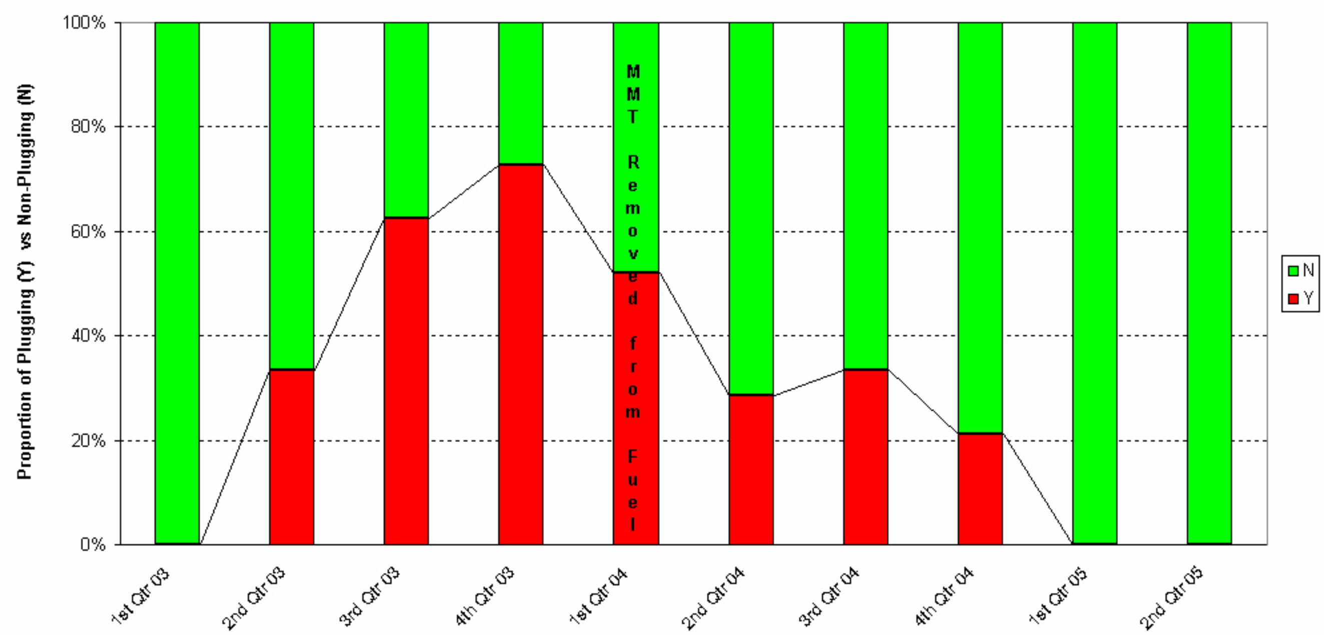
NOTE 1: All catalysts replaced under warranty were returned from dealers for inspection by the manufacturer. This graph shows the occurrence ratio for only those catalysts that were found to have surface plugging or flow restriction. The 100% inspection program ran until late summer 2004, following the removal of MMT from the majority of gasoline. After that the number of MMT plugged catalysts being received on a month-to-month basis declined dramatically and a visual inspection revealed a greatly diminished occurrence of plugging and accumulation in the catalysts that were returned. At that point in time a less comprehensive inspection protocol was adopted and only those catalysts exhibiting any kind of accumulation or plugging (approximately 10% or less) were photographed and flow tested. Catalysts that appeared to be affected by MMT were selectively retained for evidentiary and demonstration purposes.

NOTE 2: The flattening trends for each model year can be seen to begin occurring in the April 2004 time frame when MMT was rapidly disappearing from Canadian fuel. Again as in figure 7b, the 2003 model year stops tracking the prior model year around this same time period.

Best Viewed in Color

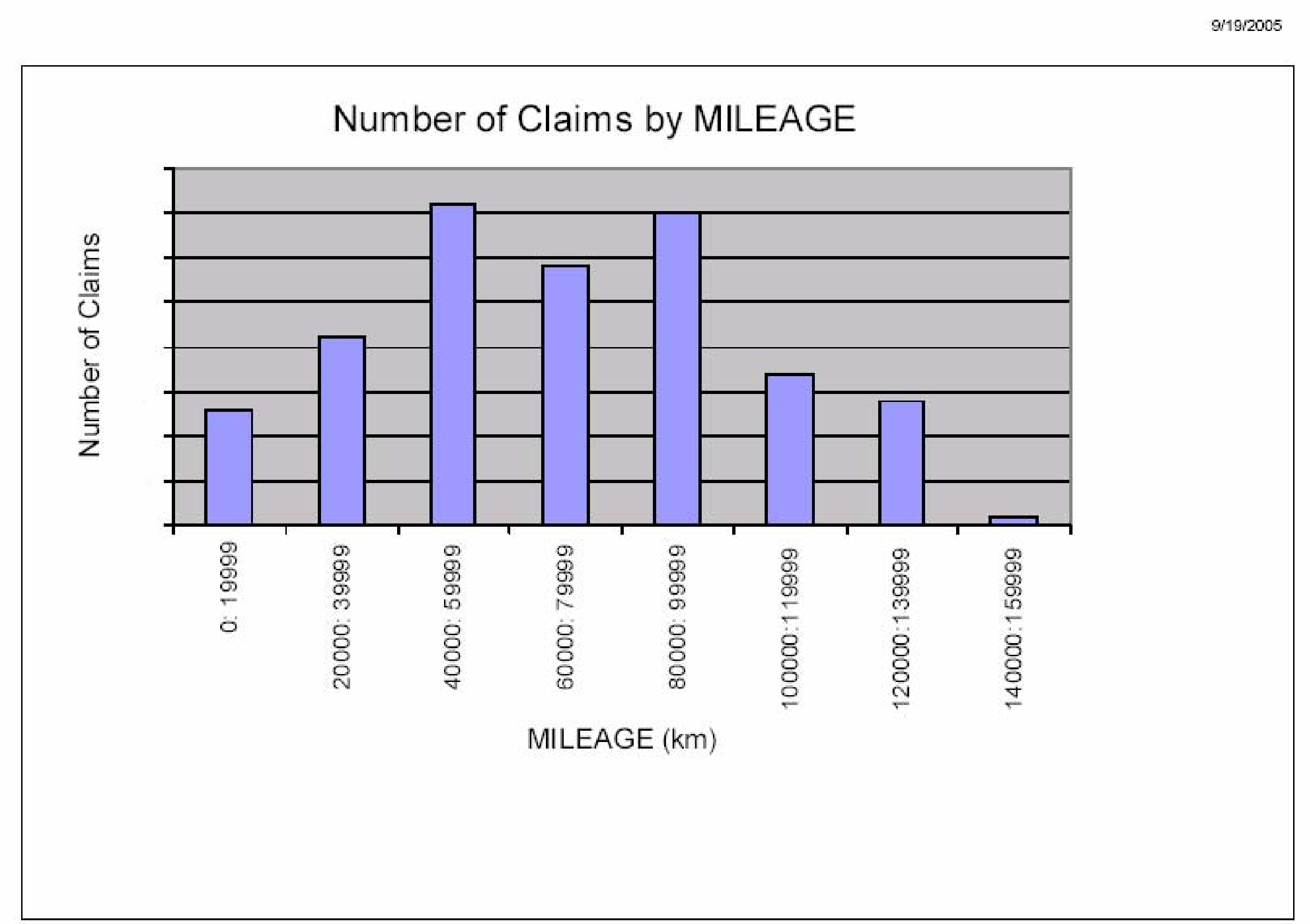
Figure 8

Catalytic Converters observed to have Surface Plugging and/or Restricted Flow
2002-2003 MYs Combined for Model M-2 w/Automatic Transmission
(Inspected Warranty Catalysts)



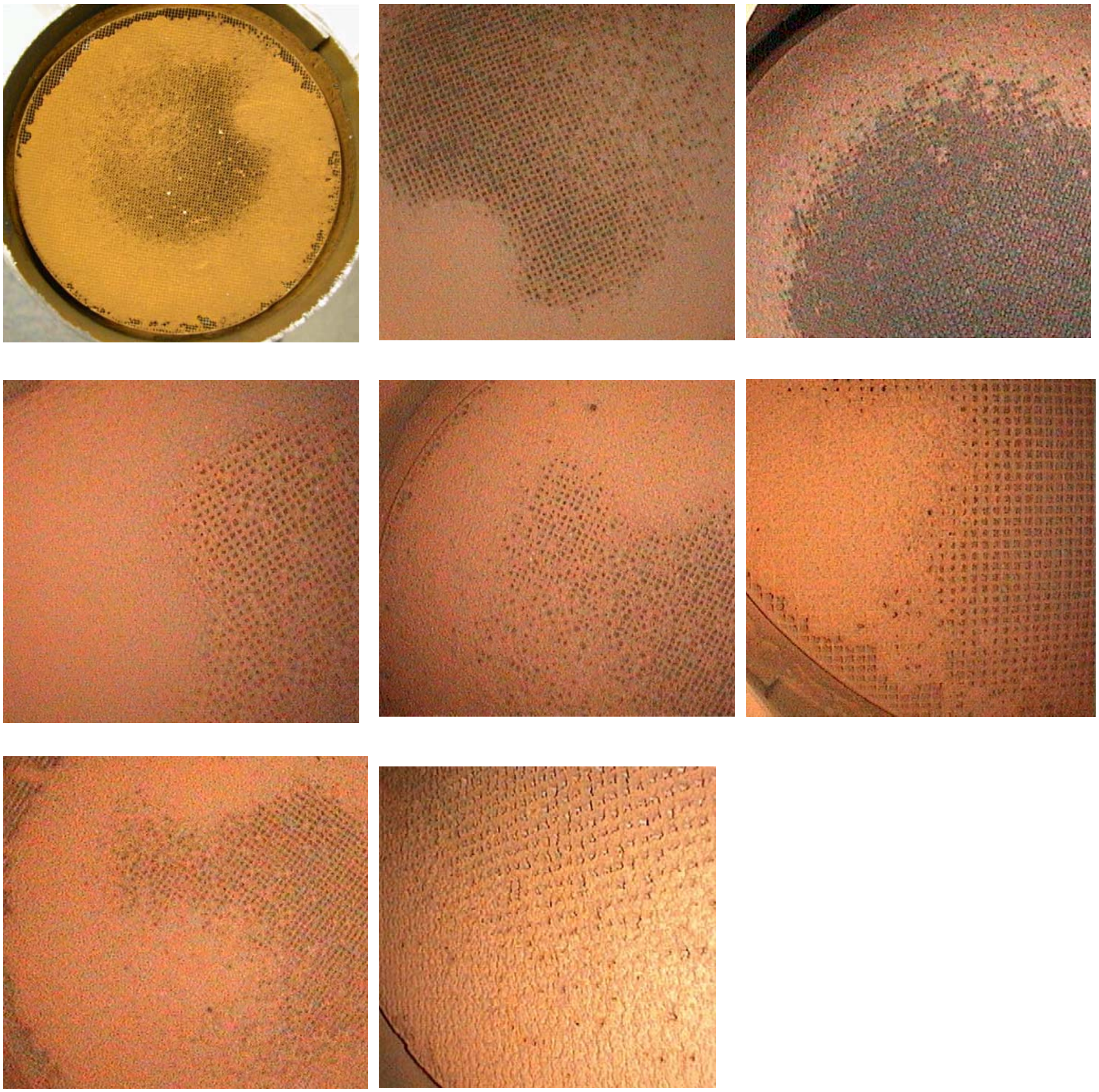
Best Viewed in Color

Figure 9 Distribution of Total Catalyst Warranty Claims vs. Mileage (in km) for Model M-2 for MY 2002-2003



Best Viewed in Color

Figure 10 Sample Pictures of Canadian Market Catalysts from Model M-2



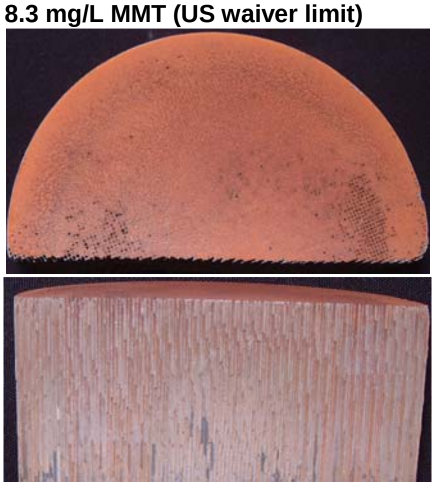
Best Viewed in Color

Figure 11a Pictures of Catalyst from Road and Dynamometer Durability Testing of MY 2001 Model M-1

2001 Model M-1 Durability Testing

Case1
Plugging occurred during vehicle durability testing on actual roads

Mileage : 38Kmile (=60,800km)
(5K w/ clear fuel, + 38K w/ MMT)
Conditions : Normal driving in US; city, highway, and mountain roads.
Engine : Model M-1 4 cylinder less than 2 liter
Catalyst : Close-coupled 600cell
Fuel : 8.3 mg/L MMT (US waiver limit)



Case2
Plugging occurred during engine bench testing

Time : 380 hours
Conditions : Equivalent to 120 km/hr cruise
3000rpm, -200mmHg, A/F: 5 – 6% CO
Engine :
Catalyst : } Same as Case 1
Fuel :

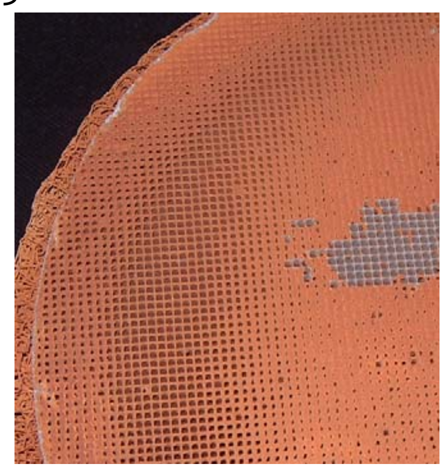
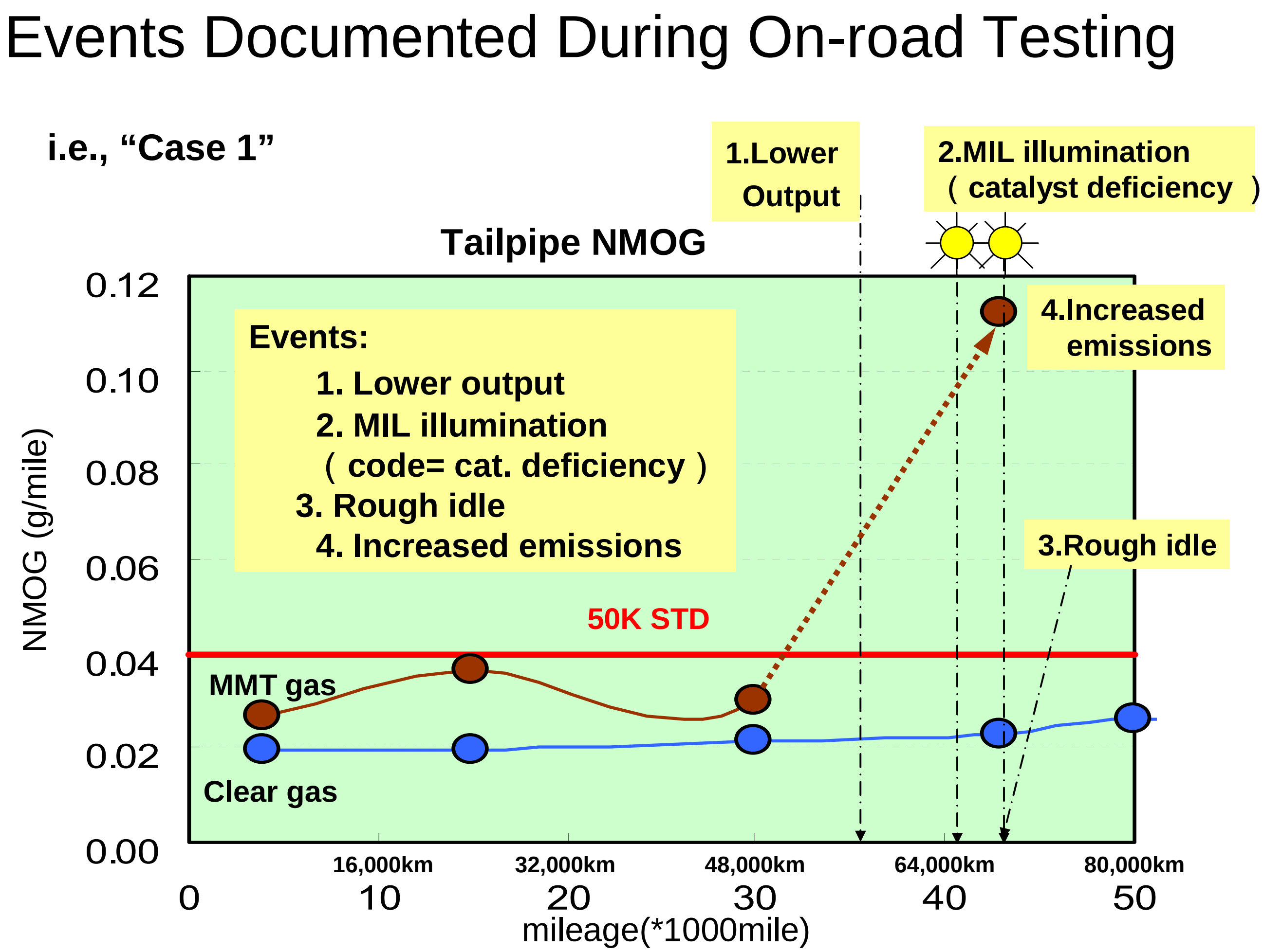
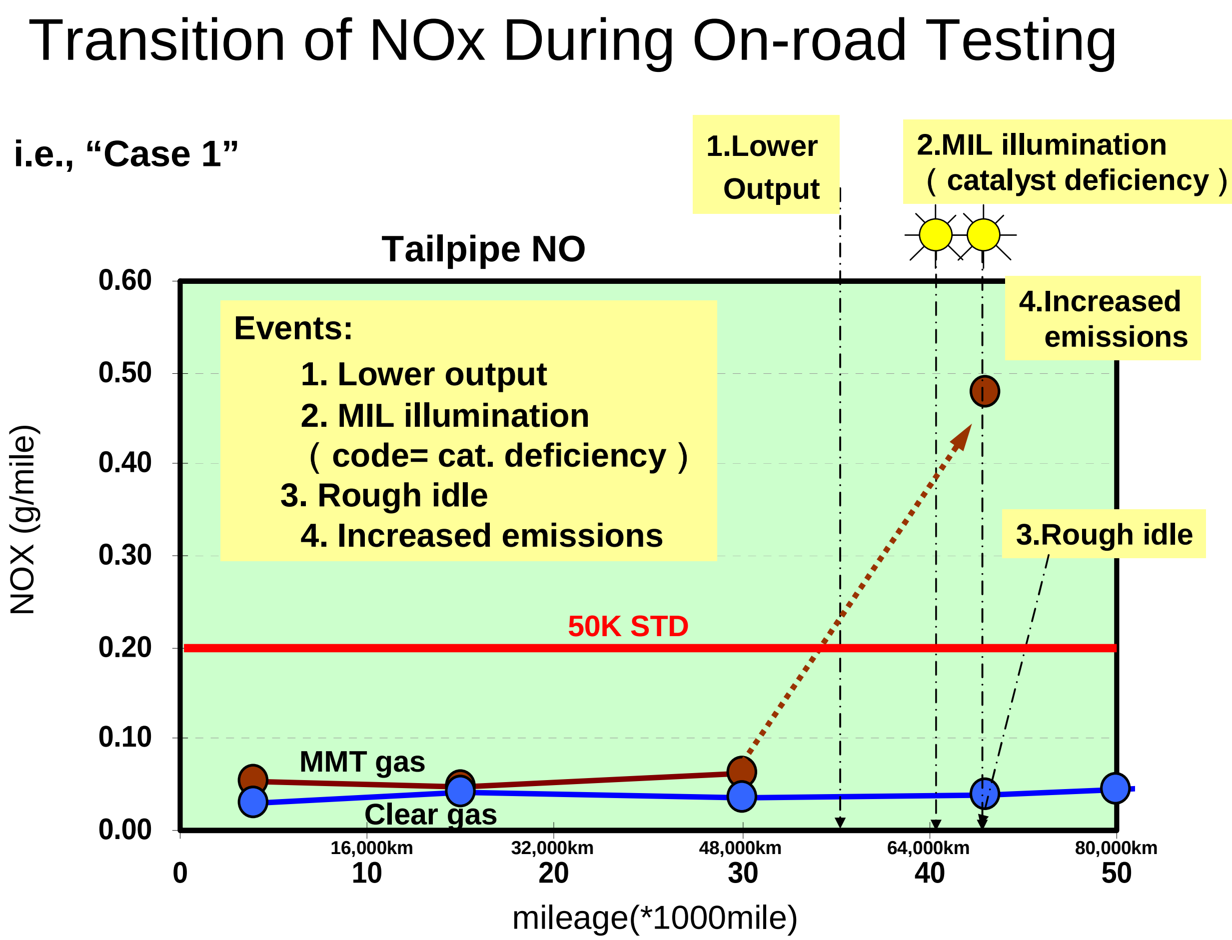


Figure 11b **<u>NMOG</u> Emissions vs. Mileage for Road Durability Testing of Model M-1**



"Clear" fuel was used for the first 5K, remainder of mileage was accumulated with MMT fuel

Figure 11c **NOx Emissions vs. Mileage for Road Durability Testing of Model M-1**

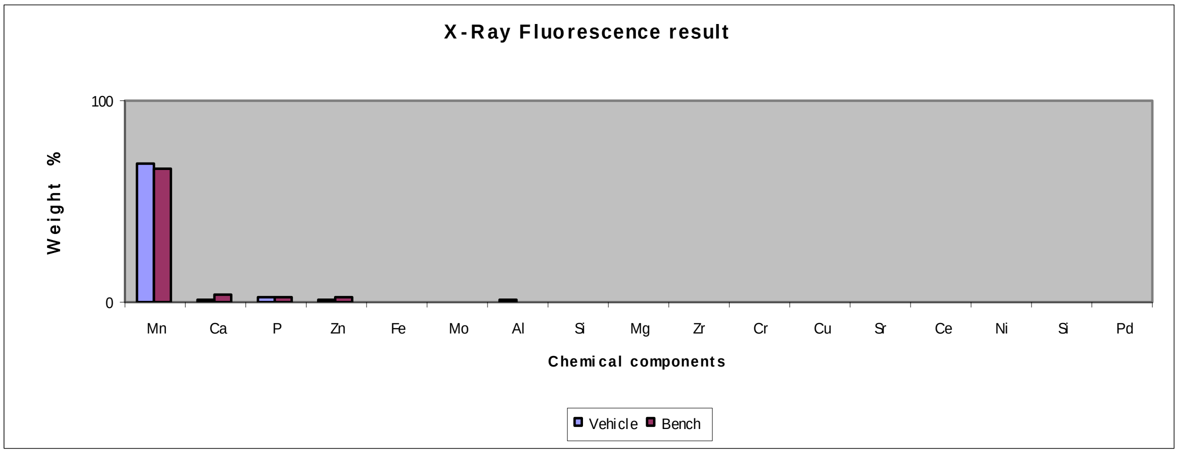


"Clear" fuel was used for the first 5K, remainder of mileage was accumulated with MMT fuel

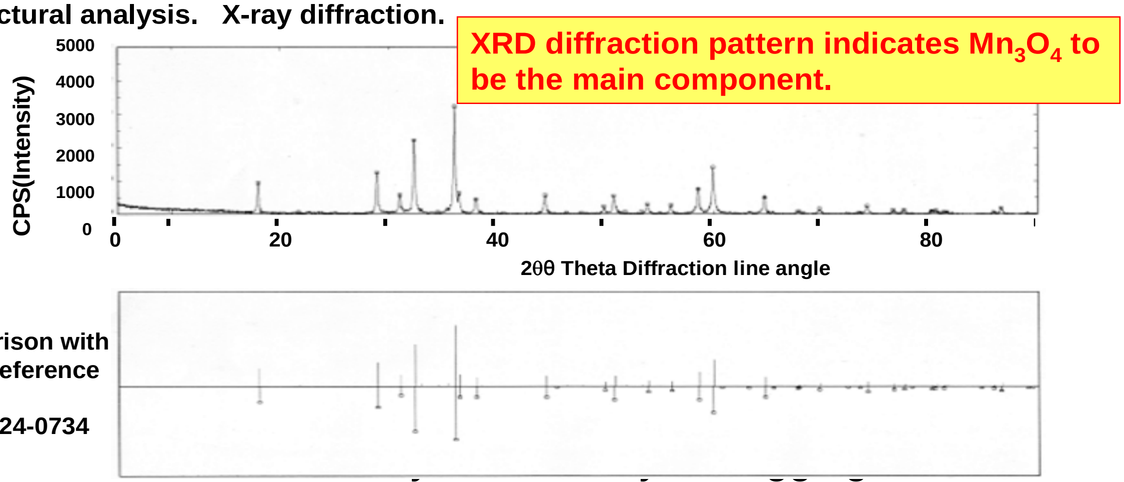
Best Viewed in Color

Figure 12 Analyses of Deposits from both the Road and Dynamometer (Bench) Durability Tests

Quantitative analysis of deposit accumulated on catalyst face indicates that Mn_3O_4 is the main component. (Data are in wt%)



Structural analysis. X-ray diffraction.



Comparison with Mn_3O_4 reference pattern JCPDS 24-0734

<u>NOTE</u>: The X-ray diffraction graph corresponds to the deposit formed in "bench" indicated above.

Best Viewed in Color

Figure 13 Pictures of plugged catalysts from model M-1 obtained from the Canadian market in an early study of the plugging situation

(These catalysts were obtained during August-September 2002)

209,600 km (131K miles)

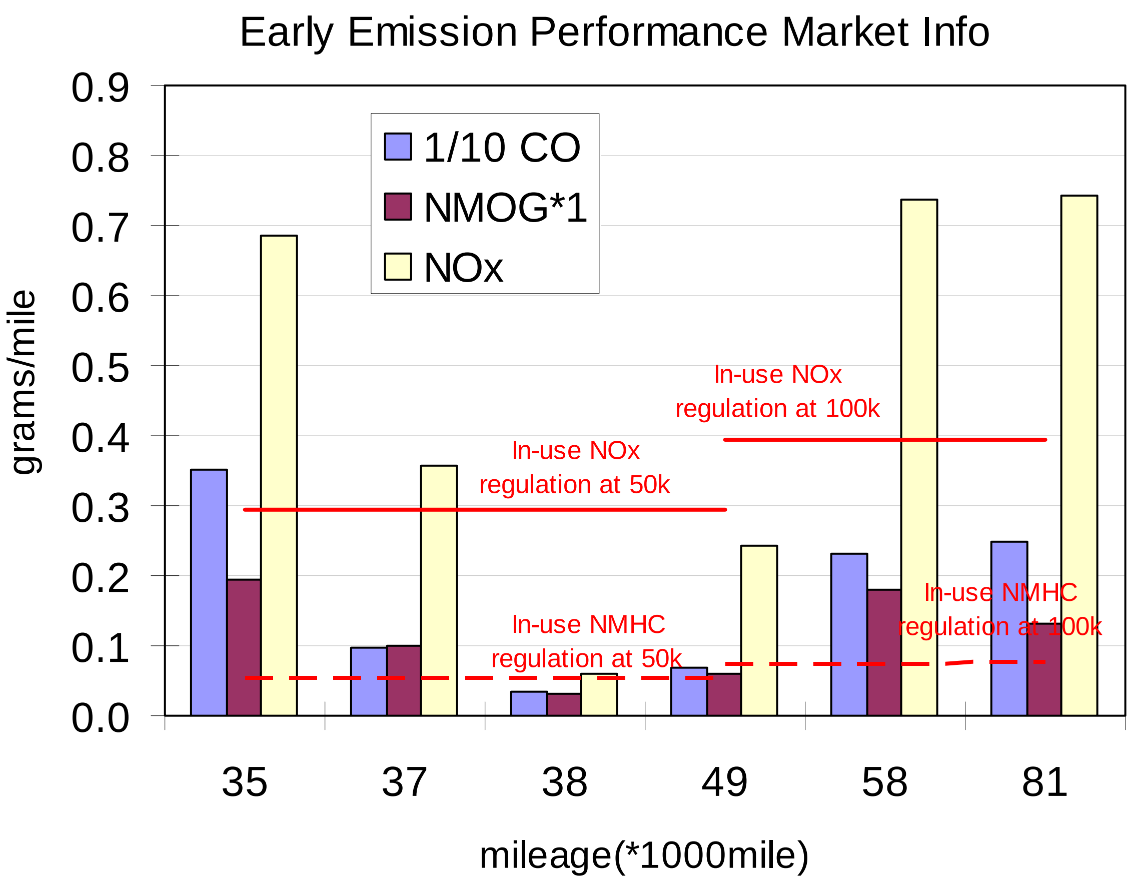
164,800 km (103K miles)

137,600 km (86K miles)

60,800 km (38K miles)

Best Viewed in Color

Figure 14a Emission Testing of Six Market Catalysts from MY 2001 Model M-1



NOTE: 3 of the 6 sample catalysts exhibited emission levels higher than what is permitted under federal in-use exhaust emission tests. More importantly, emissions from 5 of the catalysts exceeded baseline (non-MMT fleet) emissions shown in figure 14b by 3.5 to 11 times for NOx and by 2 to 6 times for THC. Note the vehicle with the lowest emissions was not a warranty case.

Profiles of the 6 catalysts:

35K miles	from Elnora, Alberta - warranty case due to claim of lack of power
37K miles	from Long Sault, Ontario - warranty case due to catalyst MIL on, and claim of poor acceleration and bad fuel economy
38K miles	from Toronto, Ontario - manufacturer survey vehicle obtain through dealer (not a warranty case)
49K miles	from Waterloo, Ontario - warranty case due to catalyst MIL on.
58K miles	from Dundas, Ontario - warranty case due to catalyst MIL on, and claim of poor acceleration and bad fuel economy.
81K miles	from Winnipeg, Manitoba - warranty case due to catalyst MIL on and claim of poor acceleration.

Best Viewed in Color

Figure 14b "Baseline" In-Use Emissions from Model M-1

Note: The "baseline" emissions shown in figure 14b are from a randomly procured non-MMT in-use fleet in the U.S. market. The vehicles were procured and tested according to mandatory "in-use verification program" (IUVP) testing requirements under EPA's "CAP2000" certification regulations. This data was the required four year old "high mileage" IUVP test data applicable to the MY2001 model M-1. Vehicles 1 through 4 were procured and tested in Ann Arbor, Michigan and vehicle number 5 was procured and tested in Denver.

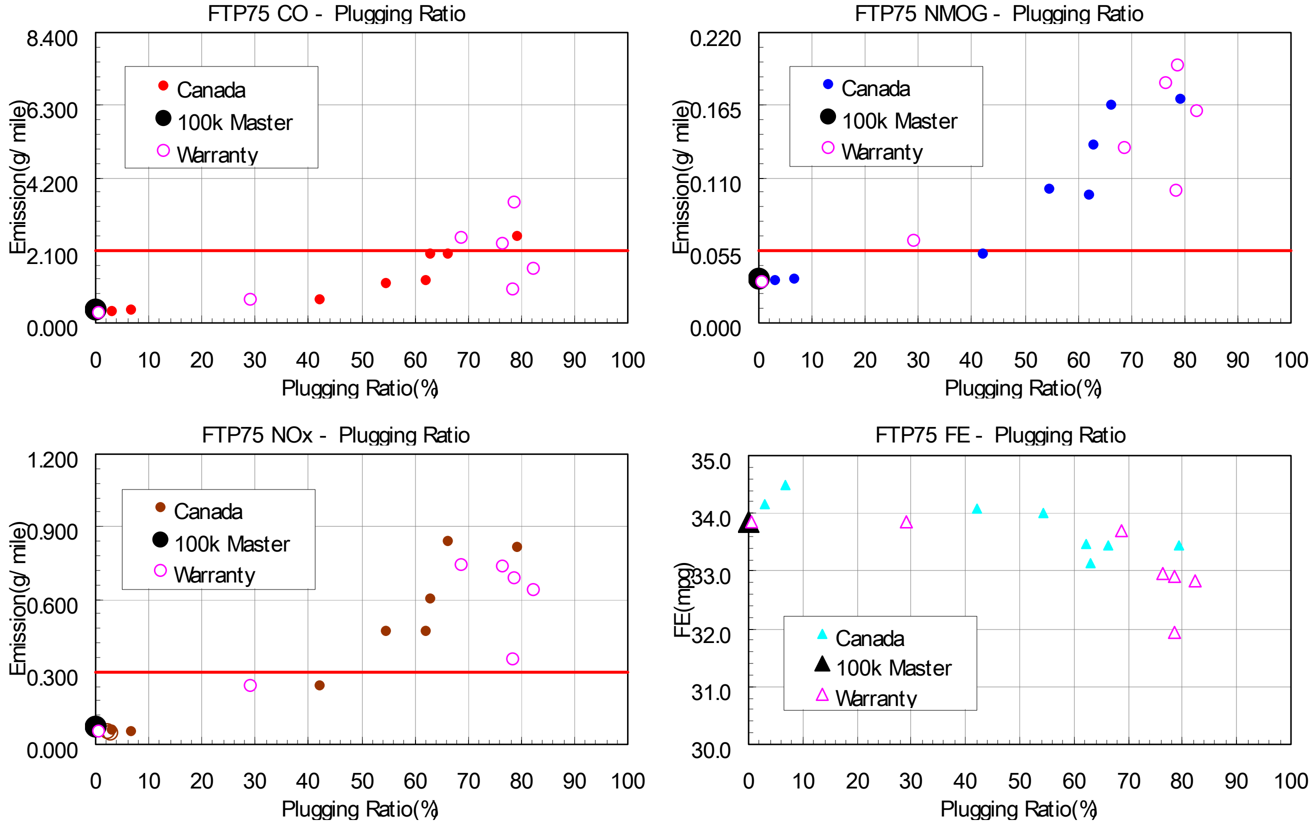
Official IUVP Data Submitted to EPA for model M-1

Test Vehicle	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5 In Denver	Average
Actual Mileage (miles)	89002	66282	71804	61859	93364	76462
Actual Mileage (Km)	143204	106648	115533	99531	150223	123028
FTP Emissions						
CO	0.43	0.41	0.39	0.43	0.32	0.3957
NOx	0.068	0.083	0.083	0.067	0.057	0.0716
NMHC	0.0356	0.0320	0.0333	0.0321	0.0296	0.0325
THC	0.0364	0.0330	0.0341	0.0327	0.0310	0.0334

Best Viewed in Color

Figure 15 Emission and Fuel Economy Plotted vs. Plugging Ratio MY 2001 Model M-1

There is a correlation between emission (&FE) degradation and plugging ratio.
"Warranty" = Customer complaint and/or MIL illumination
Red line indicates the 100K mile ULEV standard



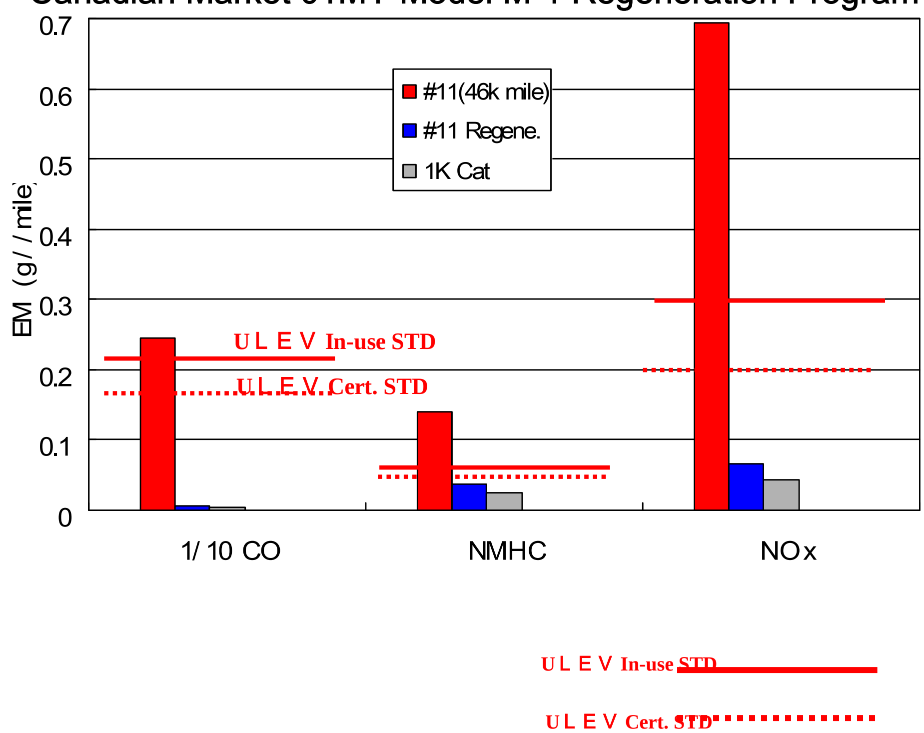
NOTE: For comparative purposes, the "100K Master catalyst" was installed on the emission test vehicle to determine baseline emissions with a thermally aged catalyst to simulate in-use operation to 100,000 miles on RFG with no MMT additive. It was free of manganese deposits on the substrate surface.

Figure 16a

01MY Model M-1 Plugged Catalyst Regeneration (as of Nov/19/2002)

After the regeneration, the emission performance of market catalyst was almost recovered.

<Canadian Market 01MY Model M-1 Regeneration Program>



<Test catalyst>
01MY Model M-1 Canada Cat
OD 73706 km (46k mile)
Ontario
Warranty
MIL on (P0420)

Figure 16b Description of Procedures Used Remove Deposit for the Testing Addressed in M-16a.

Removal of the reddish-brown deposits on the catalyst was partially accomplished by mechanical means after mileage accumulation on MMT-containing fuel was suspended. Removal of the deposits was attempted by mechanical means. Different sizes of ceramic grinding media were selected in an attempt to determine effective means of removal. The goal was to remove as much of the deposit from the catalyst face as possible without damaging the catalyst ceramic substrate. The grinding media was poured into the catalyst canister, sealed, and then the canister was physically shaken by hand for at least five minutes. Post-inspection revealed that a significant portion of the reddish brown deposits had been removed. Care was taken to avoid exposing the technician to the toxic manganese deposit dust generated in this process. [See pictures below illustrating the grinding material.]

The following describes the deposit removal process in step by step detail:

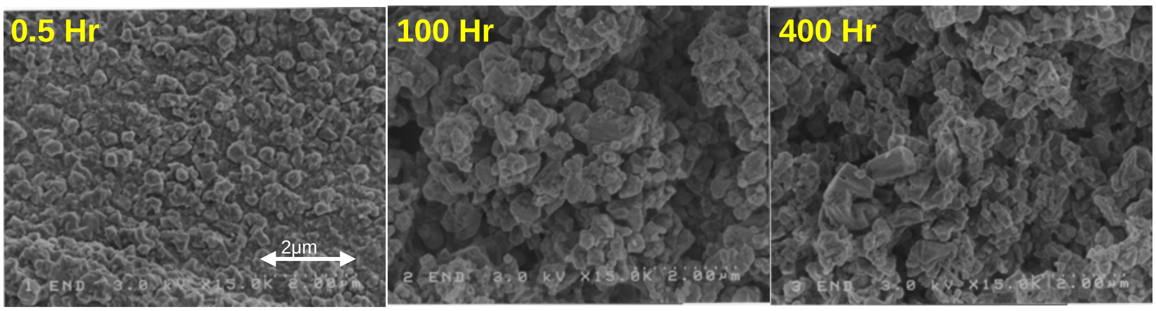
- Remove a catalyst from an engine
- Hold the catalyst upright
- Pour ceramic bead (grinding media) from one of exhaust port. Its diameter is 1/16" and shake the catalyst back and forth for five minutes by hands so this media flows on the catalyst surface.
- Take out used grinding media.
- Pour new ceramic bead (grinding media). Its diameter is 1/8" and shake the catalyst back and forth for five minutes by hands.
- Take out used grinding media
- Pour new steel bead (grinding media). Its diameter is 1/8" and shake the catalyst back and forth for five minutes by hand.
- Take out used grinding media
- Pour new ceramic bead (grinding media). Its diameter is 1/16" and shake the catalyst back and forth for five minutes by hands.
- Take out used grinding media.
- Blow catalyst substrate from back by using pressurized air

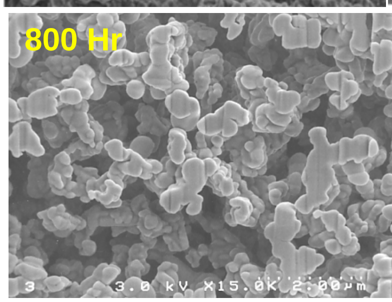
[NOTE: This process of attempting to remove the manganese oxide deposits from a contaminated catalyst's face would be impractical for anywhere outside of a controlled laboratory due to health exposure concerns and variability of results. It would not be practical in a service or warranty repair environment.]

Figure 17

Deposit Morphology

- Deposit appears porous
- Particle size range remains constant at 0.2-0.8um.





Photos by SEM ×15000

Stainless-steel bar in front of catalyst

Test conditions:

N e : 3000rpm,-200mmHg , Ex.gas temp. :715℃ , A/F : 12.5

Actual catalyst deposit by dyno test @ 800hrs

Exhaust gas temperature : 715℃

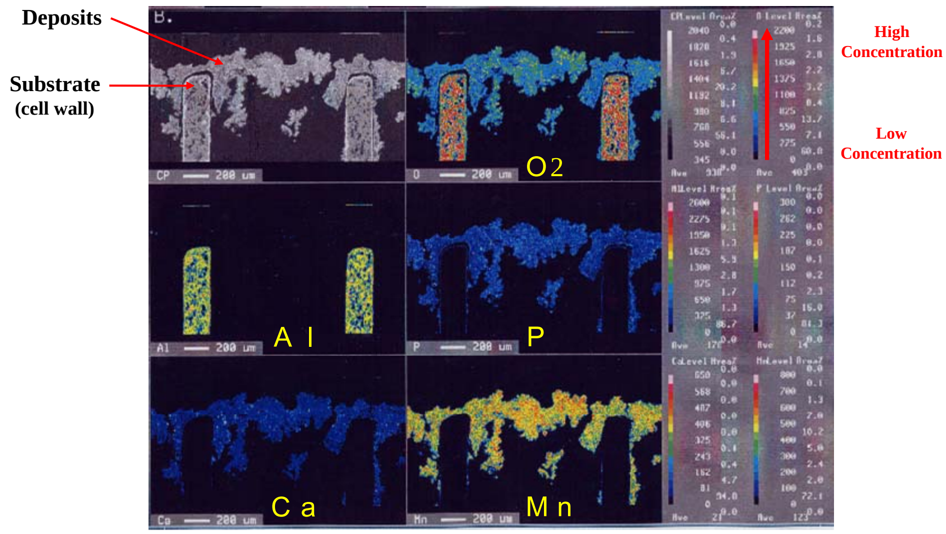
Best Viewed in Color

Figure 18 Evidence of Physical Deposition

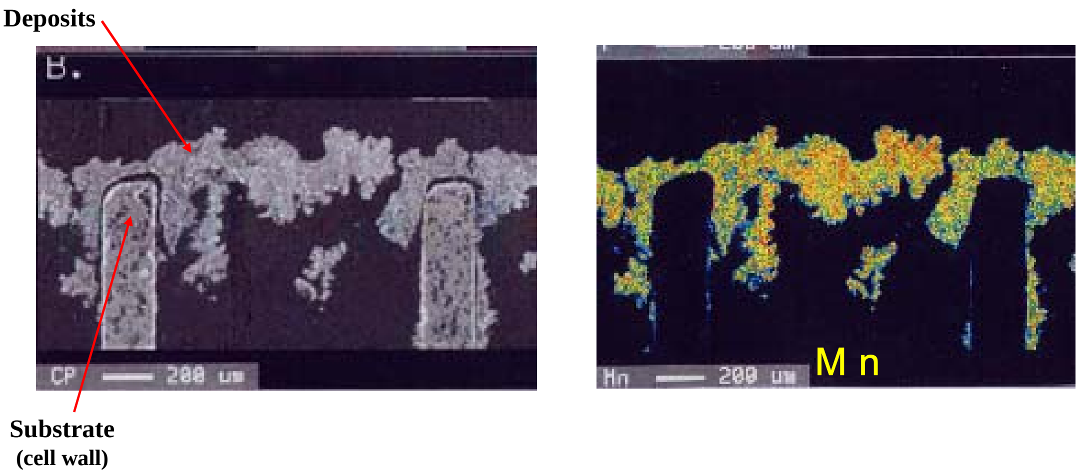
Electron Microprobe Analysis

There is no chemical bond between the substrate and the deposits. The manganese oxide has physically deposited onto the catalyst surface; it was not formed by a reaction with the substrate.

Catalyst Inlet Cross-section Durability vehicle @50,000 mi



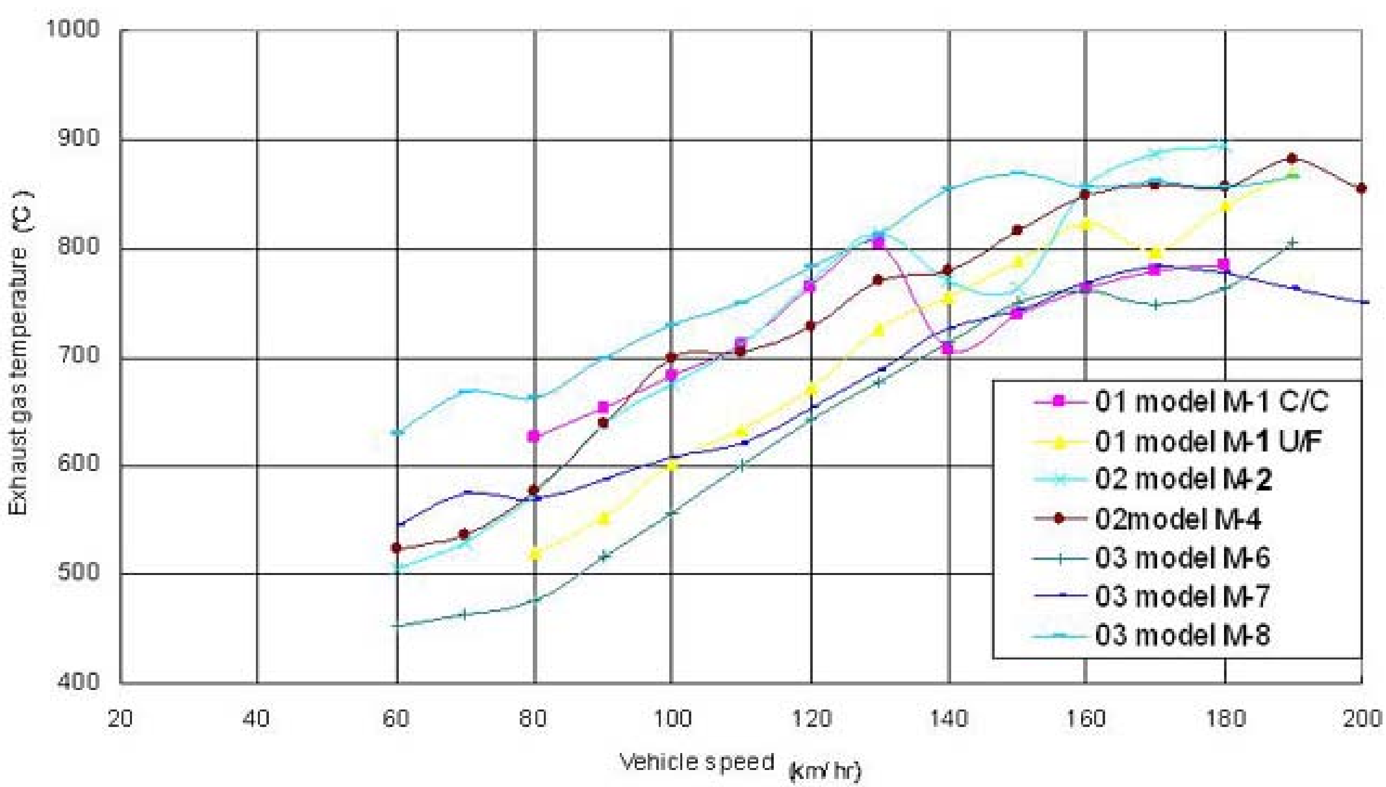
The bridge of deposits between the cell walls contains a high concentration of manganese.



Best Viewed in Color

Figure 19

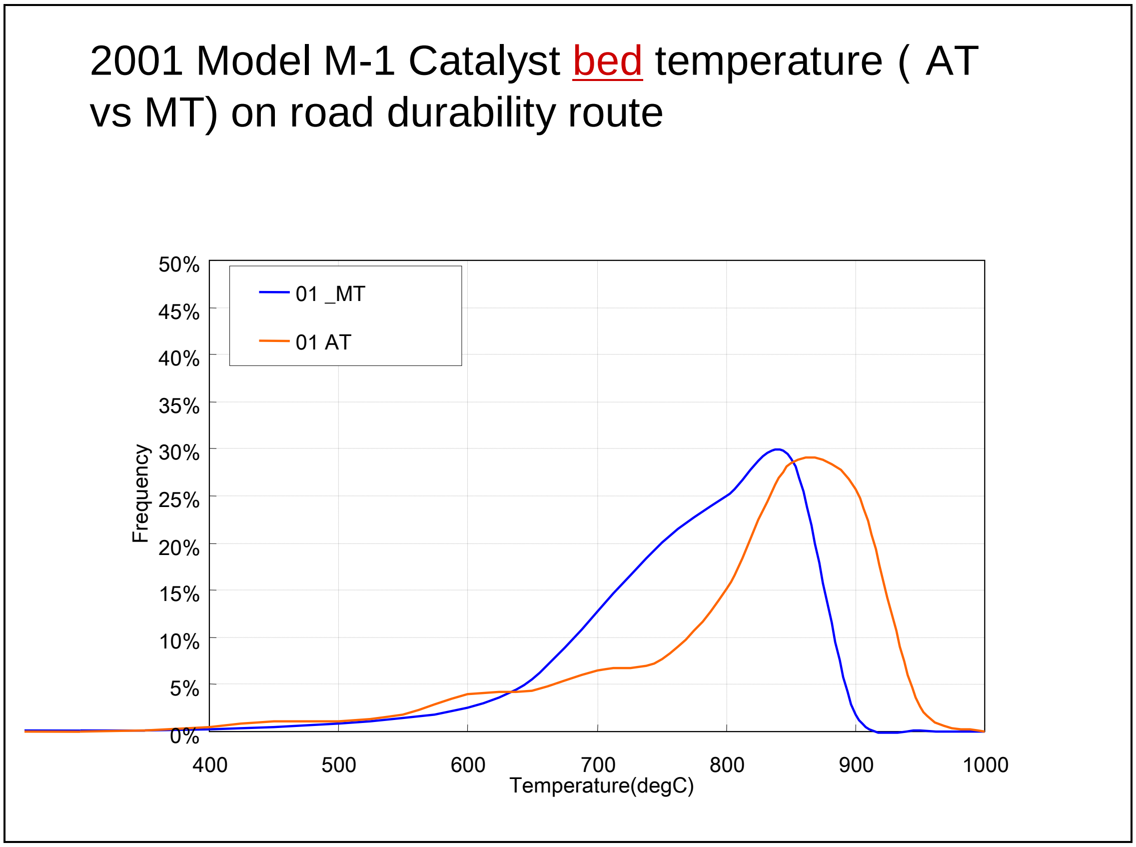
Exhaust Gas Temperature in Front of Catalyst Surface
(Measurement location was 10 mm ahead of Catalyst Surface)
(During Cruise Condition)



Note: The first two vehicles in the key for this chart had manual transmissions.

Best Viewed in Color

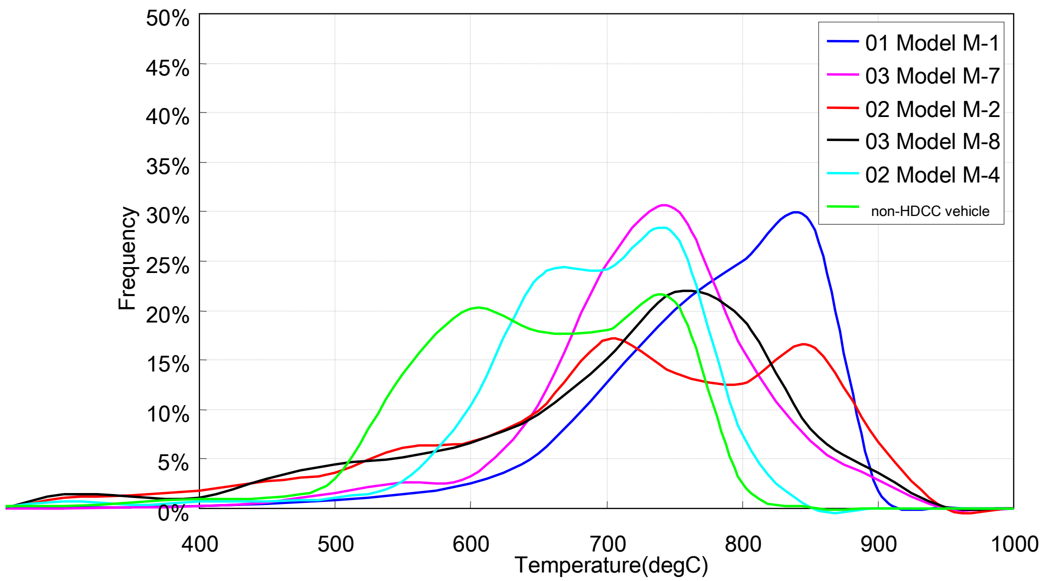
Figure 20



Best Viewed in Color

Figure 21

Catalyst bed temperature during road durability driving



Effect of MMT upon Vehicles in a Road Test Program

ABSTRACT

A recent test program conducted by the auto industry[1] confirmed that the gasoline additive MMT (Methylcyclopentadienyl Manganese Tricarbonyl) has a detrimental effect upon vehicle hardware and tailpipe emissions. Advanced technology vehicles designed to meet the most recent North American emission standards were most affected. As a consequence, Manufacturer M began to use MMT-containing fuel in test vehicles. The focus of this testing was on Manufacturer M vehicles that were popular in the Canadian market, where MMT fuel was common until recently. The MMT fuel was found to cause driveability problems, catalyst plugging, MIL illumination, tailpipe emission increases, or combinations thereof in a variety of vehicles, regardless of engine/catalyst configuration.

The testing was performed near Manufacturer M's Proving Center, using normal driving on city, highway, and mountain roads for mileage accumulation. Emission testing and vehicle inspections were performed at Manufacturer M's R&D facility. The test fuel used for mileage accumulation contained MMT at a concentration equal to the US limit for conventional gasoline, 0.031 g/gal as manganese. This is less than one half the allowable limit in the Canadian market. (It is illegal to use MMT in California market gasoline, and in federal reformulated gasoline.)

The test results indicated that all seven vehicles in this program exposed to MMT fuel developed MMT-related deposits on the primary catalyst. In almost all cases, this resulted in tailpipe emission increases for both NMHC and NOx, when compared to the results obtained from MMT-free fuel. In some cases, the catalyst surface became completely plugged at relatively low mileage intervals. Chemical analysis of the deposit material indicated that it was composed of manganese oxide, specifically Mn_3O_4, with only trace amounts of other compounds. When fueled with gasoline <u>not</u> contaminated with MMT, identical vehicles exhibited no catalyst deposits throughout their useful life, as defined by the CARB; (≥100,000 miles). This result supported the fact that catalyst deposits were not observed during vehicle development, nor were they observed in markets not using MMT.

INTRODUCTION

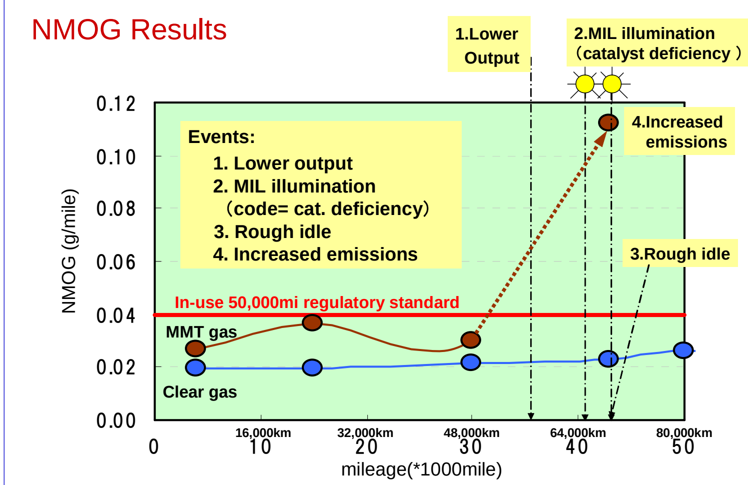
The Alliance of Automobile Manufacturers (AAM) and the Association of International Automobile Manufacturers (AIAM) recently undertook a large study of the effect of Methylcyclopentadienyl Manganese Tricarbonyl (MMT) upon vehicle emissions and performance. In the most recent phase of this study[1], the vehicles tested were all first-generation Low Emission Vehicles (LEVs), all with catalytic converter (catalyst) cell densities of

400cpsi or less. Virtually all of the MMT-fueled LEVs in this study exceeded NMOG certification standards by the end of the program, (100,000 miles). CO, NO_X, and CO_2 emissions for the MMT-fueled vehicles were also significantly higher at 100,000 miles than their counterparts, which were fueled with non-MMT fuel. One of Manufacturer M's vehicles was included in this study.

After the study, Manufacturer M began using fuel containing MMT in testing of the next generation of this vehicle, Model M1. This was the first ULEV-certified version of Model M-1, and it had a 600-cpsi catalyst, (a common cell density used to achieve ULEV levels). This test program was conducted under real-world conditions on roads near Manufacturer M's Proving Center, as described later in this paper. At about 35,000 miles, the vehicle's driver complained of a loss of power. Near the 40,000 mile point, the Malfunction Indicator Lamp (MIL) illuminated. The corresponding MIL code indicated a catalyst-related problem. At 43,000 miles, the driver complained of very rough running, and the Model M1 was brought to Manufacturer M's emission laboratory for testing.

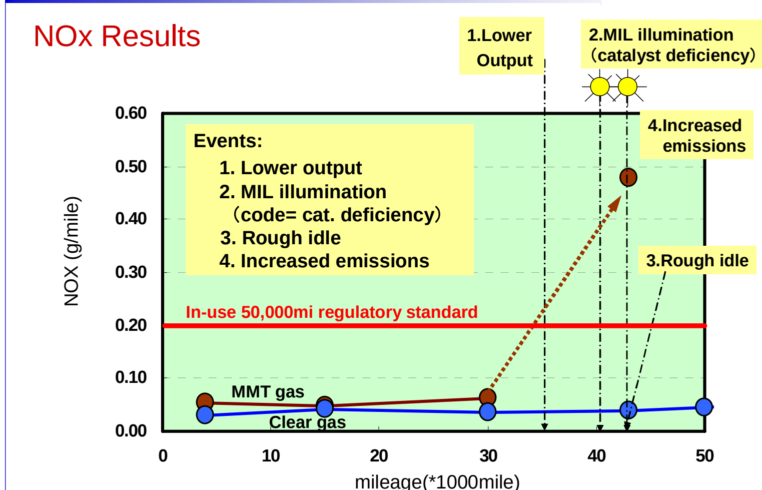
Emissions were found to have increased suddenly and drastically. This sequence of events is described in Figures 1 and 2. Since the MIL code indicated a catalyst-related problem, the converter was removed and replaced with a new one. As can be seen in Figure 3, the vehicle's emissions immediately returned to "new-vehicle" levels, even below those of an identical vehicle with similar mileage accumulation that had been fueled on MMT-free fuel. Having determined a direct relationship between the observed emission increases and the condition of the catalyst, an investigation of the catalyst was given priority over research involving other engine parts.

Figure 1 2001 Model M-1 Durability Testing



"Clear" fuel was used for the first 5K, remainder of mileage was accumulated with MMT fuel

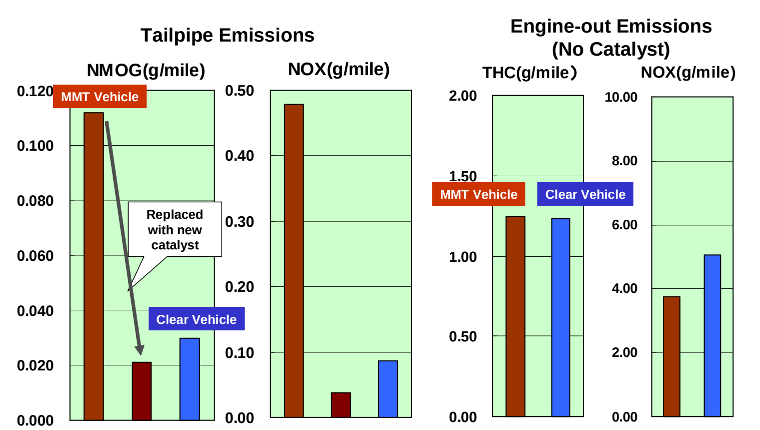
Figure 2 2001 Model M-1 Durability Testing



"Clear" fuel was used for the first 5K, remainder of mileage was accumulated with MMT fuel

Figure 3 Cause for Emission Increase

Catalyst problem was the cause for emission increase



MMT Vehicle 68,8000km (43K mile) / Clear Vehicle 80,000km(50Kmile)

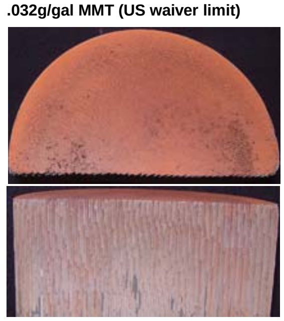
v.081307

Due to the aforementioned observations, the converter can was cut open and the catalyst inspected. The catalyst surface was found to be almost completely plugged with reddish-brown deposits. Sectioning of the catalyst revealed that the plugging was primarily a surface phenomenon, although some deposit material was present deep within the catalyst channels; see “Case 1” in Figure 4. Upon discovery of these deposits, an engine bench test being run concurrently was halted, and the catalyst removed for inspection. (The engine, catalyst, and fuel were identical to those used in the vehicle testing.) The surface of this catalyst appeared virtually identical to that from the vehicle test; i.e., the surface was extensively plugged, despite the fact that the test conditions were much different between the two test programs. See Figure 4 for details of both programs. The deposit material was scraped from the surface of both catalysts, and submitted for chemical analysis by X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD). The former test is an elemental analysis, while the latter test identifies the specific crystalline compounds present in the sample. XRF revealed that the deposits from both catalysts consisted primarily of manganese. XRD analyses indicated that manganese oxide, specifically Mn_3O_4, was virtually the only crystalline material present. Therefore, the deposit clearly consisted of MMT combustion products. Analysis results are shown in Figure 5. Note that XRF does not detect elements lighter than fluorine, so oxygen does not appear in the results.

Figure 4 Catalyst Plugging Discovered

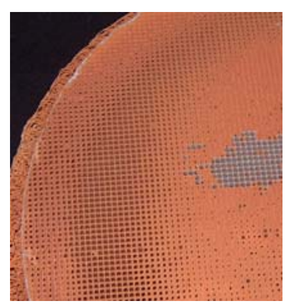
Case1
Plugging occurred during vehicle durability testing on actual roads

Mileage : 38Kmile (=60,800km) (5K w/ clear fuel, + 38K w/ MMT)
Conditions : Normal driving in US; city, highway, and mountain roads.
Engine : 1.7L SOHC
Catalyst : Close-coupled 600cell
Fuel : .032g/gal MMT (US waiver limit)



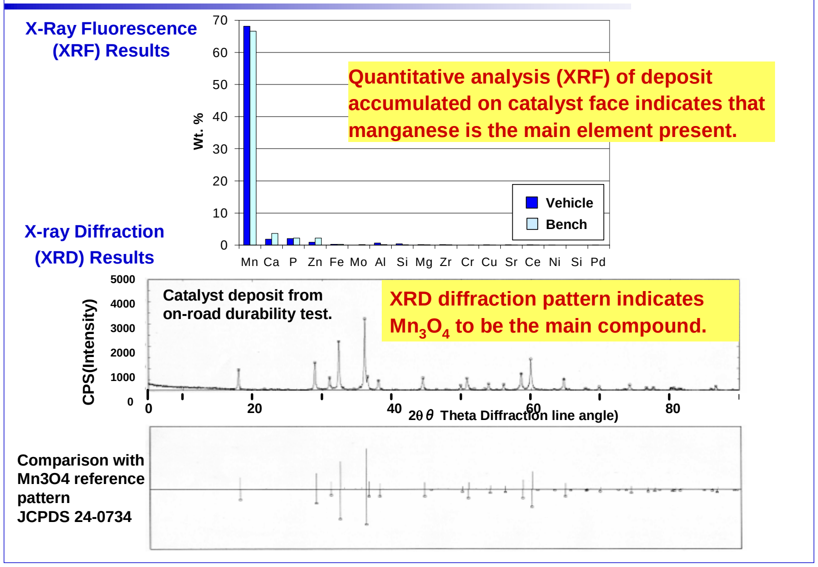
Case2
Plugging occurred during engine bench testing

Time : 380 hours
Conditions : Equivalent to 120 km/hr cruise 3000rpm, -200mmHg, A/F: 5 – 6% CO
Engine : / **Catalyst :** / **Fuel :** Same as Case 1



v.081307

Figure 5 Analysis of Catalyst Deposit



As a result of this testing, vehicles were immediately inspected in the Canadian market, where the fuel typically contained MMT at concentrations at or above that of the test fuel used for the aforementioned vehicle and bench tests.(2) Catalysts from various vehicles were inspected in the field and found to be partially plugged with manganese oxide deposits.

This report documents the test program conducted at the Proving Center and Manufacturer M's R&D facility subsequent to the observed MMT-induced catalyst plugging in Model M-1. A second test program performed at an independent laboratory was initiated to study catalysts retrieved from the Canadian market. The details and results of the latter program are described in a separate report(3).

EXPERIMENTAL

Program Design

This program evolved from a pre-existing, routine test program. This program has been used successfully for many years to ensure the emission performance of vehicles in the market. As later described, it consists of normal driving under a variety of conditions, on actual highways. The only change made to the original program was the addition of MMT to the mileage accumulation fuel. As such, a classical statistical approach was not taken. Such an approach would have required a large fleet of vehicles and a lengthy test period, and was therefore inappropriate for the purpose at hand.

Vehicles

The selection of vehicles to be included in the MMT road testing at the Proving Center was generally based on their sales volume and share of the Canadian market. For example, the Model M-1 has historically been popular in Canada. It accounts for about half of all Manufacturer M-branded sales in Canada. A total of eight vehicles were included in this program, including a matched pair of model M-7 vehicles. One of these vehicles was operated only on MMT fuel, while the other was operated only on non-MMT (“clear”) fuel. Only new, standard production vehicles were used. The specifications for vehicles selected for this program are detailed in Appendix 1. All vehicles involved in this program received maintenance procedures as per the standard maintenance schedules of Manufacturer M.

Fuel

Fuel for this program was obtained from Haltermann products, a subsidiary of Dow Chemical. The base fuel was based on a formulation for Arizona fuel with an AA volatility class. This fuel was non-oxygenated, but otherwise similar to California Phase II RFG. Haltermann added MMT to this base fuel at their refinery, analyzed it to confirm the target manganese concentration had been achieved, and shipped it to the Proving Center in tanker trucks. The base fuel was also shipped to the Proving Center for use in the clear-fuel comparison vehicle. Specifications for both fuels are shown in Appendix 2, together with typical results. Note that the specified manganese concentration for the MMT fuel was 0.031 g/gal, with a tolerance range of +/- 0.005 g/gal. This was equivalent to the US limit for manganese in conventional fuels, and about half the concentration allowed in Canada. Fuel samples were routinely sent to a credible independent contractor to confirm the manganese content. They used ASTM Method D 3831 to perform these analyses. (This contractor was chosen because of their recognized expertise with this complex method.) The reproducibility of the their results were checked in September of 2002 and March of 2003, by running the D 3831 method in triplicate on samples taken from new batches of the Proving Center test fuel. After dividing the sample, each of the resulting three samples received the complete preparation procedure; i.e., the sample was not simply analyzed three times after a single sample preparation. In both cases, all three results were within 0.001 g/gal; precision was excellent. Accuracy was maintained through the use of multiple, freshly-prepared standard manganese solutions. Manufacturer M personnel audited the contractor’s quality control procedures twice during this program.

Quality control of the vehicle fueling procedure at the Proving Center was maintained by assigning each vehicle a separate gas pump key. For example, vehicles running on MMT fuel received a key that could only activate the pump for the MMT fuel.

Driving Modes for Mileage Accumulation

All mileage accumulation for this program was performed on roads and highways near the Proving Center. The drivers followed two specific courses, but were given no instruction regarding driving behavior, other than to avoid exceeding the posted speed limit. The routes were divided into a “city course” and a “mountain course,” and covered a wide variety of driving conditions. The vehicles accumulated 3630 miles per week on the city course, and 1050 miles per week on the mountain course. (The mountain course was restricted to daytime driving only, due to safety concerns.) Since the drivers were directed to follow the posted speed limit, the actual vehicle speeds in the city course fell between 0 and 35 mph, with stop-and-go driving. This low-speed driving was bracketed by highway driving, as the vehicle traveled to and returned from the city, encountering various traffic conditions en route. The speed profile for the mountain course included intermediate speeds generally between 30 to 60 mph as the vehicle traversed the mountain roads. The highest attitude encountered on the mountain course was about 2100 meters. It should be noted that these courses were previously developed and used as representative US driving cycles for the Manufacturer M durability program; no course alterations were made for the MMT program.

Vehicle Testing

The program vehicles were driven to Manufacturer M's R&D Center to undergo test and inspection procedures. This occurred when each vehicle was new, and at nominal 15,000-mile intervals thereafter. Between test intervals, the vehicle accumulated miles on the aforementioned driving courses. The following procedures were performed at the Manufacturer M R&D Center, at nominal 15,000-mile intervals:

- Emission testing
- Catalyst backpressure measurement
- Catalyst inspection

Upon arrival at Manufacturer M R&D, the vehicle was completely drained of fuel, and subsequently re-fueled with California Phase II Certification Fuel. Emission testing was performed on a chassis dynamometer, following the standard FTP-75 test procedure. This procedure includes a preconditioning cycle, thereby allowing the vehicle to stabilize on the clean test fuel prior to the actual test. Samples of exhaust were collected from each phase of the test, and analyzed for total hydrocarbons (THC), oxides of nitrogen (NO_X), carbon monoxide (CO), and methane. Non-methane hydrocarbons (NMHC) were calculated by subtracting the methane concentration from that of the THC. Industry-standard instrumentation was used for all analyses. This instrumentation was kept calibrated and under rigid quality control, following EPA procedures. (This lab is often used for EPA-mandated in-use emission compliance checks.) A single emission test was performed during each visit to Manufacturer M R&D. A test was considered valid unless a clear procedural error had occurred, in which case the test was repeated. All data points shown on the subsequent charts represent a single test; no averaging was performed.

Catalyst backpressure was measured while the vehicle was on the dynamometer, with a digital manometer inserted at a point just upstream of the catalyst. The following conditions were maintained until the pressure stabilized, and the test was repeated twice:

Throttle:	wide open
Gear:	2
RPM:	2850
Speed:	23mph (controlled by dynamometer)

Catalyst inspection was performed by removing the front oxygen sensor and inserting a boroscope through the opening. This method was used whenever possible, to avoid disturbing the aftertreatment system. The accumulation of MMT combustion products could thus be monitored.

At the conclusion of testing, the vehicle was driven back to the Proving Center on the clean certification fuel. Upon arrival at the center, the fuel was replaced with the test fuel assigned to the vehicle.

RESULTS AND DISCUSSION

This section contains the test results for the eight vehicles in this program, together with a discussion of the findings. Backpressure data are shown in combined charts after the discussion of the individual vehicles. Appendix 1 is a summary of the vehicle specifications in tabular format, permitting comparison between the vehicles. For each of the charts in this section, emission data from the MMT-fueled vehicle are compared to clear-fueled results. In the case of Model M-7, the clean-fueled vehicle was run at the Proving Center concurrent with the MMT-fueled vehicle, using the base fuel described earlier. The MMT-fueled Model M-1 also had a clear-fueled counterpart running at the center, but the latter vehicle was run a few months before the MMT-fueled vehicle, using the same mileage accumulation courses.

The comparison emission results for the remaining vehicles are from data collected during final vehicle development. The emission results up to 4,000 miles are from a vehicle that had accumulated mileage using courses similar to those at the center. Subsequent data points are from the same vehicle, but the “mileage accumulation” had been accomplished by removing the catalyst and oxygen sensors and subjecting them to a rapid aging cycle using an engine dynamometer. This proprietary aging cycle has been demonstrated to produce emission results that very closely match those from a vehicle that has undergone conventional mileage accumulation.

As can be seen in the following test results, all vehicles in this program developed MMT-related deposits on the surface of their primary catalysts, in some cases covering the entire face of the catalyst, causing a substantial backpressure increase and driveability problems. The NO_X and NMHC tailpipe emissions of most of the vehicles running on MMT fuels increased over their clear-fueled counterparts.

The majority of Tier 2 vehicles, regardless of manufacturer, will use a primary catalyst with a 600cpsi cell density or greater. Therefore, the results of this study are significant in that such catalysts were confirmed to be susceptible to plugging by MMT combustion products. The assumption is that the high cell density of these advanced-technology catalysts facilitates the accumulation of MMT combustion products. A similar phenomenon has been observed on catalysts with lower cell densities, but the accumulation rate was less rapid. Based on the effects observed in this study, there is some evidence that a “straight” exhaust flow configuration might help mitigate the accumulation of MMT deposit material in some cases. However, such a configuration is often difficult to achieve on Tier 2 vehicles. The need for fast light-off necessitates a catalyst placement near the exhaust manifold. In many cases this results in a “manifold-mounted” placement, in which the catalyst is mounted directly onto the exhaust manifold, (or is integral with the manifold). Given the geometry of the engine, such manifold-mounted catalysts must be angled to fit within the engine compartment. This is especially true for V6 applications. In cases where the catalyst can be mounted slightly downstream of the manifold, the driveshaft (when present) and transmission components often preclude the use of a straight exhaust flow configuration. Another factor that favors an angled design is the fact that sufficient turbulence of the exhaust flow must be achieved at the head of the catalyst to permit proper functioning of the oxygen sensor.

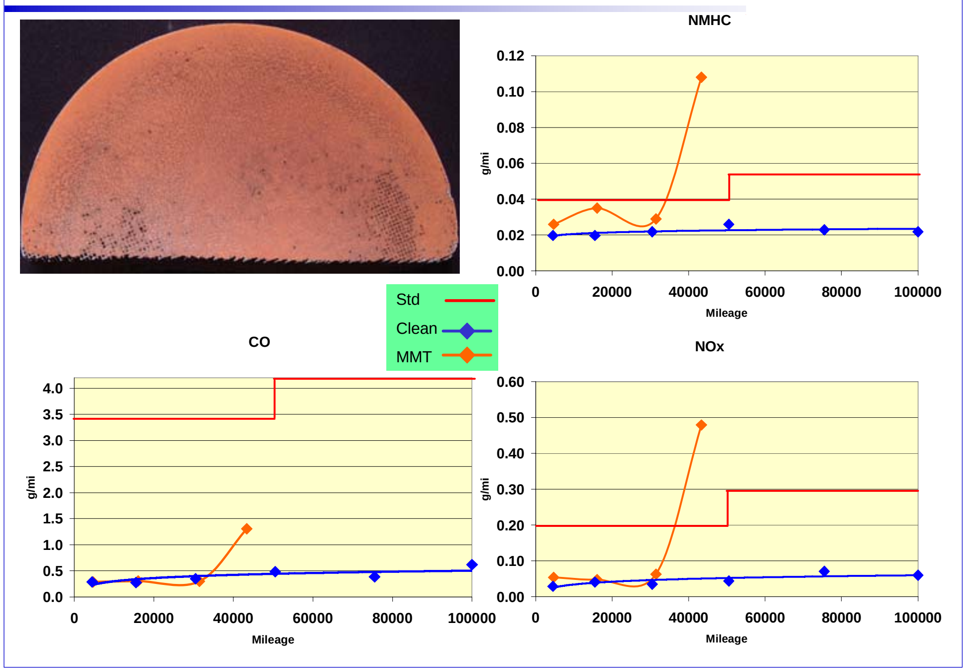
2001 Model M-1, ULEV-certified, (Figure 6)

The data from this vehicle were discussed earlier in this paper, but are presented here in a format consistent with the data shown for the remaining vehicles. The Model M-1 assigned to MMT fuel was purposely driven on clear fuel during the first 5,000 miles to establish an emissions baseline, after which it was switched to MMT fuel for the duration of the program. The M-7 model, described later, was the only other vehicle to be broken in using clear fuel; the remaining vehicles (assigned to MMT) received MMT fuel from the beginning of their mileage accumulation.

Driveability problems with this vehicle became obvious at 35,000 miles, and at 43,000 miles became too severe to continue mileage accumulation. Between these intervals, the MIL illuminated, with a code corresponding to a catalyst efficiency problem. Test results indicated that the Model M-1's emissions were substantially above the ULEV standard. The measured backpressure of the catalyst was very high. The emissions immediately returned to baseline levels when the catalyst was replaced. The emissions from the clear-fueled companion vehicle remained very low throughout its 100,000-mile mileage accumulation.

As mentioned before, the catalyst surface was completely covered with a reddish-brown deposit, identified as manganese oxide. Model M-1 catalysts with similar mileage accumulation were retrieved from the Canadian market, and found to be similarly plugged with MMT combustion products. A series of tests were performed on these catalysts by an independent laboratory, and are documented in a separate report.

Figure 6 2001 Model M-1

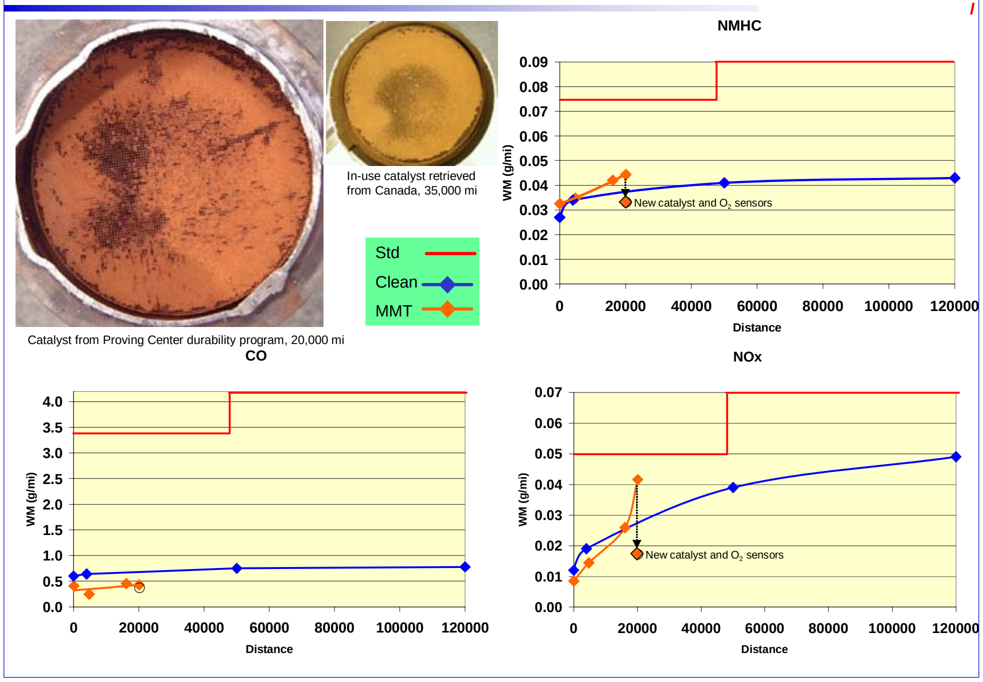


2003 Model M-2, Tier 2 Bin 5 certified, (Figure 7)

Like the Model M-1, the Model M-2 is a popular vehicle in the Canadian market, and was therefore chosen for this program. The engine type and catalyst configuration of the Model M-2 were different than that of the Model M-1; for example, the Model M-1 used a manifold-mounted catalyst, while the Model M-2 used a mid-underfloor configuration.

The Model M-2 experienced driveability problems with the MMT fuel more rapidly than did the Model M-1. By the 20,000-mile point, the MIL had illuminated (catalyst efficiency code) and vehicle acceleration had degraded so much that further mileage accumulation was not possible, due to safety concerns. NO_X emission levels had increased rapidly, and were clearly on track to exceed the standard. NMHC emissions had also increased, while CO emissions were unaffected. Backpressure increased substantially. When the converter can was opened, the catalyst surface was found to be covered with manganese oxide. Figure 9 also includes a photo of a Model M-2 catalyst retrieved from the Canadian market. The catalyst and oxygen sensors were replaced on the Model M-2, and a final emission measurement made. The emission levels with the new parts dropped down to the level of the clear-fuel vehicle development data for that level of mileage accumulation.

Figure 7 2003 Model M-2



2003 Model M-7, Tier 2 Bin 5 certified, (Figures 8, 9, 10)

The Model M-7 testing was unique in this program, in that the clean-fueled vehicle was run at the same time as its MMT-fueled counterpart. That is, mileage accumulation and testing activity occurred during the same time period and in the same locations.

NO_X and NMHC emission results for the two vehicles began to clearly diverge by the 75,000-mile point. At 100,000 miles, the MIL illuminated on the MMT-fueled vehicle with a catalyst efficiency code, for the same reason as that noted for the Model M-2. Emission results were about three times those of the clear-fueled vehicle for NMHC and NO_X.

As can be seen in Figure 9, the surface of both primary catalysts from the MMT-fueled vehicle was severely obstructed by manganese oxide. (Model M-7 has a separate 900cpsi manifold-mounted catalyst for each bank of three cylinders, and a single underfloor 350cpsi catalyst. Since the engine is mounted transversely, the catalysts are typically referred to as the "front bank" and "rear bank.") The corresponding catalysts for the clear-fueled vehicle remained completely clean, even at 120,000 miles.

Photos of the spark plugs from both vehicles are shown in Figure 10. Note the heavy deposits present on the spark plugs from the MMT-fueled vehicle. This deposit was found on all spark plugs from the MMT-fueled vehicles in this program. In some cases, the deposit was much worse than that shown for this vehicle. Analysis of the deposit material indicated that it consisted of 90% to 94% manganese oxide, depending on the plug.

As with all vehicles in this program, the Model M-7 vehicles received their regularly-scheduled maintenance procedures. One exception to that for these vehicles was the replacement of oxygen sensors. Both the primary and secondary oxygen sensors were replaced on the MMT- and clear-fueled vehicles. This occurred at 4,000 miles for the MMT vehicle and at 15,000 miles for the clear vehicle. For durability programs, Manufacturer M uses oxygen sensors with a measured response curve that falls near the center of the tolerance window, to ensure that the durability vehicles are representative of the average vehicles in the market. (These "average tolerance" sensors are identical to the original equipment sensors.) These sensors were late arriving from the supplier, so the mileage accumulation was begun with the "as-received" sensors.

Figure 8 2003 Model M-7

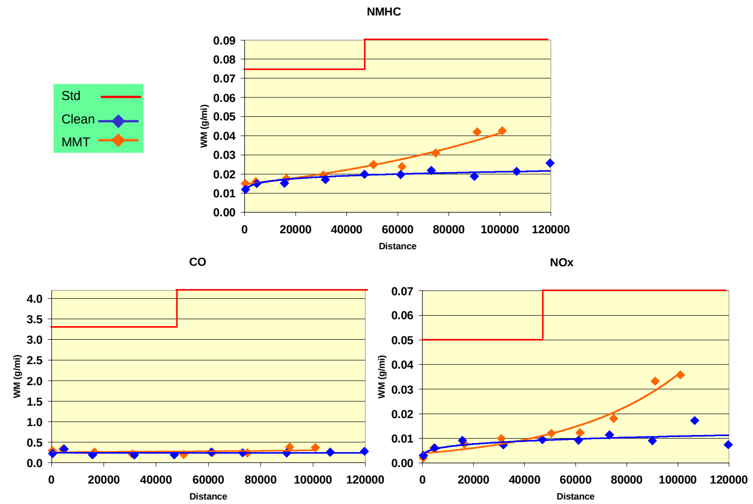


Figure 9 Model M-7 Catalyst Photos

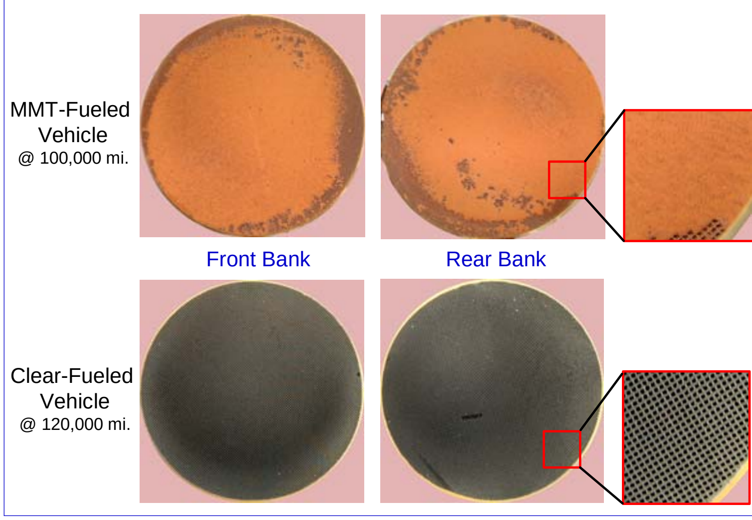
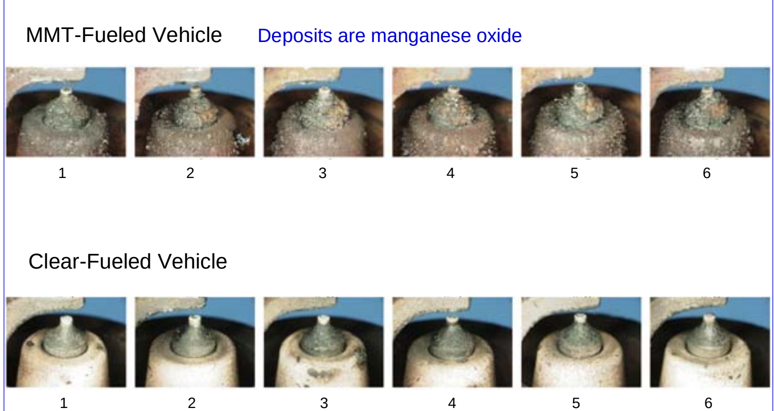


Figure 10 Model M-7 Spark Plug Photos



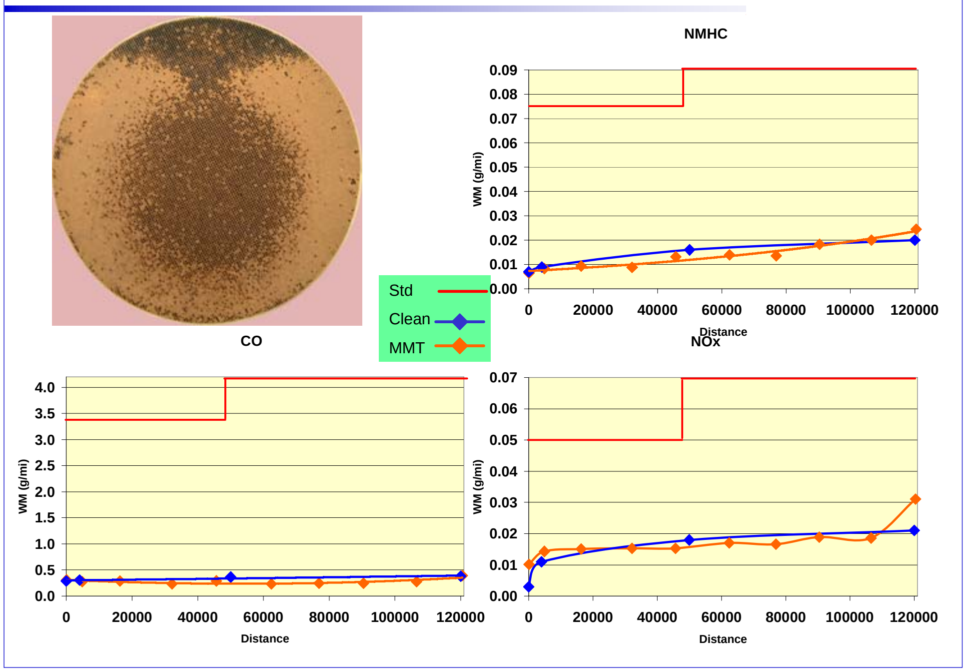
v.081307

2003 Model M-6, Tier 2 Bin 5 certified, (Figure 11)

The catalyst from Model M-6 was mounted in the mid-underfloor position. The catalyst surface was over 50% covered with MMT-related deposit material at the 120,000 mile point. Emission data were similar between the fuels through the 100,000-mile point, but the NMHC and NO_X emissions had increased sharply for the MMT-fueled vehicle by the end of the test. Backpressure also increased, but to a lesser extent than the vehicles mentioned previously. Backpressure results for all test vehicles are detailed later in this paper.

In retrospect, it would have been useful to continue mileage accumulation on this vehicle, given that an emission increase was noted on the last test. However, the two criteria for halting mileage accumulation for the MMT-fueled vehicles in this program were (1) MIL illumination or (2) end of emission system warranty period reached. This vehicle met the latter criterion of 120,000 miles, and was removed from the program.

Figure 11 2003 Model M-6



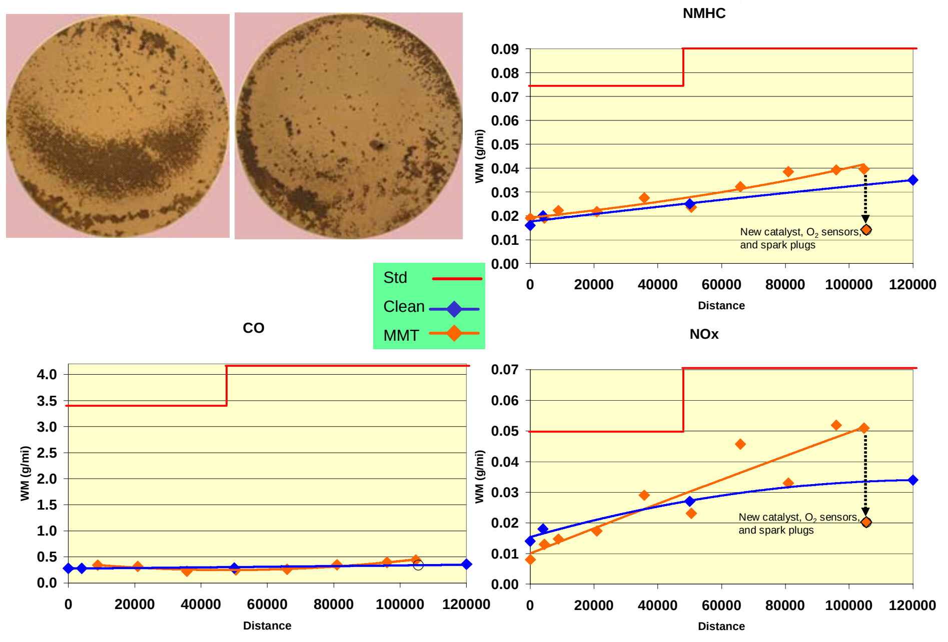
v.081307

2003 Model M-8, Tier 2 Bin 5 certified, (Figure 12)

This SUV had the largest engine in this program at 3.5L. The catalyst configuration of this SUV was generally similar to that of Model M-7. As with the aforementioned Model M-1, the Model M-8 received clean fuel during its break-in period (4000 miles). At this mileage point, the original oxygen sensors were replaced with the Manufacturer M "average tolerance" sensors, for the same reasons as previously described for the M-7 models.

The measured emissions and catalyst backpressure increased steadily as the vehicle accumulated mileage. The MIL illuminated at 105,000 miles with a "catalyst problem" code, for the same reason as that noted for the Model M-2 and Model M-7. Both the front- and rear-bank catalysts were heavily coated with manganese oxide at this point. The catalyst, oxygen sensors, and spark plugs were replaced on the Model M-8, and a final emission measurement made. The emission levels with the new parts dropped below the clear-fuel vehicle development data for that level of mileage accumulation, which strongly implied that the observed emission increase was mainly attributable to the contamination of those components by MMT.

Figure 12 2003 Model M-8



<u>2003 Model M-3 and M-4, Tier 2 Bin 5 certified, (Figures 13 - 14)</u>

Models M-3 and M-4 are similar, the latter being a sport version of the former. The history of these two models in the program was problematic. However, the data are included in this paper in the interest of completeness. The caveats listed in the following paragraph should be considered when reviewing the results from these two vehicles.

These vehicles were run early in the program, when the focus was still on potential exhaust valve problems. When both vehicles had accumulated 15,000 miles on MMT fuel, they were sent to another Manufacturer M facility for extended testing. The exhaust valves were checked for leakage, and the entire valve train was removed and disassembled for inspection. The parts were replaced, and the vehicles sent back to the Proving Center. However, these vehicles had been outside the quality control auspices of this program for five to six months. Model M-4 was not tested again until it had accumulated another 30,000 miles, so the effect of the work performed at the other facility was unknown. The base model <u>was</u> tested before and after its trip to the other facility, and the emissions were clearly affected. The "bumps" seen in Figure 15 at the 15,000-mile point indicated an apparent enleanment in the air-fuel ratio of this vehicle. In addition, Model M-3 received a modified engine control computer at 75,000 miles, to enable the monitoring of engine data in real time. The control algorithms of this unit were identical to those of the stock computer, but this still represented a mid-program change to the vehicle. As a final point, it's important to note that the emission results of the MMT-fueled Model M-3 were offset at the beginning of the program from the comparison data; NMHC emissions were higher and NO_X emissions were lower before the start of mileage accumulation.

Model M-3 and M-4 were both equipped with a mid-underfloor catalyst configuration. Model M-3 had a 600cpsi catalyst, and Model M-4 a 900cpsi catalyst. Model M-3 was exhibiting a NO_X emission increase near the end of its mileage accumulation, but the vehicle reached the 120,000-mile "stop" criterion and was removed from the program. As with Model M-6, it would have been useful to have extended the mileage accumulation of this vehicle. The emissions of Model M-4 were apparently unaffected by the MMT fuel within the 120,000 miles of this program; the vehicle emission results closely followed the vehicle development data. The catalyst surface contained areas of heavy MMT-related deposits for both vehicles, but most of the cells appeared to remain open.

Figure 13 2002 Model M-3

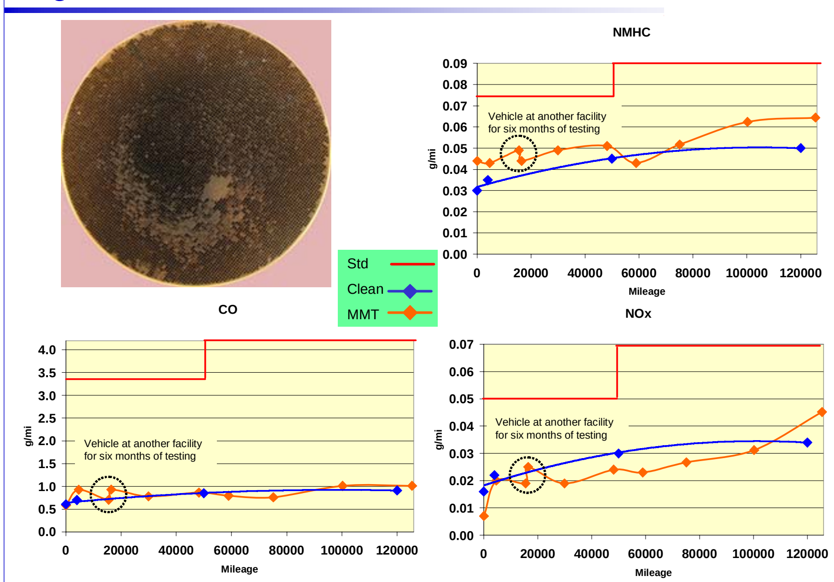
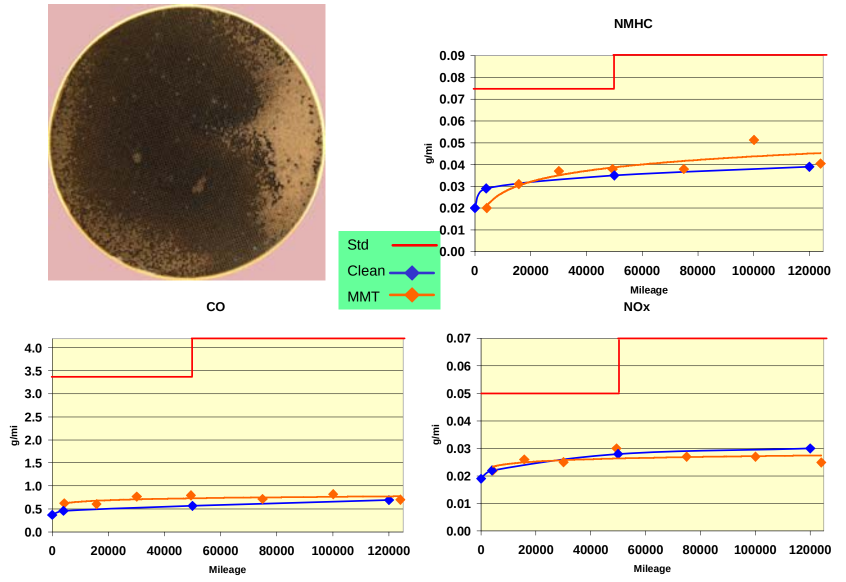


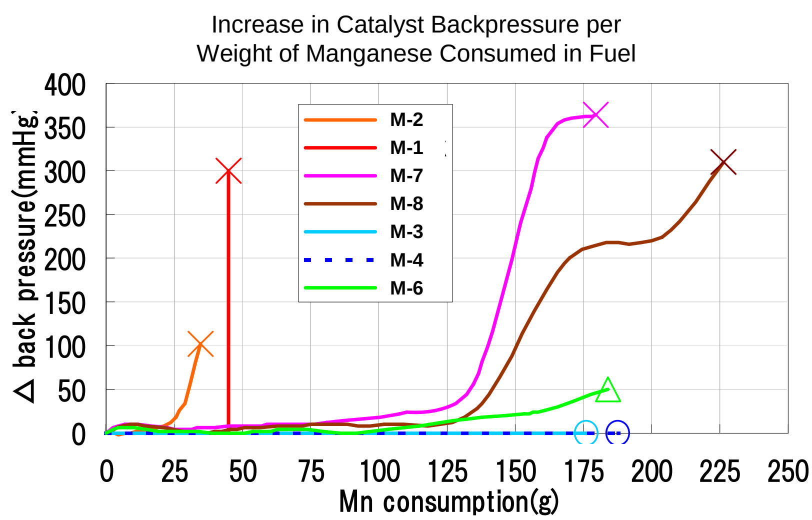
Figure 14 2002 Model M-4



Backpressure Results

The backpressure measurements taken during this program are summarized in Figure 15. Backpressure increase in shown as a function of the amount of manganese consumed through the mileage accumulation period, as calculated from the volume of fuel used. All MMT-fueled vehicles except Models M-3 and M-4 exhibited an increase in backpressure through the mileage accumulation period. The four vehicles with the highest backpressure all experienced an MIL illumination.

Figure 15 Catalyst Backpressure Data



v.081307

SUMMARY AND CONCLUSIONS

- All vehicles operating on MMT fuel in this program developed MMT-related deposits on the surface of their primary catalysts, despite the fact that a wide variety of engine/catalyst configurations were tested. (See summary in Appendix 1.)

- The catalyst deposit material was confirmed to consist of MMT combustion products. Elemental analysis by XRF indicated that a significant percentage of the material was manganese. Mineral analysis by XRD revealed that Mn_3O_4 was virtually the only crystalline material present.

- In some cases, the deposit covered virtually the entire face of the catalyst, causing a substantial backpressure increase and driveability problems.

- The NO_X and NMHC tailpipe emissions of most of the vehicles running on MMT fuels increased over their clear-fueled counterparts. CO emissions remained relatively unaffected. In no case was a net decrease observed in the emissions of the MMT-fueled vehicles.

- The MIL (Malfunction Indicator Lamp) illuminated on four of the vehicles, with a code corresponding to a catalyst problem. In some cases, this occurred after relatively low mileage accumulations. All of these vehicles were operated on MMT fuel.

- Vehicles retrieved from the Canadian market, where MMT fuel was common, exhibited catalyst deposits identical in composition to those from the test vehicles in this program. (Detailed in a separate report.)

- In all cases, spark plugs from the MMT-fueled vehicles in this program were also heavily coated with manganese oxide.

- The vehicles accumulated mileage on real-world courses. These were the same courses historically used by Manufacturer M for their vehicle durability program. However, the results from this testing do not necessarily reflect the average market experience in Canada, due to the fluctuation of the MMT concentration of Canadian gasoline, and the variability in vehicle operational patterns.

- This paper represents the first detailed study of the effect of MMT upon Tier 2 vehicles. This research confirmed that emission systems designed to meet the stringent Tier 2 emission standards are clearly less tolerant of MMT.

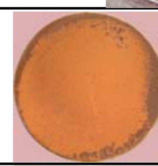
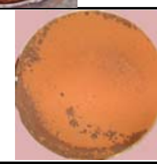
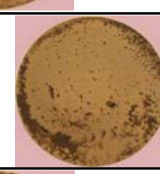
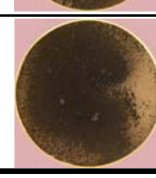
REFERENCES

1. Benson, J.D. & Dana, D. (2002). The Impact of MMT Gasoline Additive on Exhaust Emissions and Fuel Economy of Low Emissions Vehicles (LEV). Society of Automotive Engineers, SAE Paper 2002-01-2894

2. Alliance of Automobile Manufacturers, North American Fuel Survey, 1996 to 2002.

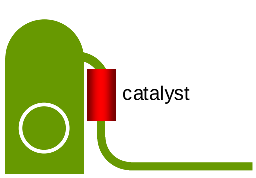
3. Evaluation of Catalytic Converters Retrieved from the Canadian Market. 2005, unpublished.

Appendix 1 Test Vehicle Specifications

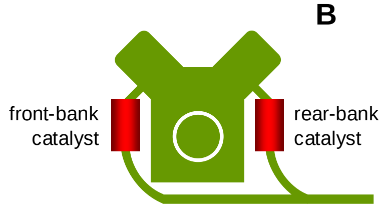
Vehicle Year & Model	Primary Catalyst	Config	MIL On?	Mn Conc	Catalyst Photos
2001 M-1	manifold-mounted 600cpsi	A	**Yes**	.032 g/gal	 @ 43,000 miles
2003 M-2	mid-underfloor 600cpsi	C	**Yes**	.032 g/gal	 @ 20,000 miles
2003 M-7	manifold-mounted 900cpsi	B	**Yes**	.032 g/gal	  @ 100,000 miles
2003 M-7	manifold-mounted 900cpsi	B	No	**No MMT**	  @ 120,000 miles
2003 M-6	mid-underfloor 900cpsi	C	No	.032 g/gal	 @ 120,000 miles
2003 M-8	manifold-mounted 900cpsi	B	**Yes**	.032 g/gal	  @ 105,000 miles
2003 M-3	mid-underfloor 900cpsi	C	No	.032 g/gal	 @ 120,000 miles
2003 M-4	mid-underfloor 900cpsi	C	No	.032 g/gal	 @ 120,000 miles

Configurations

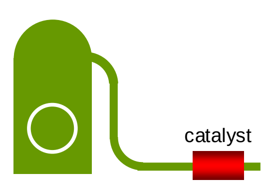
A



B



C



v.081307

Appendix 2 Test Fuel Specifications

Clear Fuel

PRODUCT INFORMATION

Haltermann PRODUCTS

T (281) 457-2768 F (281) 457-1469

RESPONSIBLE CARE ISO 9001 CERTIFIED

Johann Haltermann Ltd.
A Subsidiary of The Dow Chemical Company

PRODUCT: ARIZONA CLASS -AA Honda

PRODUCT CODE: HF492

Batch No.: RI2521LS02
TMO No.: 2007929
Tank No.: 623
Analysis Date: 9/26/03
Shipment Date: 9/27/03

TEST	METHOD	UNITS	SPECIFICATIONS MIN	TARGET	MAX	RESULTS
Distillation - IBP	ASTM D86	°C				39
5%		°C				63
10%		°C			70	70
20%		°C				82
30%		°C				92
40%		°C				101
50%		°C	77		121	107
60%		°C				112
70%		°C				118
80%		°C				130
90%		°C			185	159
95%		°C				167
Distillation - EP		°C			225	194
Recovery		vol %		Report		98.1
Residue		vol %			2.0	1.0
Loss		vol %		Report		0.9
Gravity	ASTM D4052	°API		Report		57.8
Reid Vapor Pressure	ASTM D5191	kPa			48	48
Oxygen	ASTM D4815	wt %			0.05	<0.05
Sulfur	ASTM D4294	wt %			0.1	<0.015
Lead	ASTM D3237	g/gal			0.05	<0.01
Manganese	ASTM D3831	g/gal			0.01	0.001
Composition, aromatics	ASTM D1319	vol %		Report		26.3
Composition, olefins	ASTM D1319	vol %		Report		0.5
Composition, saturates	ASTM D1319	vol %		Report		73.2
Oxidation Stability	ASTM D525	minutes	240			>240
Copper Corrosion	ASTM D130				1	1
Existent gum, washed	ASTM D381	mg/100mls			5	<1
Research Octane Number	ASTM D2699		91.0		93.0	91.9
Motor Octane Number	ASTM D2700		82.0			85.3
R+M/2	D2699/2700		87.0			88.6

APPROVED BY: Buddy Washert

ANALYST HVD/JCM

v.081307

Appendix 2 Test Fuel Specifications

MMT Fuel

PRODUCT INFORMATION

Haltermann PRODUCTS

RESPONSIBLE CARE ISO 9001 CERTIFIED

T (281) 457-2768 F (281) 457-1469

Johann Haltermann Ltd.
A Subsidiary of The Dow Chemical Company

PRODUCT: ARIZONA CLASS -AA W/ MMT

PRODUCT CODE: HF545

Batch No.: QK2221LS01
TMO No.: 2003051
Tank No.: 601
Analysis Date: 11/25/02
Shipment Date: 11/30/02

TEST	METHOD	UNITS	SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F				97
5%		°F				136
10%		°F			158	151
20%		°F				172
30%		°F				189
40%		°F				203
50%		°F	170		250	213
60%		°F				223
70%		°F				234
80%		°F				251
90%		°F			365	306
95%		°F				332
Distillation - EP		°F			437	369
Recovery		vol %		Report		98.1
Residue		vol %			2.0	1.0
Loss		vol %		Report		0.9
Gravity	ASTM D4052	°API		Report		60.5
Reid Vapor Pressure	ASTM D5191	psi			7.0	7
Oxygen	ASTM D4815	wt %		Report		<0.05
Sulfur	ASTM D4294	wt %			0.1	0.02
Lead	ASTM D3237	g/gal			0.05	<0.01
Phosphorous	ASTM D3231	g/gal			0.005	<0.0008
Manganese	ASTM D3831	g/gal	0.026	0.031	0.036	0.029
Composition, aromatics	ASTM D1319	vol %		Report		24.4
Composition, olefins	ASTM D1319	vol %		Report		0.3
Composition, saturates	ASTM D1319	vol %		Report		75.3
Oxidation Stability	ASTM D525	minutes	240			>240
Copper Corrosion	ASTM D130				1	1a
Existent gum, washed	ASTM D381	mg/100mls			5.0	<1
Research Octane Number	ASTM D2699		91.0		93.0	92.4
Motor Octane Number	ASTM D2700		82.0			86.0
R+M/2	D2699/2700		87.0			89.2

APPROVED BY: Buddy Wiskot ANALYST HVD/JM

v.081307

Evaluation of Catalytic Converters Retrieved from the Canadian Market

ABSTRACT

A recent test program conducted by the auto industry[1] confirmed that the gasoline additive MMT (Methylcyclopentadienyl Manganese Tricarbonyl) has a detrimental effect upon vehicle hardware and tailpipe emissions. Advanced technology vehicles designed to meet the most recent North American emission standards were most affected. As a consequence, Manufacturer M began test programs to study the effect of MMT upon a new ULEV model. During the course of these programs, the catalysts became plugged with an MMT-induced deposit. This finding led to the initiation of a program to evaluate in-use (market) catalytic converters.

Catalysts were collected from the Canadian market, where MMT fuel was common at the time. The catalysts were sent to an independent laboratory for flow testing, emission testing, photography, and chemical analysis. All catalysts were found to be plugged to some extent. Catalysts with higher plugging ratios exhibited higher emissions. Emission standards were exceeded at the higher plugging ratios. Catalyst light-off time was first affected, followed by continuous emission breakthrough at the higher plugging ratios. Analysis of the deposit material revealed that manganese and manganese oxide were the primary element and phase, respectively, in all of the analyzed deposits.

EXPERIMENTAL

Program Design

A random survey conducted by a third-party company was chosen as the means to select candidate vehicles for the program, with the objective of providing statistically valid and unbiased data. Retention Marketing[5] was chosen to conduct the written and verbal components of the study, and to report the results to Manufacturer M's Canadian branch. The survey was developed by the Manufacturer M Canada Service Engineering department to gain information about customer driving patterns, fuel use, vehicle operating conditions, etc. The complete written survey is attached as Appendix 1. A complete list of 2001 Manufacturer M Model M-1 vehicle identification numbers (VINs) from Ontario was provided to Retention Marketing, who then randomly selected customers for mailing. Based on the results of this written survey, a subgroup of customers was chosen for a verbal survey, also conducted by Retention. The verbal survey was based upon a questionnaire designed to choose vehicles for the EPA-mandated In-Use Verification Program (IUVP), and is attached as Appendix 2. (Question 14 was omitted.) The criteria used for this subgroup selection, and the criteria used for the final catalyst selection, are described in the next section of this report.

The 2001 Model M-1 was chosen as the target vehicle for the random survey. This Model M-1 was chosen for the following reasons:

- Warranty claims made this a vehicle of interest.
- This vehicle was among the first to feature a 600-cell catalyst in that market. Other Tier 2 vehicles and 600-cell catalysts were released in subsequent years, but the Model M-1 had experienced the longest exposure period to MMT fuels.
- There was a sufficiently large range of mileage represented by 2001 vehicles, and the Model M-1 was a best-seller. Therefore, the survey could start with a sample set of sufficient size.
- It was the first vehicle in a separate test program to have been run on MMT fuel, and confirmed to exhibit catalyst plugging with that fuel. (Subsequent vehicle models tested in that program also exhibited catalyst plugging.[2])

The province of Ontario was chosen as the focus area for the survey because it represents 38% of the Canadian population, and 42.5% of 2001 Model M-1 sales. MMT was also widely used in Ontario at the time of the survey.[3][4]

Catalyst Selection Criteria

The written survey was distributed by Retention to a total of 1600 randomly-selected Model M-1 customers across the province of Ontario. A set of pre-determined selection criteria was applied to evaluate these surveys and to select the subgroup of customers for a verbal survey, which Retention conducted by phone. The verbal survey results were also subjected to selection criteria. Some examples of survey responses that would disqualify the vehicle from further consideration were as follows:

Written Survey:

- Factory emission components changed or damaged
- Off-the-shelf fuel additives used
- Vehicle used for towing purposes

Verbal Survey:

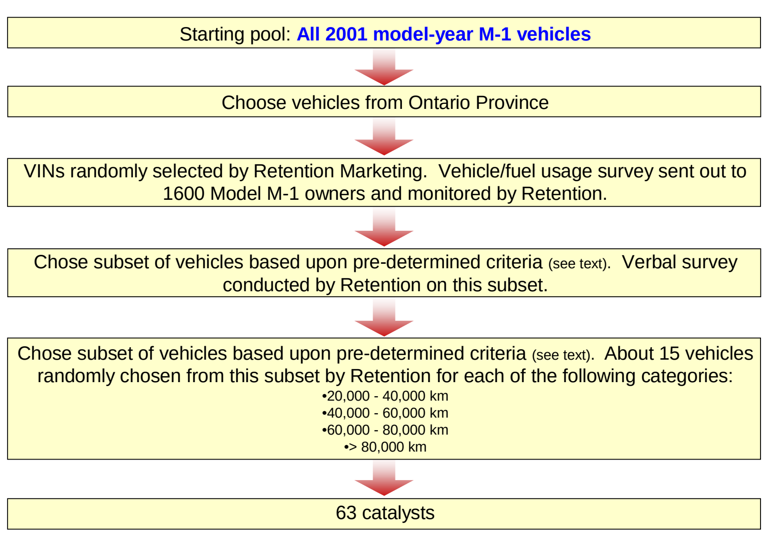
- Customer was unwilling to participate in program
- Vehicle used for severe activity, such as racing and plowing snow
- Vehicle involved in a significant traffic accident
- A major engine repair had been performed
- Catalytic converter replaced

The group of candidate vehicles that passed these selection rounds qualified for selection in the next phase of the study, the collection of emission hardware components. The vehicles that qualified for hardware collection were first segregated into four mileage categories:

- Category 1: 20,000 – 39,999 km
- Category 2: 40,000 – 59,999 km
- Category 3: 60,000 – 79,999 km
- Category 4: > 80,000 km

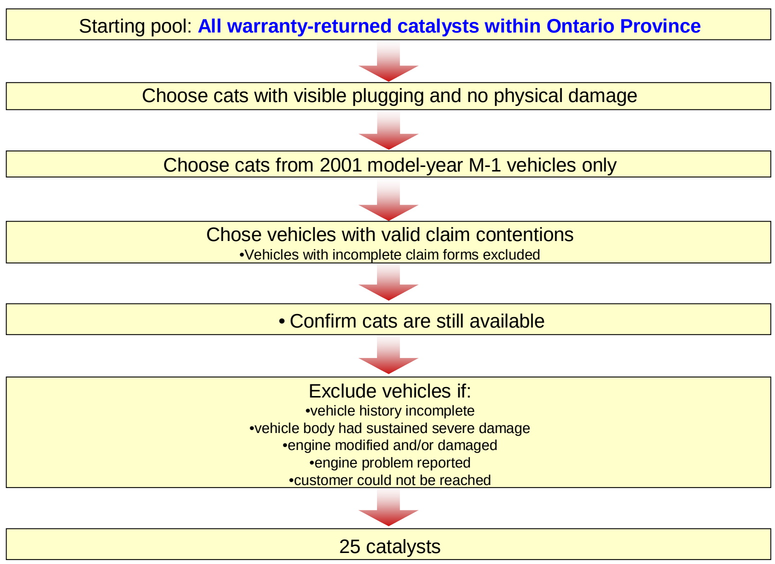
The vehicles were placed within the above categories in the order in which the written surveys were received by Retention. To maintain a representative sample of the Ontario market, a mix of 75% automatic and 25% manual transmission cars were selected. The objective was to populate each category with 15 vehicles. That target was achieved, except for Category 3 which received 18 vehicles due to inconsistencies between mileage reported on the surveys and the actual mileage. Therefore, an initial 63 vehicles were selected for hardware collection. In the hardware collection phase, the catalytic converters, spark plugs, and oxygen sensors were replaced. A small oil sample and a 1 US gallon fuel sample were taken from the vehicles also. A summary of the catalyst selection method is shown in Figure 1.

Figure 1 Initial Catalyst Selection Method



As will be explained in the forthcoming "Results and Discussion" section, the 63 catalysts chosen for this program produced a surprising result when subjected to flow testing. No catalysts exhibited a plugging percentage between 30% and 80%; they were either below or above this range. One potential reason for this phenomenon was that the catalyst selection criteria were too severe; e.g., catalysts that had already failed were not collected. Emission testing of the catalysts indicated that it was important to address this data gap, to confirm the apparent data trends that were emerging. Without addressing this gap, data points at the high plugging percentages might be considered statistically insignificant. In an attempt to populate this data gap, an additional catalyst collection program was conducted. In this follow-up program, the focus was on warranty-returned catalysts, i.e., the important category of catalysts that was missed in the original collection. As before, the catalysts were subjected to a series of collection criteria, as shown in Figure 2. One of the primary criteria

Figure 2 Warranty Catalyst Selection Method



was that the catalysts had to have a complete vehicle history, and it was required that the vehicle owner be available to validate this history. The starting sample pool consisted of all warranty-returned catalysts within Ontario. A total of 25 catalysts passed all of the selection criteria.

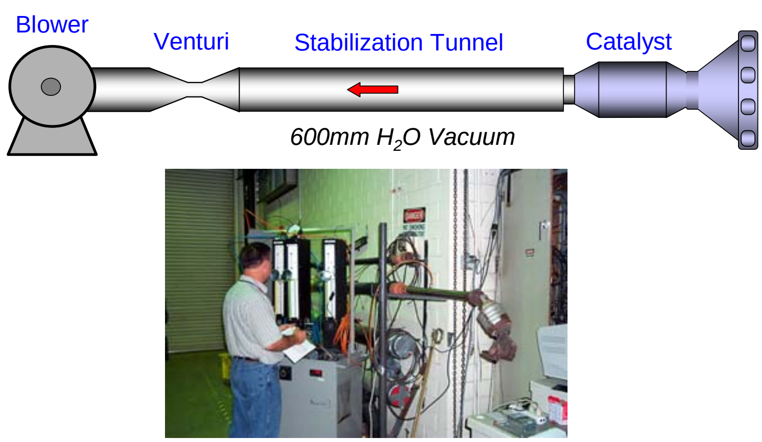
<u>Test Program</u>

The 63 catalysts (and later the next 25 catalysts) were inspected by Manufacturer M's Canadian Service Engineering department, and then forwarded to a credible independent contractor for testing. The gasoline samples were sent to the contractor's laboratory for analysis. Manufacturer M provided an appropriate Model M-1 vehicle to act as a slave vehicle for all catalyst testing. That is, a single vehicle was used for all testing. A description of the test procedures follows.

Catalyst Flow Testing

The contractor used a calibrated Laminar Flow Element (LFE) to measure the air flow through each catalyst. The flow through the assembly was adjusted to achieve a reference vacuum of 600mm H_2O; see Figure 3. The catalyst flow rate was then measured at this vacuum. The plugging percentage was calculated in relation to the reference catalyst, which was the original factory-installed catalyst present on the Model M-1 when delivered to the contractor. This catalyst (and vehicle) had accumulated 2082 miles of real-world driving before being sent to them. Two catalysts that had accumulated nominally 60,000 real-world miles in the California market were tested during the program, to provide a baseline for the higher-mileage catalysts collected from the Canadian market. (The average flow results of the California catalyst were used.) Manufacturer M provided reference catalysts of known plugging percentages to correlate the results obtained with the contractor's apparatus with those of the Manufacturer M laboratory, which used a somewhat different instrument configuration.

Figure 3 Catalyst Flow Testing



$$Plugging\,\% = \frac{Flow_{REFERENCE} - Flow_{TEST\ CONVERTER}}{Flow_{REFERENCE}} * 100$$

Emission Testing

The fuel used for all emission testing was California Phase II gasoline, which contained 2% oxygen, and was provided by the contractor. The testing was performed on a 48-inch single-roll chassis dynamometer. Emissions were collected and analyzed in a manner consistent with EPA protocols. The following cycles were used:

- Federal Test Procedure (FTP-75)
- SFTP-US06 aggressive driving cycle
- Highway Fuel Economy Test (HFET)

Catalyst Photography

After the flow testing and emission testing had been completed, a subset of catalysts was selected to be opened and photographed. As described later, the front face of these catalysts was also sampled for chemical analysis. Due to time and expense concerns, a subset of 22 catalysts was chosen for these procedures. Care was taken to select catalysts such that a representative range of deposit colors and morphologies could be photographed and sampled. Photography was performed by the contractor's in-house specialist, and included two types of catalyst face photos and a close up of an area of interest.

Deposit Sampling and Analysis

Deposit material was carefully scraped from the catalyst face using a sterile scalpel, and analyzed using the following techniques:

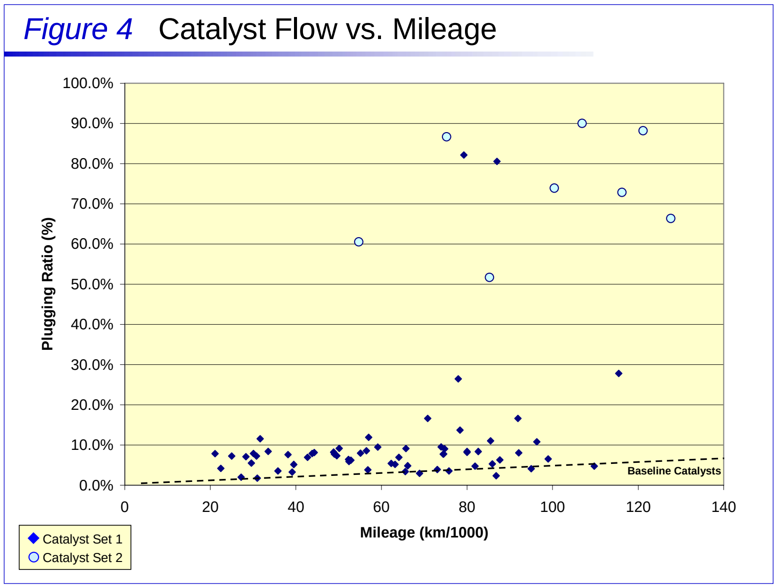
- PIXE (Particle Induced X-Ray Emission) This technique measures the elemental composition of the sample.
- XRD (X-Ray Diffraction) This technique determines the crystalline phases present in the sample.

A description of these instruments can be found in Appendix 3.

RESULTS AND DISCUSSION

Catalyst Flow Testing

As mentioned previously, the initial flow testing of the 63-catalyst set produced an unexpected data gap between the 30% and 80% plugging ratios. All 25 of the next set of catalysts were subjected to flow testing, and a number of "target" catalysts emerged with plugging ratios within the desired range. Catalysts from this range were randomly selected, and subjected to FTP and US06 emission testing. It became apparent after testing the first eight catalysts that the emission data were consistent with the previous data set; i.e., the results generally fell into the expected trends and successfully addressed the data gap. Therefore, emission testing was stopped at that point. The flow test results for the 63 + 8 samples are shown in Figure 4, plotted against catalyst mileage. Note that the eight catalysts from the second sample set are differentiated from the other catalysts through the use of a different data point style; this convention will be used for all remaining charts in which the two data sets appear together. The baseline data shown in this figure represent the reference catalyst and the average of the two aged catalyst flow test results. No direct relationship was apparent between plugging ratio and mileage. This was to be expected, since the vehicles were exposed to varying concentrations of MMT in the fuel, as discussed in the upcoming "Fuel Analysis" section. Throughout the flow testing, the reference catalyst and selected sample catalysts were re-run as a quality control check. The flow test rig proved to be very stable; the maximum deviation ever observed between repeat tests was 0.9%.

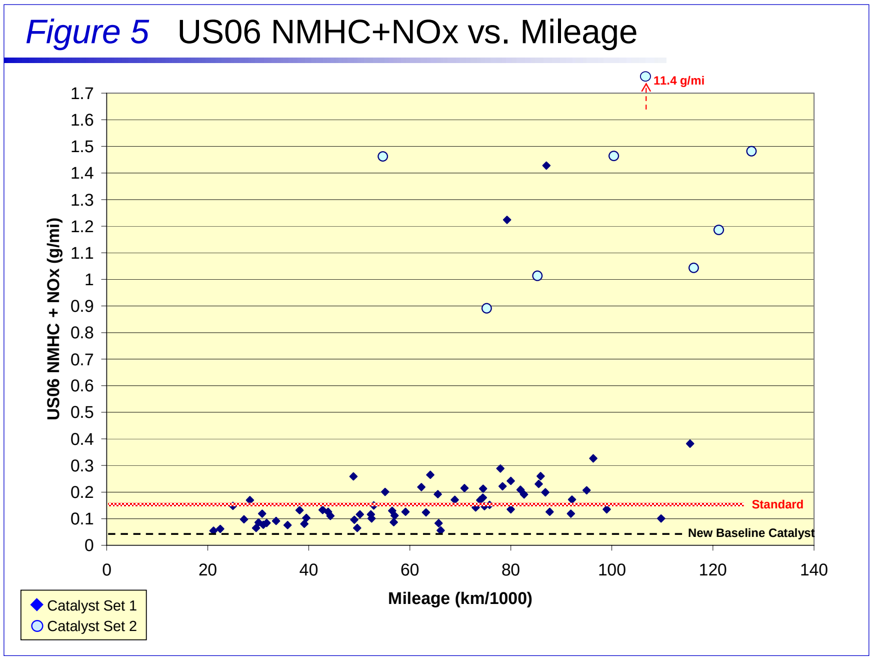


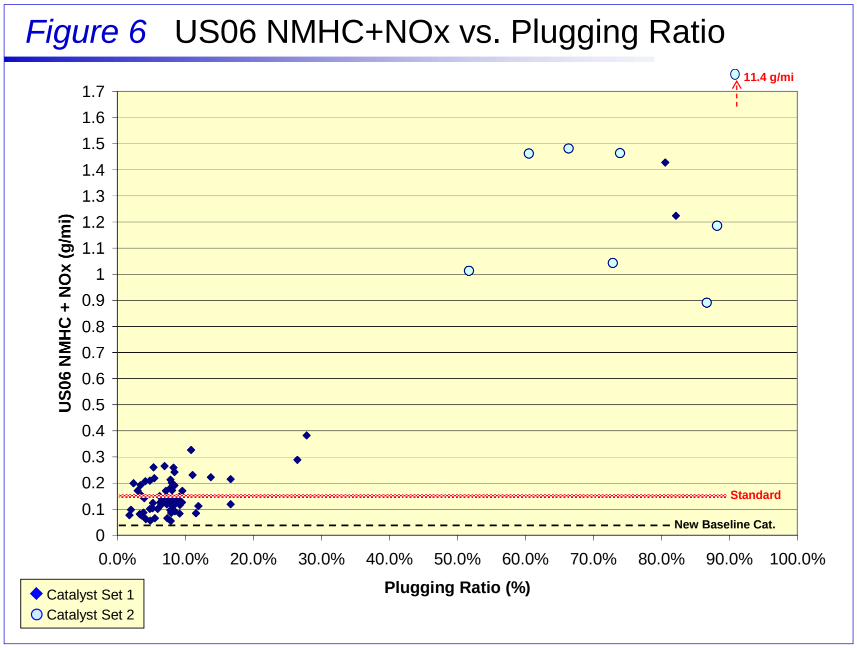
Emission Testing

US06 Cycle

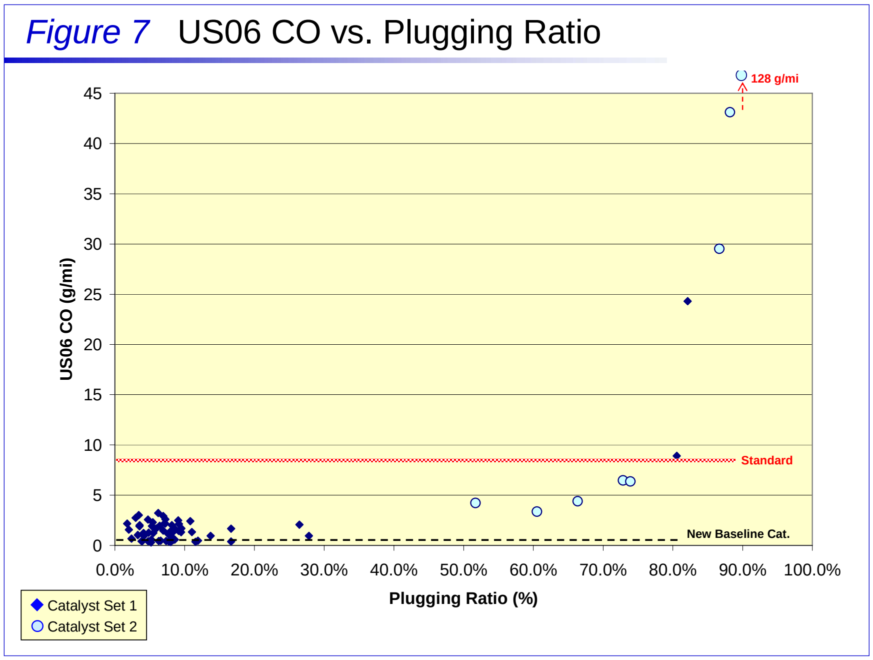
The US06 driving cycle is more aggressive than the FTP, and captures driving patterns that are not covered by the FTP. Target emission standards for the US06 are in terms of CO (carbon monoxide) and NMHC+NO_X (the sum of non-methane hydrocarbons and measured oxides of nitrogen). The 2001 Model M-1 was certified to meet the US06 emission standards. Unlike the FTP emission results, there was no comparable data available from high-mileage catalysts that had never been exposed to MMT. Therefore, the baseline data shown in the US06 charts is that from the original reference catalyst.

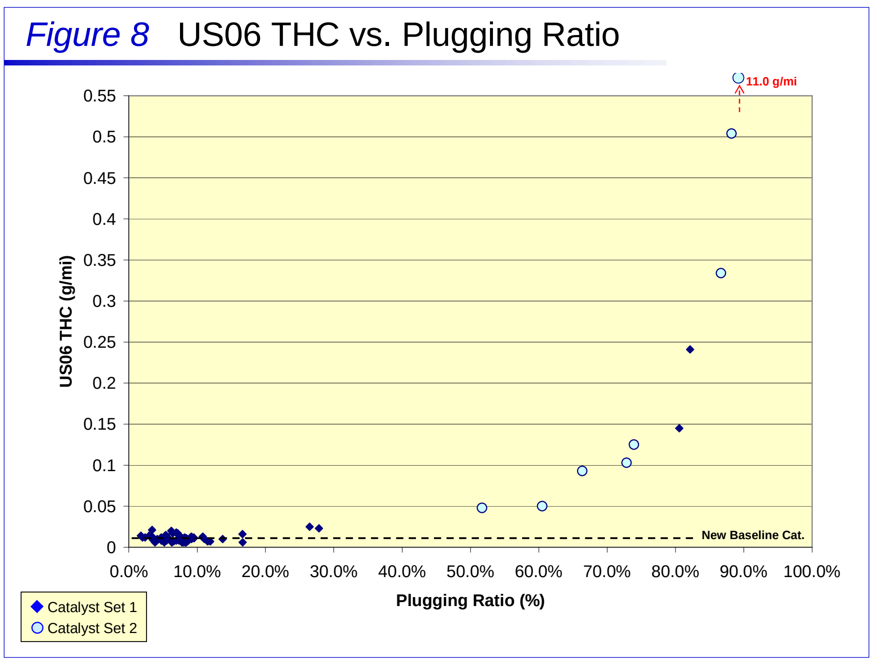
Figure 5 indicates that there is no strong relationship between NMHC+NO_X and catalyst mileage. However, a trend does emerge when these same emission data are plotted against the plugging ratio, as in Figure 6. The US06 standard is exceeded by many of the catalysts, including all those with a plugging ratio above 20%. Note the presence of a data point far off the chart scale, at 11.4 g/mi. This catalyst was 90% plugged, and the driver reported severe drivability problems during the test cycle. The vehicle could not keep up with the US06 acceleration targets with this catalyst installed.





The CO results in Figure 7 exhibit a trend that is even clearer. The data from the second group of catalysts fits in well with the larger set. Most emission results exceeded those of the baseline catalyst, even at low plugging ratios. Again, the 90% plugged catalyst produced a data point far beyond the other results, at 128 g/mi CO. There is no THC (total hydrocarbon) standard for the US06, but the data are shown in Figure 8 just to demonstrate the strong relationship with plugging ratio.





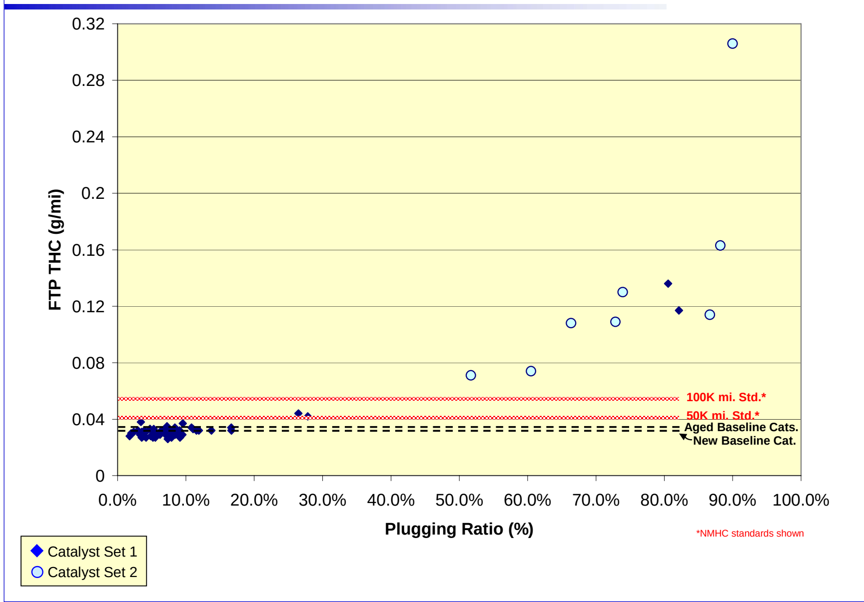
FTP Cycle

The FTP charts include two baselines: A baseline from the original low-mileage reference catalyst, and a second baseline derived from high-mileage catalysts retrieved from in-use vehicles. These in-use vehicles consisted of five 2001 Model M-1s that were retrieved from the U.S. market for the purpose of an in-use emission performance confirmation study unrelated to this project, specifically the aforementioned In-Use Verification Program (IUVP). Vehicles chosen for the IUVP program are randomly selected by a third party, and are screened to reject vehicles that have been abused, tampered with, or have experienced major engine or catalyst

v.081407

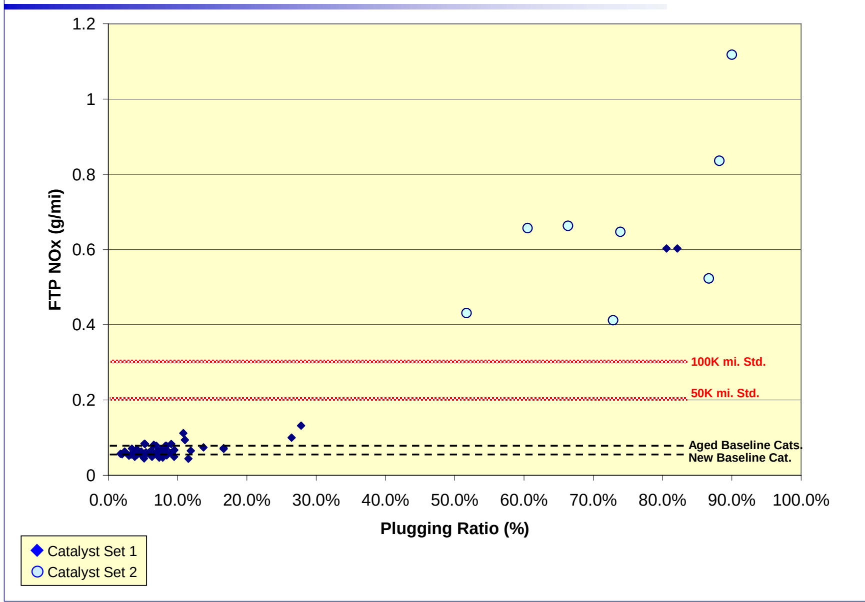
repairs. The questionnaire used for this screening is shown in Appendix 2. The vehicle mileage ranged from 61,859 miles to 93,364 miles, with an average of 76,462 miles (123,054 km). Two emission target levels are also shown; one applies to vehicles with mileage between 4,000 and 50,000 miles, and the other applies up to the "full useful life" of the vehicle. The latter mileage is 100,000 for the Model M-1's emission class. As with the US06, the THC data show a trend with the plugging ratio; Figure 9. All catalysts with a plugging ratio above 50% caused the vehicle to exceed its useful life standards. (Note that THC data are shown in place of NMHC data; three NMHC data points were unavailable due to an instrument problem. For this data set, THC was generally only a few milligrams higher than NMHC.)

Figure 9 FTP THC vs. Plugging Ratio



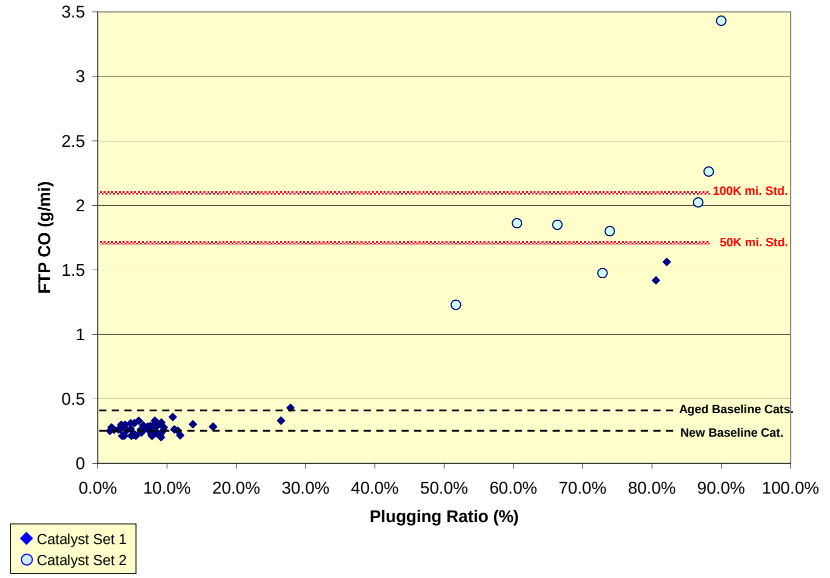
The trend for NO_X and CO (Figures 10 and 11) was not as clear, but was still apparent. For NO_X, all catalysts with a plugging ratio above 50% caused the vehicle to exceed its useful life standards.

Figure 10 FTP NOx vs. Plugging Ratio



v.081407

Figure 11 FTP CO vs. Plugging Ratio



Emission data discussed thus far represent traditional average cycle emissions. The contractor also acquired some continuous tailpipe emission data as part of this program. These continuous measurements reveal the time and cycle locations in which emission events occur. Figures 12 and 13 show such data for the THC and NO_X emissions in the first two phases of the FTP cycle. The three catalysts compared in these charts are the reference catalyst, and catalysts with plugging ratios of 26% and 82%. Light-off time is the main emission performance difference between the reference catalyst and the 26%-plugged catalyst. The MMT contamination slows the light-off time for the latter catalyst, but after that point the two catalysts have similar performance. The 82%-plugged catalyst suffers not only from a light-off time deficiency, but also from decreased efficiency throughout both phases of the FTP. The MMT contamination causes continuous emissions breakthrough.

Figure 12 THC Accumulation in FTP

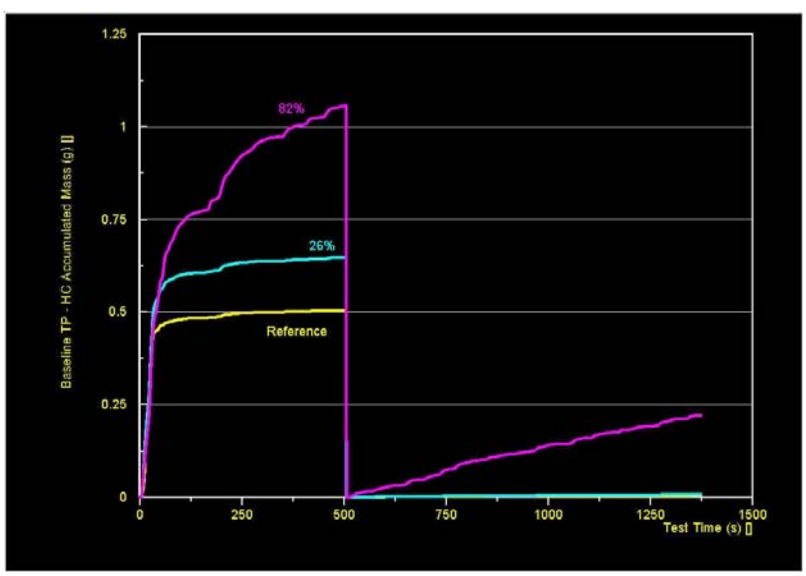
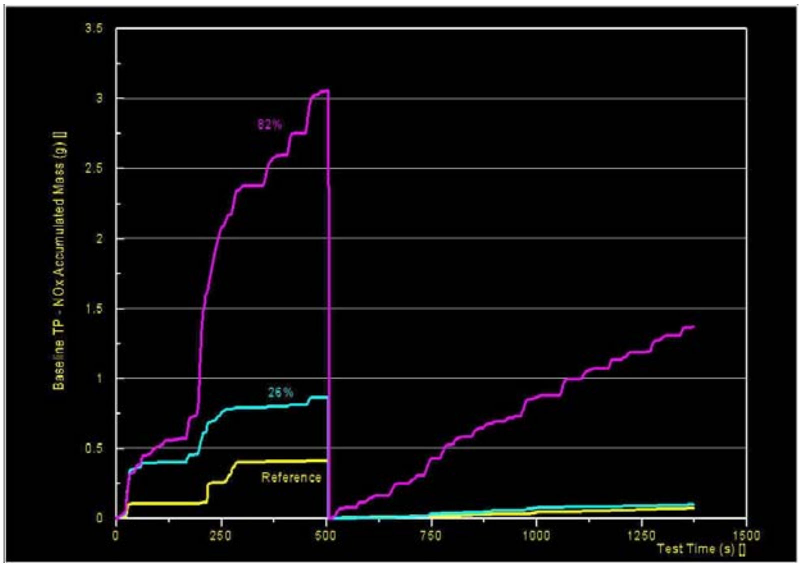


Figure 13 NOx Accumulation in FTP

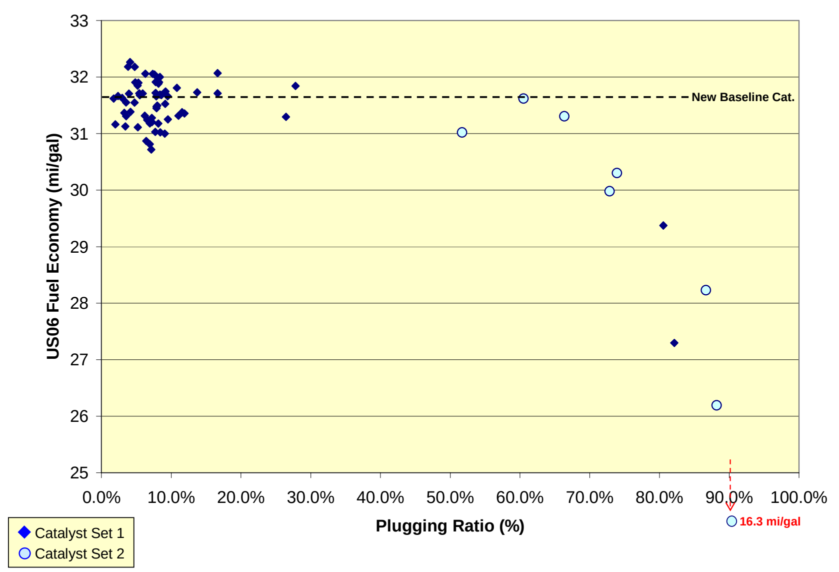


Throughout the program, the reference catalyst was run at various time intervals as a quality control check for the vehicle, dynamometer, and test equipment. Stability was excellent.

Fuel Economy

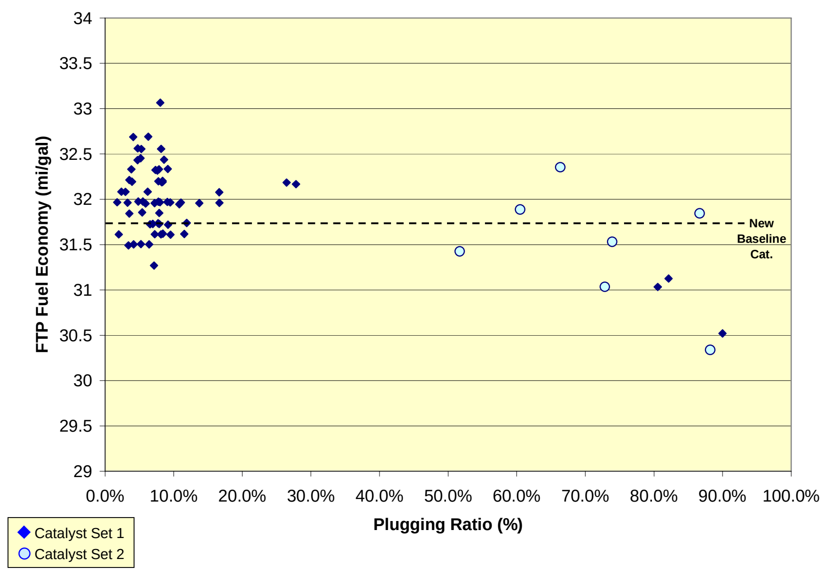
The most pronounced effect on fuel economy was apparent during the US06 cycles; Figure 14. Catalysts with a plugging ratio greater than 65% caused a clear degradation in fuel economy. For the 90%-plugged catalyst, the fuel economy was approximately half that of the reference catalyst. The effect of plugging ratio on FTP fuel economy is shown in Figure 15. Catalysts with high plugging ratios again caused a decrease in fuel economy, but the effect was less pronounced. Results from the Highway cycle indicated a fuel economy trend similar to that of the FTP. (Highway cycle testing was not performed for all catalysts in the program, so the results are not shown.)

Figure 14 US06 Fuel Economy vs. Plugging Ratio



v.081407

Figure 15 FTP Fuel Economy vs. Plugging Ratio

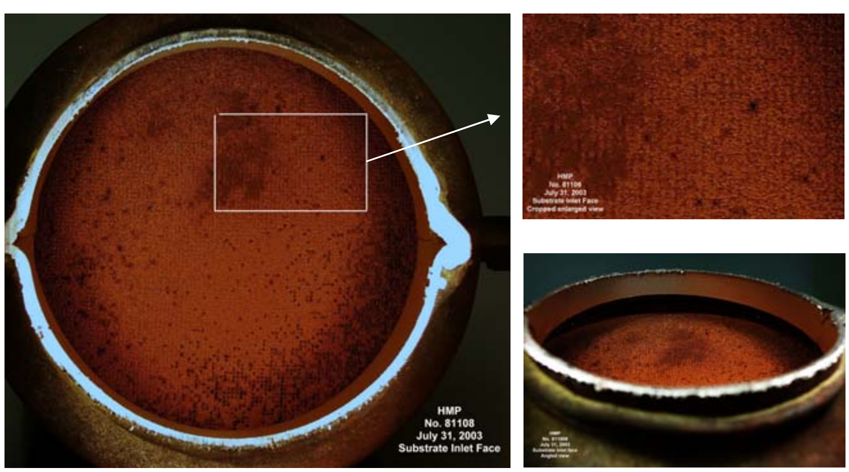


Catalyst Photography

The 82%-plugged catalyst discussed in the emissions accumulation section above is shown in Figure 16. The catalyst face is substantially covered by a rust-covered deposit, with very few open cells apparent. Most of the catalyst deposits examined during this project were of this color.

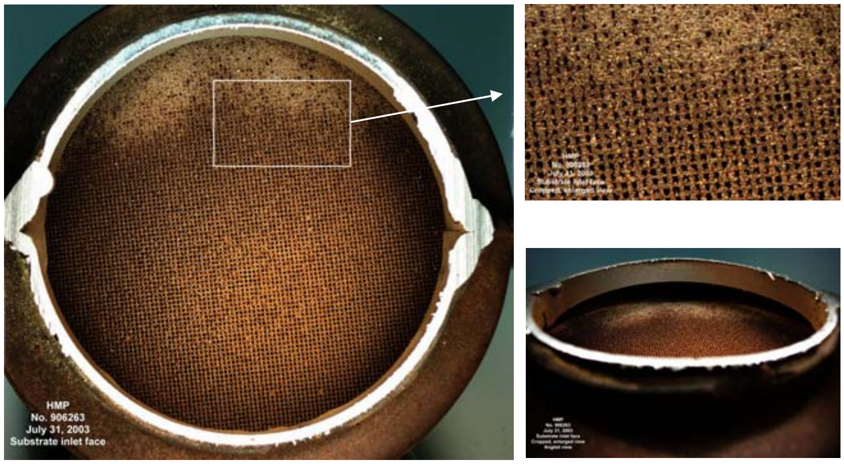
A few of the examined catalysts have deposits that were closer to brown in color. One example in shown in Figure 17. This catalyst had a plugging ratio of 11%.

Figure 16 Catalyst Photograph – 82% Plugged



v.081407

Figure 17 Catalyst Photograph – 11% Plugged



Deposit Material Analysis

The two catalysts shown in Figures 16 and 17 can be considered to represent a range of plugging ratios, deposit color, and deposit morphology observed in the samples chosen for photography and analysis. Regardless of these differences, the elemental analyses performed using PIXE produced results that were very similar; see Figure 18. The complete PIXE analyses of these catalyst deposits are listed in Appendix 4, together with detection limits for the elements. For all catalyst deposits tested, the primary component was manganese. Aside from one sample at 36%, all manganese concentrations fell between 42% and 59%.

Figure 18 PIXE Analysis Summary

	Catalyst 1 • 82% plugged • Rust-colored deposit	Catalyst 2 • 11% plugged • Brown-colored deposit
Manganese	58 %	55 %
Oxygen*	33 %	34 %
Phosphorus	3.7 %	3.8 %
Calcium	2.9 %	1.8 %
Zinc	1.1 %	0.9 %
Iron	0.6 %	0.5 %

*calculated

v.081407

The XRD results for these same two catalysts are shown in Figures 19 and 20. The catalysts produced virtually identical spectra. Comparison with the reference spectrum below each sample spectrum confirms that the predominant crystalline phase is clearly manganese oxide, specifically Mn_3O_4, as it was for all catalyst deposits tested. In some samples, minor amounts of other crystalline phases were detected, such as Mn_2O_3 and Mn-Mn_6SiO_{12}.

Figure 19 Catalyst XRD Analysis – 82% Plugged

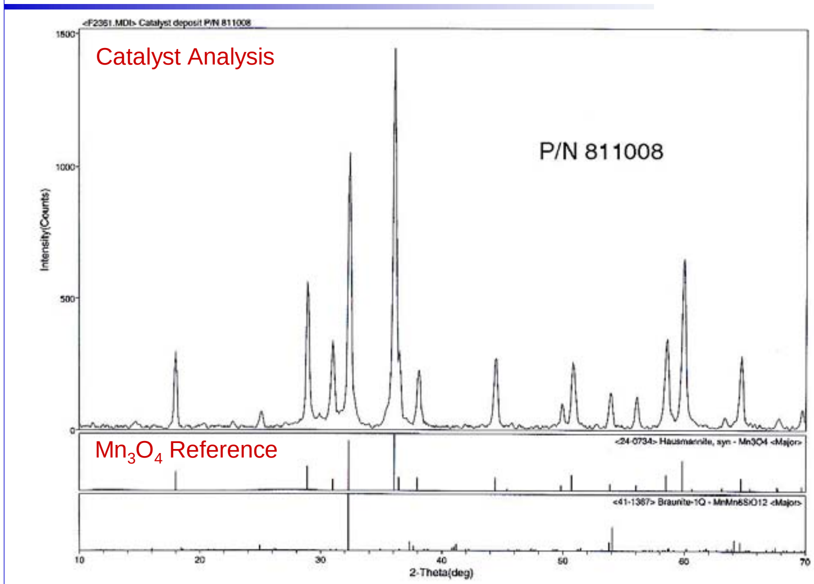
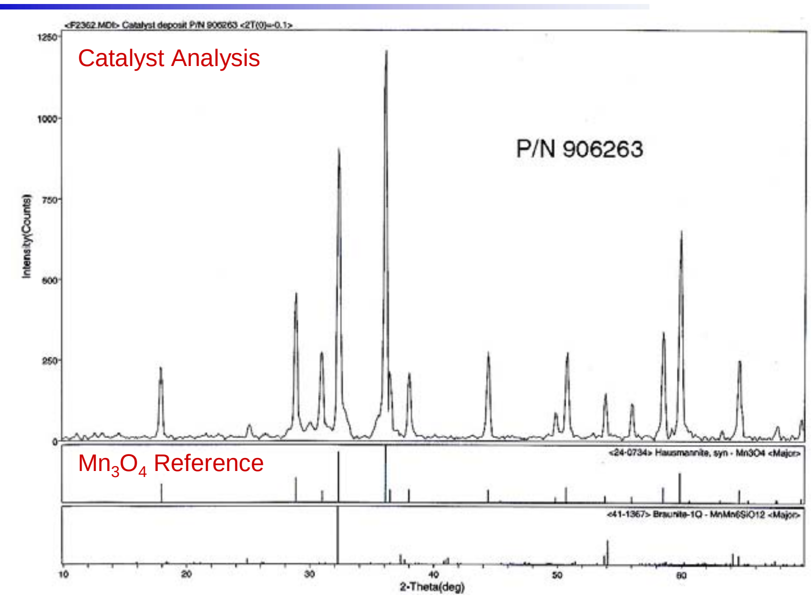


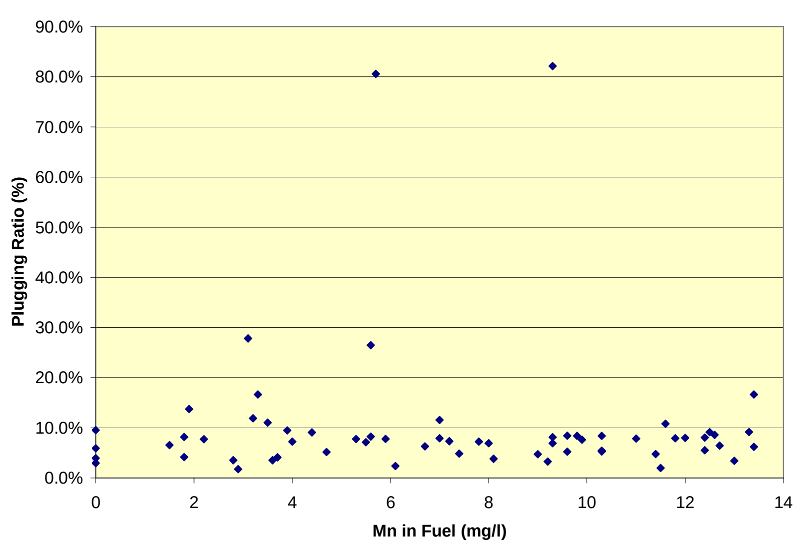
Figure 20 Catalyst XRD Analysis – 11% Plugged



Fuel Analysis

The analysis of MMT in gasoline is somewhat technique sensitive, and should therefore be performed by a laboratory with experience in such analyses. The contractor's laboratory was chosen to analyze the fuel samples acquired at the start of this project. This lab has been audited by Manufacturer M R&D, and confirmed to have excellent quality control for this analysis. The results indicated a broad distribution of MMT in the gasoline samples, ranging from 0 to 13.4 mg/l Mn. (MMT is reported in terms of manganese concentration.) As can be seen in Figure 21, no correlation was found with the catalyst plugging ratio. No correlation with emission results could be found either. This was not surprising, since the fuel sample collected at the time of hardware acquisition represented only a snapshot in time; the fueling history of the vehicle could not be determined in this manner. Note that the data shown in Figure 21 do not represent the second set of catalysts collected, since fuel samples were not available.

Figure 21 Plugging Ratio vs. Manganese in Fuel



SUMMARY AND CONCLUSIONS

A test program was conducted on a set of 63 randomly-selected catalysts from Ontario, Canada. The gasoline additive MMT was commonly used in Ontario at the time of the program. This sample set was augmented by a second set of 25 warranty-returned catalysts. The catalysts were sent to an independent contractor for flow testing, emission testing, photography, and chemical analysis.

- All catalysts tested were found to be plugged to some extent, when compared to the reference catalyst. The range of plugging was 2% to 90%.

- Catalysts with higher plugging ratios exhibited higher emissions. On the US06 cycle, the NMHC+NO_X standard for the test vehicle was exceeded by many of the catalysts, including all samples with plugging ratios over 20%. One of the severely-plugged catalysts essentially turned the ULEV Model M-1 into a gross emitter, with emissions over 300 times greater than the reference catalyst.

- On the FTP cycle, all catalysts with plugging ratios over 50% caused the vehicle to exceed its useful life emission standards for NMHC and NO_X.

- Continuous tailpipe emission data revealed that the light-off time is slowed for catalysts with moderate levels of plugging, causing an emission increase from the very beginning of the driving cycle. For catalysts with heavy levels of plugging, efficiency is decreased throughout the entire cycle, causing continuous emission breakthrough.

- Vehicle fuel economy was affected at higher plugging ratios, as measured on the US06 cycle. At the extreme case of 90% plugging, the fuel economy was about half that of the reference catalyst.

- Analysis of the deposit material revealed the primary element to be manganese, and the primary phase to be manganese oxide, specifically Mn_3O_4. These findings were consistent across all tested catalysts, regardless of plugging ratio, deposit color, or deposit morphology.

REFERENCES

1. Benson, J.D. & Dana, D. (2002). The Impact of MMT Gasoline Additive on Exhaust Emissions and Fuel Economy of Low Emissions Vehicles (LEV). Society of Automotive Engineers, SAE Paper 2002-01-2894

2. Manufacturer M (2005). Effect of MMT upon Vehicles in a Road Test Program. Unpublished.

3. Alliance of Automobile Manufacturers, North American Fuel Survey, 1996 to 2002.

4. Manufacturer M, Canadian and US divisions (2003), Survey of Ontario Gasoline Quality. Unpublished.

5. Retention Marketing, 82 Berkely Street, Studio 201, Toronto, ON, M5A 2W7

SURVEY INSTRUCTIONS

Please mark the box next to your selection. For some questions marking more than one box may be appropriate.

1. Concerning the gasoline you use in yourvehicleplease provide the following information.

(a) Brand name of gasoline you normally use? ☐ Shell ☐ Esso ☐ Petro Canada ☐ Other

If other, please specify________________

(b) If you specified more than one brand in (a) which one do you use the most often _______________

(c) Do you always use the same brand of gasoline? ☐ Yes ☐ No

(d) If you specified more than one brand for (a) and marked "No" for (c), please indicate the percentage of the brand of gasoline you use the most.

☐ -30% ☐ 31–40% ☐ 41– 50% ☐51 – 60% ☐61– 70% ☐71– 80% ☐81 – 90%

(e) Which grade of gasoline do you usually use? ☐ regular ☐ mid-grade ☐ premium

(f) Do you usually fill up with gasoline at the same station? ☐ Yes ☐ No

(g) If you answered "Yes" for (f) what is the location of the gasoline station?__________________________________

(h) Have you ever used a gasoline additive? ☐ Yes ☐ No

If you marked "Yes" for (h), please write the name and purpose of the additive.

Name of the Additive ____________________ Purpose of the Additive________________________________

2. Concerning your car, please provide the following information.

(a) Purchasing ☐ New Car ☐ Used Car ☐ Lease Program

(b) Date of Purchase Year __________ Month__________

(c) If purchased used, how many owners other than you have there been? ________

(d) Is/was the vehicle used for commercial purposes?: ☐ Yes ☐ No

(e) Current odometer reading?_______________ kms

3. Have you ever experienced the following conditions? Please fill in as applicable.

(a) Have you ever driven your car under the following conditions?

(1) Drive less than 15 kms in freezing temperatures ☐ Usually ☐ Sometimes ☐ Seldom ☐ Never

(2) Extended idling or stop-and-go driving. ☐ Usually ☐ Sometimes ☐ Seldom ☐ Never

(3) Driving in mountainous conditions. ☐ Usually ☐ Sometimes ☐ Seldom ☐ Never

(4) Driving with a car-top carrier. ☐ Usually ☐ Sometimes ☐ Seldom ☐ Never

(b) Do you operate your engine in the "red zone" rpm range? ☐ Usually ☐ Sometimes ☐ Seldom ☐ Never

(c) Has your car ever overheated? ☐ Several times ☐ 1 time ☐ Never

(d) Has your car ever completely run out of gasoline? ☐ Yes ☐ No

(e) Are you likely to overtake other vehicles on freeways? ☐ Yes ☐ No

(f) Has your car ever been driven a long time with the parking brake applied? ☐ Yes ☐ No

(g) Have you ever use an engine oil additive?

Name of Additive ____________________ Purpose of the Additive ____________________________

(h) Have you perceived any changes in the driveability or fuel economy of your vehicle? ☐ Yes ☐ No

(i) If you indicated "Yes" for (h), please explain briefly:

____

____

4. Please answer to the following questions concerning the in-use driving conditions of your vehicle.

(a) What percent of the time do you operate the car's air conditioning system each year? _______ %

(b) Do other people drive your car? If "Yes", what percent of the time do others use your car? ☐ Yes (___%), ☐ No

(c) In terms of distance, what percentage do you use your car for the following? (Total should equal 100%.)

Commute to and from work? _____% Weekend outing?_____% Other travel (shopping, errands, etc)____%

(d) In terms of distance, what percentage of your driving is done for ...

(1) Work Commute (Total should equal 100%)

Highways/Freeways _____% Rural Roads _____% City, Suburban, Residential Streets

(2) Weekend Outing (Total should equal 100%)

Highways/Freeways _____% Rural Roads _____% City, Suburban, Residential Streets____%

(3) Other purposes like shopping, errands, etc (Total should equal 100%)

Highways/Freeways _____% Rural Roads _____% City, Suburban, Residential Streets_____%

(e) In terms of distance, what percentage of your rural road driving is done on the following surface types ...

(1) Work Commute (Total should equal 100%)

Paved Road __________% Unpaved Road __________% Off-road __________%

(2) Weekend Outing (Total should equal 100%)

Paved Road __________% Unpaved Road __________% Off-road __________%

(3) Other purposes like shopping, errands, etc. (Total should equal 100%)

Paved Road __________% Unpaved Road __________% Off-road __________%

(f) Usually, how many people typically travel in your car at one time?

During Work Commute _______

During Weekend Outings ________

During other travel like shopping, errands, etc. ________

(g) Usually, how much luggage or cargo weight (excluding passengers) do you put in your car?

(1) For Work Commute

☐ 0 kg(0 lb) ☐ 11 kg(25 lbs) ☐ 22 kg (50 lbs) ☐ 45 kg (100 lbs) ☐ 90 kg (200 lbs)

☐ 135 kg (300 lbs) ☐ 180 kg (400 lbs) ☐ over 225 kg (500 lbs)

(2) For Weekend Outings

☐ 0 kg (0 lb) ☐ 11 kg (25 lbs) ☐ 22 kg (50 lbs) ☐ 45 kg (100 lbs) ☐ 90 kg (200 lbs)

☐ 135 kg (300 lbs) ☐ 180 kg (400 lbs) ☐ over 225 kg (500 lbs)

(3) For other travel like shopping, errands, etc.

☐ 0 kg (0 lb) ☐ 11 kg (25 lbs) ☐ 22 kg (50 lbs) ☐ 45 kg (100 lbs) ☐ 90 kg (200 lbs)

☐ 135 kg (300 lbs) ☐ 180 kg (400 lbs) ☐ over 225 kg (500 lbs)

(h) How many kilometers do you commute round trip to work each day?

Highways/Freeways________kms Rural Roads________kms City, Suburban, Residential Streets________kms

(i) Please name two of the highways/freeways that you most frequently travel. Further, please write the typical driving speed of each highway/freeway (excluding heavy congestion).

Highway/Freeway ____________________ Vehicle Speed __________km/h

Highway/Freeway ____________________ Vehicle Speed __________km/h

(j) Please name one of the city, suburban, or residential streets that you most frequently travel. Further, please write the typical driving speed on the road (excluding during heavy congestion).

Name of the road _________________ Vehicle Speed __________km/h

(k) Please name three of the rural roads that you most frequently travel. Further, please write the typical driving speed on the road (excluding during heavy congestion).

Paved Road ____________________ Vehicle Speed __________km/h

Unpaved Road ____________________ Vehicle Speed __________km/h

Off- Road ____________________ Vehicle Speed __________km/h

(l) Estimate your average annual accumulated mileage? ____________kms

5. Please answer the following questions as applicable.

(a) Other than during normal engine start-up, has the "Check Engine Lamp" of your vehicle ever been illuminated?

☐ Yes ☐ No

(b) If your answer for (a) is "Yes", how far did you drive the car under such a condition? About __________kms

(c) If your answer for (a) is "Yes", how did you fix such condition?

☐ The necessary inspection and repair was made.

☐ The lamp automatically turned off (no re-illumination occurred).

☐ Other

(d) To your knowledge, has the "Check Engine Lamp" not illuminated temporarily when turning the key on to start the engine? ☐ Yes ☐ No

(e) Has the "Check Engine Lamp" ever blinked / flashed? ☐ Yes ☐ No

(f) If your answer for (e) is "Yes", how far did you drive the car under such a condition? About __________kms

(g) If your answer for (e) is "Yes", how did you fix such condition?

☐ The necessary inspection and repair was made.

☐ The lamp automatically turned off (no re-illumination occurred).

☐ Other

6. Please answer the following questions regarding towing.

Have you ever towed a trailer or other vehicle?

A. Business purposes ☐ Yes ☐ No

B. Private purposes ☐ Yes ☐ No

If your answer is "Yes" to either or both of the above please answer the following questions also.

A. If you tow for business purposes ...

(1) What do you mainly tow? ☐ Camper ☐ Boat etc. ☐ Other _________________

(2) How much does it weigh? About __________ kgs / lbs.(circle kgs or lbs)

(3) How far do you tow? About _____% of total annual mileage

(4) As a percentage of total annual mileage, how much of your towing is on ... (Total should be 100%)

Highways/Freeways ____% Rural Roads ____% City, Suburban, Residential Streets____%

(5) What is the typical towing speed for each road type?

Highways/Freeways______kms Rural Roads_____kms City, Suburban, Residential Streets_____kms

B. If you tow for private purposes ...

(1) What do you mainly tow? ☐ Camper ☐ Boat etc. ☐ Others ________________

(2) How much does it weigh? About [ ] lbs.

(3) How far do you tow? About _____% of total annual mileage

(4) As a percentage of total annual mileage, how much of your towing is on ... (Total should be 100%)

Highways/Freeways______% Rural Roads_____% City, Suburban, Residential Streets _____%

(5) What is the typical towing speed for each road type?

Highways/Freeways______kms Rural Roads_____kms City, Suburban, Residential Streets____kms

7. Please provide the following information.

(a) Sex ☐ Male ☐ Female

(b) Age ☐ 20 or under ☐ 21 – 30 ☐ 31 – 40 ☐ 41 – 50 ☐ 51 or over

(c) Follow-up phone call information:

Phone number(s) at which I can be reached: Work #: ______________ Times ___to____ AM ___to____ PM

Home#:______________ Times ___to____ AM ___to____ PM

Cell # : ______________ Times ___to____ AM ___to____ PM

(d) Name, if different than addressee_________________

Additional Comments

Appendix 2 IUVP Questionnaire

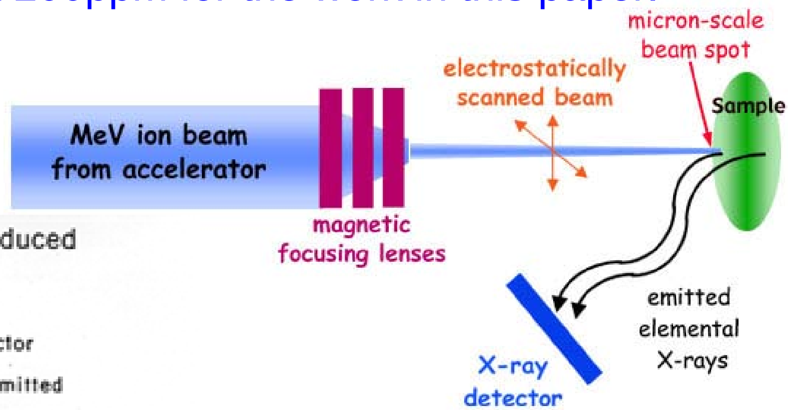
Date:_________ Air Conditioning: ☐YES , ☐NO REJECT IF NO
Transmission: ☐AUTO , ☐MANUAL
Vehicle:____________________ Phone(Home):__________
Owner:____________________ Times:__________
Address:____________________ (Work)__________
City/State/Zip____________________ Times:__________
VIN:______________ License Plate__________ State______

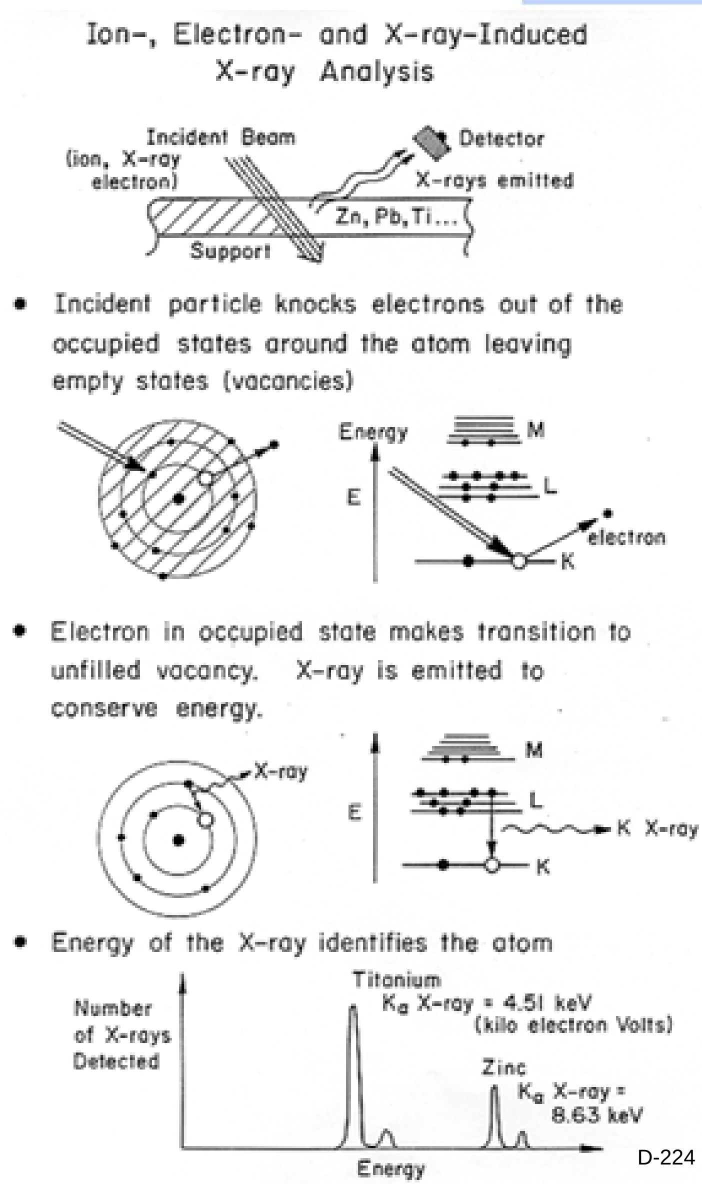
No.	Question	Answer
1	Has the speedometer/odometer ever failed to work?	☐Yes ☐No
2	Has the speedometer been replaced?	☐Yes ☐No
3	What is the odometer reading? 1/ ☐2001MY(High): 50,000-Full Usefull Life miles(refer to schedule) ☐2005MY(Low): over 10,000 miles (Pre-selected by mfr.)	_____miles
4	Have you used your vehicle for any of the following activities? a) As a taxi? b) As a commercial delivery vehicle? c) To race in competitive speed events? d) To plow snow?	 ☐Yes ☐No ☐Yes ☐No ☐Yes ☐No ☐Yes ☐No
5	Do you often pull a trailer? If yes, what are the trailer weight, and the maximum trailer capacity weight? If yes, how often do you pull it per month? How many occupants are in car when you pull it?	☐Yes ☐No TRA._______Lbs CAP._______Lbs _______Times _______Persons
6	Have you ever operated your vehicle on leaded gasoline?	☐Yes ☐No
7	Has your vehicle ever been involved in a significant accident or flood damage?	☐Yes ☐No
8	Is any performance equipment installed? or, Have you ever installed? (e.g., power-improvement device or lowered suspension)	☐Yes ☐No
9	Is there any history of major engine repair such as piston, crankshaft, cylinder head or engine block replacement?	☐Yes ☐No
10	Has the catalytic converter of your vehicle ever been replaced or missing?	☐Yes ☐No
11	Are there any ominous noises or serious leaks of coolant, oil or fuel from engine or transmission?	☐Yes ☐No
12	Are there any audible leaks from the exhaust system?	☐Yes ☐No
13	Does the check engine indicator flash (not turn on) when you drive?	☐Yes ☐No
14*	Was the vehicle's primary area of operation above 4,000 ft.?	☐Yes ☐No

* Applied only for high altitude procurement.

Appendix 3 PIXE: Particle-Induced X-Ray Emission

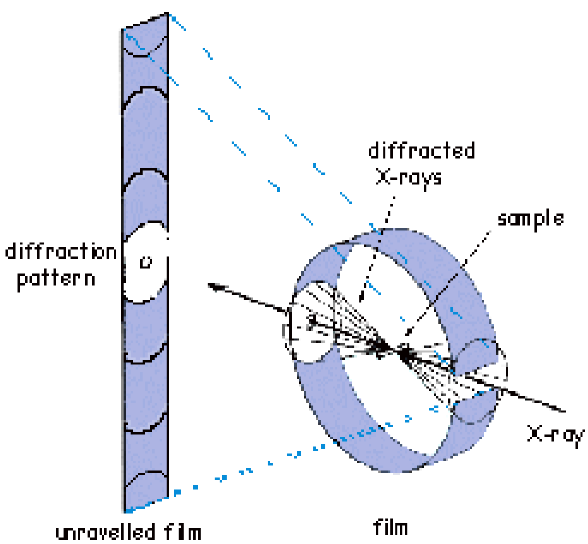
- PIXE is similar in concept to the XRF and XPS techniques.
- PIXE differs in that the incident beam consists of high-energy ions from an accelerator. This permits a broader range of elements to be analyzed, and leads to detection limits in the ppm region.
- The detection limit is sample and element dependant, but for manganese it was about 200ppm for the work in this paper.



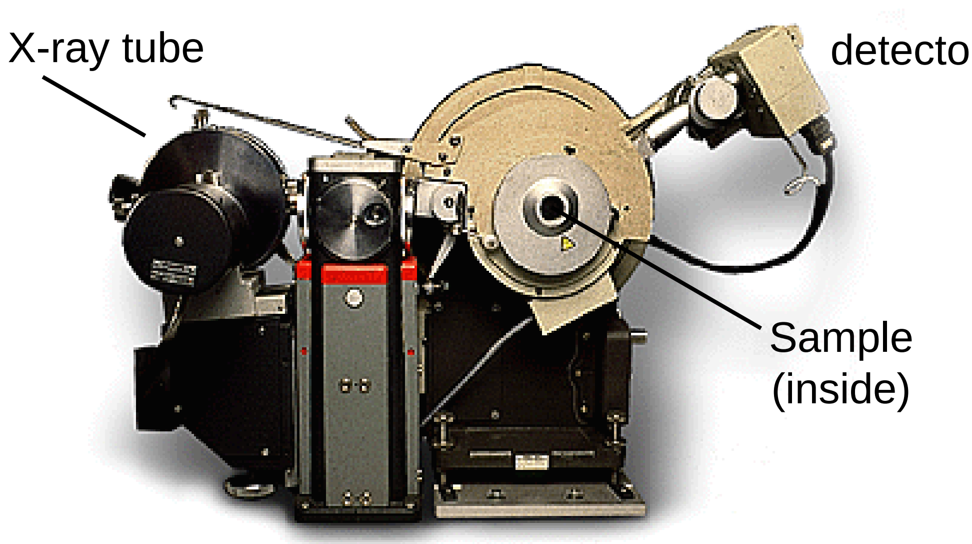


Appendix 3 XRD: X-Ray Diffraction

- X-rays are fired at a crystalline sample, and are diffracted by the regular crystal structure. A detector scans across the diffracted X-ray beam, and records a "peak" when a diffracted beam is encountered. Specific minerals can be identified based upon their characteristic diffraction pattern.
- Amorphous (non-crystalline) materials do not diffract X-rays in a regular pattern, and can therefore not be detected by this method.



Film-based instrument



Modern instrument

Appendix 4 PIXE Results – 82% Plugged Catalyst

Element Name	Energy (keV)	Det. Limit 95% Conf.	Concentration Mass	Error
* O			32.785%	
Na	1.041	0.412%		
Magnesium	1.254	670.600 ppm		
Aluminum	1.487	350.800 ppm	0.425%	0.026%
Silicon	1.740	255.000 ppm	0.187%	0.016%
Phosphorus	2.010	206.100 ppm	3.747%	0.037%
S	2.308	102.200 ppm		
Cl	2.623	60.680 ppm		
K	3.314	50.510 ppm		
Calcium	3.692	171.200 ppm	2.918%	0.031%
Sc	4.091	269.200 ppm		
Ti	4.511	78.010 ppm		
V	4.952	68.710 ppm		
Cr	5.415	101.000 ppm		
Manganese	5.899	258.700 ppm	58.071%	0.581%
Iron	6.405	0.306%	0.579%	0.140%
Co	6.930	64.840 ppm		
Nickel	7.478	43.210 ppm	212.236 ppm	43.020 ppm
Copper	8.048	56.090 ppm	593.979 ppm	58.566 ppm
Zinc	8.639	99.850 ppm	1.143%	0.022%
Ga	9.250	44.390 ppm		
Ge	9.887	29.720 ppm		
As	10.544	25.730 ppm		
Se	11.222	45.300 ppm		
Br	11.924	251.000 ppm		
Rb	13.395	50.490 ppm		
Sr	14.165	153.300 ppm		
Y	14.959	97.280 ppm		
Zirconium	15.775	367.600 ppm	640.729 ppm	221.500 ppm
Nb	16.615	104.300 ppm		
Mo	17.480	48.070 ppm		
Tc	2.424	165.800 ppm		
Ru	2.559	139.100 ppm		
Rh	2.697	115.400 ppm		
Pd	2.839	106.600 ppm		
Ag	2.984	108.700 ppm		
Cd	3.133	112.600 ppm		

* Oxygen is not a measured element; it is calculated based upon the concentrations of other sample components.

Appendix 4 PIXE Results – 82% Plugged Catalyst *cont.*

Element Name	Energy (keV)	Det. Limit 95% Conf.	Concentration Mass	Error
In	3.286	129.600 ppm		
Sn	3.444	163.500 ppm		
Sb	3.604	842.800 ppm		
Te	3.768	0.108%		
I	3.937	452.500 ppm		
Cs	4.288	269.500 ppm		
Ba	4.466	233.000 ppm		
La	4.648	300.300 ppm		
Ce	4.841	278.200 ppm		
Pr	5.034	226.300 ppm		
Nd	5.230	277.000 ppm		
Pm	5.431	339.700 ppm		
Sm	5.632	525.400 ppm		
Eu	5.841	0.645%		
Gd	6.050	0.193%		
Tb	6.271	606.800 ppm		
Dy	6.492	0.314%		
Ho	6.725	377.500 ppm		
Er	6.945	225.000 ppm		
Tm	7.182	207.900 ppm		
Yb	7.416	183.700 ppm		
Lu	7.655	127.900 ppm		
Hf	7.899	197.900 ppm		
Ta	8.149	212.600 ppm		
W	8.398	170.200 ppm		
Re	1.836	0.107%		
Os	8.911	160.300 ppm		
Ir	9.174	115.300 ppm		
Pt	9.443	417.100 ppm		
Au	9.712	352.600 ppm		
Hg	9.989	91.290 ppm		
Tl	10.267	56.590 ppm		
Pb	10.551	67.460 ppm		
Bi	10.838	113.000 ppm		
Th	2.992	217.000 ppm		
U	13.616	43.320 ppm		

Appendix 4 PIXE Results – 11% Plugged Catalyst

Element Name	Energy (keV)	Det. Limit 95% Conf.	Concentration Mass	Error
* O			34.153%	
Na	1.041	0.693%		
Magnesium	1.254	0.163%		
Aluminum	1.487	497.900 ppm	2.050%	0.069%
Silicon	1.740	360.500 ppm	1.337%	0.040%
Phosphorus	2.010	303.700 ppm	3.844%	0.052%
S	2.308	160.900 ppm		
Cl	2.623	109.600 ppm		
K	3.314	120.600 ppm		
Calcium	3.692	114.300 ppm	1.768%	0.038%
Sc	4.091	508.800 ppm		
Ti	4.511	123.100 ppm		
V	4.952	99.730 ppm		
Cr	5.415	90.570 ppm		
Manganese	5.899	149.500 ppm	54.976%	0.550%
Iron	6.405	0.285%	0.462%	0.130%
Co	6.930	51.620 ppm		
Nickel	7.478	34.020 ppm	182.716 ppm	33.802 ppm
Copper	8.048	41.270 ppm	936.064 ppm	60.002 ppm
Zinc	8.639	94.960 ppm	0.913%	0.017%
Ga	9.250	31.100 ppm		
Ge	9.887	29.060 ppm		
As	10.544	34.030 ppm		
Se	11.222	30.390 ppm		
Br	11.924	223.800 ppm		
Rb	13.395	36.330 ppm		
Sr	14.165	141.700 ppm	0.107%	0.017%
Y	14.959	53.090 ppm		
Zirconium	15.775	484.700 ppm	0.278%	0.033%
Nb	16.615	43.210 ppm		
Mo	17.480	135.200 ppm		
Tc	18.367	208.500 ppm		
Ru	19.279	62.040 ppm		
Rh	20.216	79.790 ppm		
Pd	2.839	278.800 ppm		
Ag	2.984	263.400 ppm		
Cd	3.133	221.600 ppm		

* Oxygen is not a measured element; it is calculated based upon the concentrations of other sample components.

Appendix 4 PIXE Results – 11% Plugged Catalyst *cont.*

Element Name	Energy (keV)	Det. Limit 95% Conf.	Concentration Mass	Error
In	3.286	307.800 ppm		
Sn	3.444	297.800 ppm		
Sb	3.604	0.106%		
Te	3.768	0.128%		
I	3.937	622.400 ppm		
Cs	4.288	515.100 ppm		
Ba	4.466	396.900 ppm		
La	4.648	451.900 ppm		
Ce	4.841	449.700 ppm		
Pr	5.034	312.500 ppm		
Nd	5.230	363.000 ppm		
Pm	5.431	330.000 ppm		
Sm	5.632	517.900 ppm		
Eu	5.841	0.620%		
Gd	6.050	0.179%		
Tb	6.271	570.700 ppm		
Dy	6.492	0.287%		
Ho	6.725	358.900 ppm		
Er	6.945	184.900 ppm		
Tm	7.182	140.800 ppm		
Yb	7.416	172.600 ppm		
Lu	7.655	72.120 ppm		
Hf	7.899	176.200 ppm		
Ta	8.149	216.300 ppm		
W	8.398	147.400 ppm		
Re	8.652	0.109%		
Os	8.911	197.400 ppm		
Ir	9.174	84.930 ppm		
Pt	9.443	276.900 ppm		
Au	9.712	260.700 ppm		
Hg	9.989	102.000 ppm		
Tl	10.267	84.180 ppm		
Pb	10.551	103.600 ppm		
Bi	10.838	43.990 ppm		
Th	12.968	312.600 ppm		
U	13.616	100.700 ppm		

Best Viewed in Color

Manufacturer O

Use and Experience with High Density Close Coupled (HDCC) Catalyst Systems in the Canadian Market with Exposure to MMT®

Manufacturer "O" Information

High Density Close Coupled (HDCC) Catalysts Used Prior to MY2004:

- 600 cpsi HDCC catalysts have been used across the board, with a few exceptions, for all vehicle applications certified to LEV standards since MY2001. See the attachment 1 for a table summarizing these configurations.
- One of these MY2001 applications beginning in MY2001 involved a close coupled manifold mount design. This was a mid-size vehicle with a ~ 3 L V6 engine certified to the LEV standards. It had a close coupled 600 cpsi, 4.32 mil wall thickness, ceramic catalyst on each side of the V engine.
- There have been several limited applications of high density ceramic catalysts as early as MY2000. One of these was certified to ULEV standards but in Canada was sold in low volume only in British Columbia. The other which was sold across Canada used a 600 cpsi metallic catalyst and was certified to LEV standards.
- A vehicle meeting ULEV was only sold in low volume in British Columbia for MY2001. This was a small vehicle with a ~ 2 L engine. This case is of interest because some limited testing on one of these vehicles was conducted on MMT containing fuel. This is discussed below.

Experience w/MMT Plugging:

- Through 2005, no field experience has been identified with HDCC catalysts that indicate an MMT plugging problem. Examination of the warranty data base did not show any catalyst replacement cases where the failure codes would indicate a symptom of MMT plugging.
- Returned catalysts stored at catalyst recycler's location were examined to look for evidence of MMT plugging. Some catalysts exhibited the characteristic orange like color attributable to MMT coating, but none showed significant cell plugging.
- Catalysts from a few of the mid-size vehicle configurations mentioned above that had a close coupled manifold mounted catalyst were examined. Again MMT coating was observed but with no cell plugging.
- For about two months in 2004 a warranty return program was in place, wherein dealers had to return the original catalyst from the above mentioned manifold mount catalyst configuration in order to get approval for warranty reimbursement for any type of catalyst replacement. About 20 catalysts were returned under this program. Replacements ranged from approximately 500 – 58,000 kilometres. Again, there was evidence of MMT coating without significant signs of cell plugging. [NOTE: This program was discontinued since most fuel refiners had voluntarily stopped the addition of MMT to gasoline.]

Future Technology Plans:

- HDCC systems are planned across the board for all vehicles certified to Tier 2 Bin 5 (and lower). [NOTE: All corporate "front" bricks were 600 cpsi by MY2004 regardless of standards except for turbo and performance vehicle option (PVO) applications.]
- Most applications will involve ceramic 600 cpsi catalysts, although there will be some movement toward 900 cpsi catalysts. Additionally, some of the larger light duty truck models which had been using metallic catalysts were switched to ceramic designs by MY2004.
- A few "turbo and PVO" applications may be continued without high density catalysts, but will most likely be certified to higher than Bin 5 standards under available averaging rules.
- Several HDCC systems do not involve placement of the catalyst in the engine compartment, but they are placed under the "toe board" on vehicles with a transverse mounted engine. These designs still result in a location that is about as close to the engine exhaust ports as other designs involving catalysts inside a relative large engine compartment.

Emission Testing and Mechanism Analysis:

- A limited test program was run involving the MY2001 small vehicle mentioned above. This was the ULEV certified vehicle that was sold in Canada only in British Columbia. The catalyst was a ceramic high density design, located in the under toe board position.

- There has been no field catalyst related MMT problem identified with this vehicle. This may in part be due to the MMT concentrations used by gasoline marketers supplying fuel to British Columbia through the spring of 2004 appear to have been lower on average than a large portion of Canada based on fuel survey sampling data.
    - One of these vehicles was placed in service at a company facility in Ontario. The vehicle was driven as a company fleet vehicle for normal company business uses. This application resulted in relatively rapid mileage accumulation. It was fueled using brands of premium fuel that were known to have MMT concentrations around the average or higher level observed in the Alliance fuel surveys for Canada.
    - This was not a highly controlled experiment. The vehicle was placed in relatively normal service in an environment that would ensure that it saw MMT within a reasonably predictable range. The purpose was to get some indicator of what might happen if it was exposed to fuel having MMT at a concentration at or above average levels but within the CGSB standard limit.

- The vehicle was tested periodically for emissions. The vehicle was run for approximately 75,000 miles/120,000 km.
- The vehicle showed the beginning of catalyst plugging. Attachment 2 is a picture of the catalyst face at the end of the test program. Vehicle emission testing determined that emissions had increased over the last 43,500 miles/70,000 km. Average NMOG emissions were at the 100,000 mile/160,000 km certification level and NOx emissions had doubled. These finding are consistent with findings of the Auto MMT Study, Part 2 on LEVs. The testing was stopped too early (in part due to the stopping of addition of MMT to Canadian fuel) to observe whether the plugging would reach the point observed by other manufacturers where the degree of plugging begins to accelerate and plug the flow passages enough to result in a loss of performance, increase in fuel consumption, significant increase in emissions, or illumination of the MIL.

- Manufacturer O has been asked to submit exhaust temperature profile data, along with other manufacturers, on the FTP and US06 driving cycles so that comparisons between known plugging and non-plugging cases could be made to help evaluate the hypothesis that vehicles experiencing plugging are operating at higher temperatures.
  - FTP temperature information follows for a MY2004 ~2 L vehicle and the MY2005 ~3 L mid-size vehicle. These temperatures did not change appreciably on the FTP from the prior model year vehicles. No US06 temperature data for these earlier non-SFTP certified vehicles is available. This FTP temperature information is included in attachment 3.
  - Also supplied is US06 temperature data for a MY2003 small-size vehicle. However this information is not directly comparable for characterizing the operating temperatures of the older version (i.e., MY2002 and earlier) of this vehicle since it was initially certified to SFTP standards in MY2003. It is likely changes made for SFTP compliance increased operating temperatures, but the extent is not available. This temperature trace is included as attachment 4.

- With regard to the temperature issue, a possibility for why pre-SFTP certified vehicles might run somewhat cooler than those of other manufacturers follows;
  - Comparison testing with comparable competing products indicates that the fuel economy may be on the lower end of the range.
  - One reason for this observation might be that fuel enrichment strategies for the purposes of achieving exhaust cooling may be employed that may go beyond what other manufacturers are doing. This was done to prevent certain critical components (other than the catalyst) from reaching certain design temperature limits. Design temperature limits are continually being assessed and that higher temperatures may be allowed with newer

technology components and materials, however at this time the exhaust gas temperature design guidelines have not been revised upward.

  - Market and regulatory pressures are also pushing design limits on fuel control strategies. While the SFTP standards limit the amount of fuel enrichment strategies that might be employed, there is still limited room to use such strategies and still meet the standards. [NOTE: The California Air Resources Board has recently begun consideration of setting new more stringent SFTP standards. The US EPA has also said they will soon also begin to consider updating SFTP standards. Hence, there is a potential for further limitation of fuel enrichment strategies which in turn to contribute to driving catalyst temperatures even higher.]

- Initial Tier 2 Bin 5 designs did not force appreciably higher temperatures; however other factors will potentially cause future design temperatures to rise.
  - Tier 2 Bin 5, or lower bin, type engine calibrations will focus on achieving faster light off and lowering emissions during the first 15 to 30 seconds of the FTP.
  - Bag 2 and 3 emissions on earlier LEV products are very low and there is no pressing need to significantly reduce emissions during these modes to achieve Tier 2 Bin 5 levels.
  - Hence activities, similar to other manufacturers, will be looking at ways to achieve fast light off and keep start up operation as lean as possible. However, fuel enrichment cooling strategies may not be necessarily changed to meet Tier 2 Bin 5 standards.
  - On the other hand, consideration for fuel economy optimization while simultaneously meeting stringent emission standards could push future designs into higher operating temperature ranges.

- The following dimensional information is provided for the catalyst configurations used on the ~ 2 L and ~ 3 L vehicles that used the very close coupled (manifold mounted) catalyst for the 2005 model year and earlier:

  - The inlet pipe diameter for the ~ 2 L application was 2.25" and the catalyst diameter was 4.16". For the ~ 3 L application, there was no inlet pipe to the catalyst as the converter was mounted to the manifold. The manifold opening was 4.16" (same as the catalyst).

  - In terms of exhaust flow rates, the ~ 2 L application peaked at 30 g/sec (one catalyst for the 4 cylinder flow). There was 620 scf of flow as measured by FTP exhaust volume.

For the ~ 3 L application, the FTP exhaust volume was 810 scf. The peak flow rate was under 20 g/sec.

Best Viewed in Color

Attachment 1

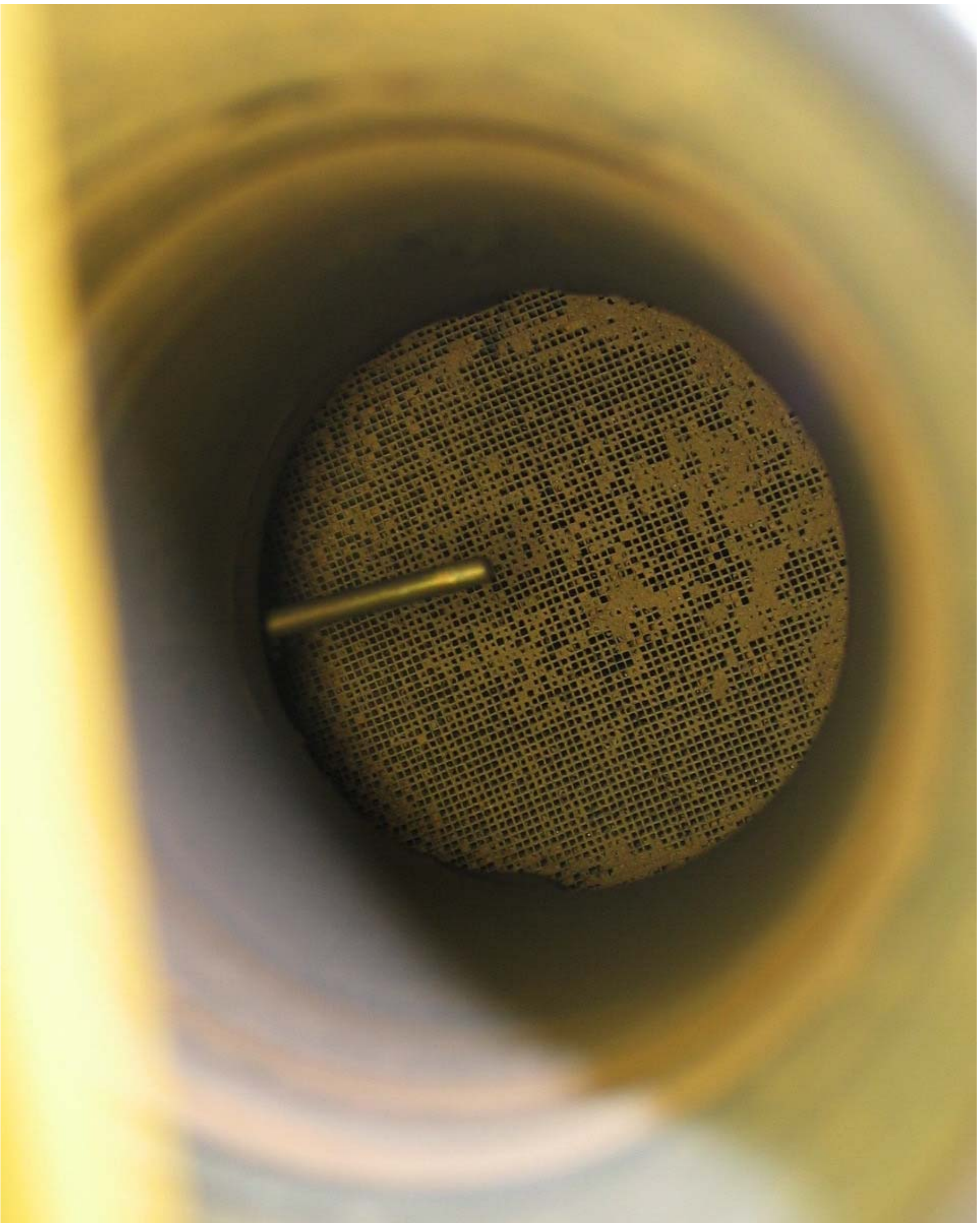
Description of Manufacturer "O" HDCC Systems Sold Prior to MY2004

Engine Specification; Displacement / Configuration (e.g., I4, V6, V8)	~2 L I4 2000MY+	~3 L V6 2000MY+	~5 L V8 2000MY+	~2 L I4 2001MY+	~3 L V6 2001MY+	~3 L V6 2001MY+
Coupling; Dimensions from Exit flange of manifold (Ranges reflect multiple banks on V engines, except note special case on ~3 L V6 which uses one catalyst)	400 mm	250-280 mm (2 cc cats, one each side)	118-140 mm (2 cc cats, one each side + 1 underfloor)	150 mm	25 mm (2 cats, one each side, same dimensions)	188 mm (1 cat, dimension for shorter side)
Catalyst Location	Toe-board	Cat in engine compartment	Cat in engine compartment	Cat in engine compartment	Very close coupled w/high turbulence	Cat in engine compartment
Catalyst Substrate Material (Metal, Ceramic)	CER	METAL Ceramic in ’05	METAL Ceramic in ‘04	CER	CER	CER
Front Substrate; cpsi / wall thickness (metallic - µm / ceramic - mil) / dia. (mm)	600 4 105.7	600 40 98.4	600 30 -	600 4.3 -	600 4.3 -	600 4.3 -
Catalyst Configuration (e.g., single bed, double bed)	DB	SB	SB (All 3)	DB	SB	DB
Emission Cert Level (e.g., Tier 1, LEV, ULEV, T2B5, etc.)	ULEV	LEV	LEV	LEV	LEV	LEV
Canada and U.S. Model Identical (Y/N)	N*	Y	Y	Y	Y	Y
Model	Small Car	Large Car	Standard Size Light Duty Truck	Mid-Size Car then on small vehicle in ‘02	Mid-Size Car	Light Duty Truck
	*US only, except was sold in Canada only in British Columbia 2001MY			Also used in some LDTs, but these NOT offered in Canada		

Best Viewed in Color

Attachment 2

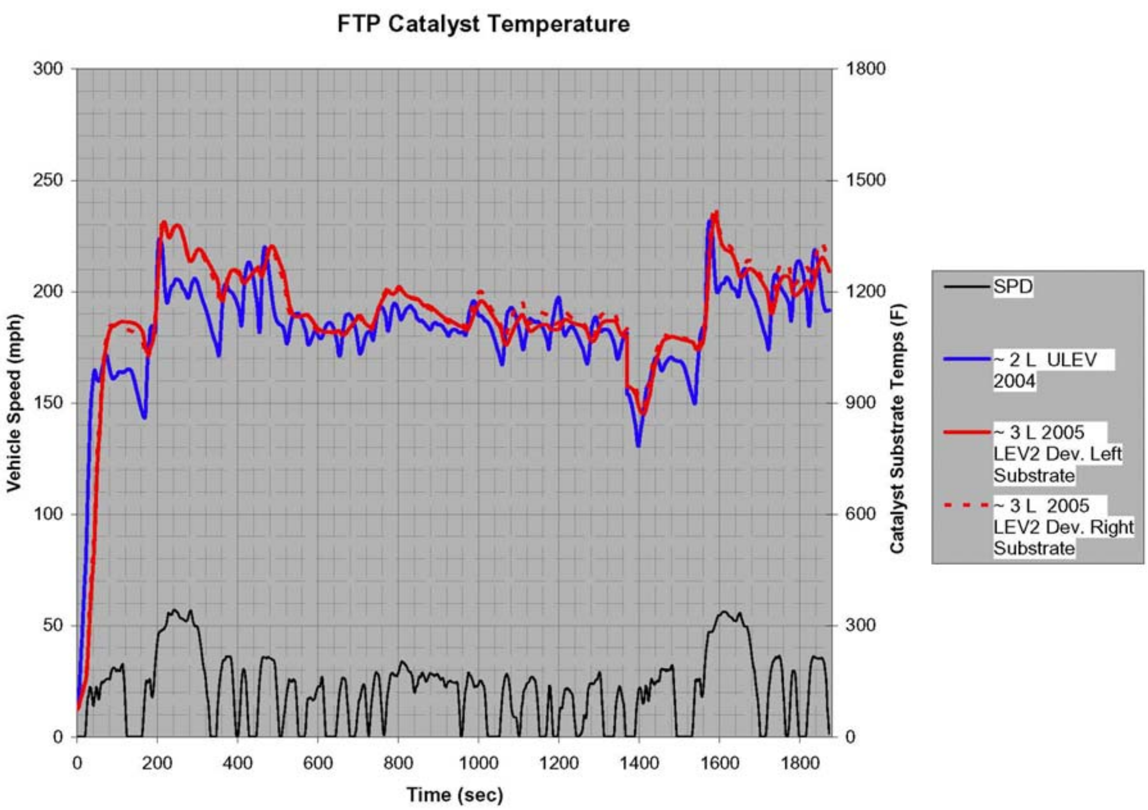
MY2001 ULEV - Catalyst Face after 75,000 mile / 120,000 km



Best Viewed in Color

Attachment 3

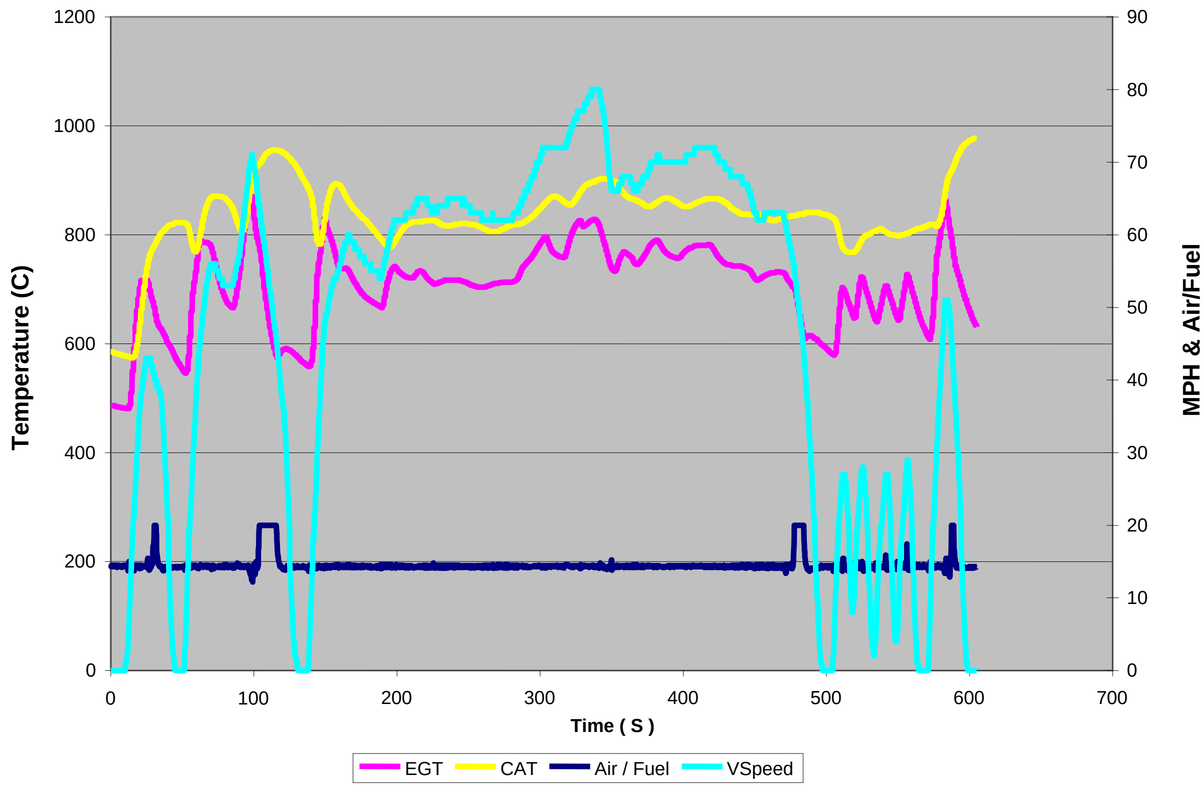
FTP temperature information for a MY2004 ~ 2 L vehicle and the MY2005 ~ 3 L vehicle



Best Viewed in Color

Attachment 4

US06 - MY2003 Small Vehicle w/I-4 engine



Appendix E

On-Road Vehicle Emission Inventory Impacts in Canada of the Gasoline Additive MMT®

FINAL REPORT

On-Road Vehicle Emission Inventory Impacts in Canada of the Gasoline Additive MMT®

April 15, 2008

For:
Canadian Vehicle Manufacturers' Association (CVMA), and
Association of International Automobile Manufacturers of Canada (AIAMC)

Air Improvement Resource, Inc.
47298 Sunnybrook Lane, Suite 103
Novi, Michigan 48374
Ph: 248-380-3140
Fax: 248-380-3146
tdarlington@airimprovement.com

Table of Contents

On-Road Vehicle Emission Inventory Impacts in Canada
Of The Gasoline Additive MMT®

1.0 Executive Summary

The gasoline additive methylcyclopentadienyl manganese tricarbonyl, or MMT®, was in widespread use as an octane enhancer in Canada prior to 2005. The manganese in MMT® forms manganese oxides, sulfides, and phosphates during combustion, some of which deposit on the spark plugs, combustion chamber, and the exhaust system, including the catalytic converter. The remainder of manganese compounds not deposited in engine and exhaust system are emitted into the atmosphere as particulates. Automakers have long been concerned that manganese compounds can also have negative impacts on engines and emission control systems.

In 2002, AIR studied the impacts of MMT® use on on-road motor vehicles in Canada ("Effects of MMT® in Gasoline on Emissions from On-Road Motor Vehicles in Canada"). This study projected the VOC, CO, and NOx emission inventory impacts on light and heavy-duty gasoline vehicles of MMT® use out to calendar year 2020. Modeling results showed that with continued use of MMT®, VOC emissions would be between 26%-36% higher, CO emissions would be 35%-75% higher, and NOx emissions would be 45%-65% higher in 2020 than if MMT® were not used (the new study and older study results are compared at the end of the Executive Summary).

The vehicle emission impacts in the 2002 study were based on an extensive testing program conducted by the Alliance of Automobile Manufacturers, the Canadian Vehicle Manufacturers' Association, and the Association of International Automobile Manufacturers. In this program, fourteen model year 1996-1999 Tier1, TLEVs, and LEV vehicles, representing the latest and most stringent vehicle emission control technology available at that time, were fueled with either MMT-containing or non-MMT gasoline, and were tested at discrete mileage points using California Phase 2 gasoline. AIR developed MMT® correction factors from these data, and incorporated these correction factors into the Canadian on-road emissions model MOBILE5C, and developed inventory projections using this model.

In the spring and summer of 2004, many if not all oil companies in Canada voluntarily discontinued using MMT® as an octane enhancer, even though MMT® use is not prohibited. Prior to the discontinuation of MMT® by the oil companies, automobile manufacturers were testing various vehicles on MMT® in their in-house testing programs and evaluating reports of operational issues with MMT® use in the Canadian market. When MMT®'s use was discontinued, many of these manufacturers continued these test and evaluation programs for a while afterward to develop additional data on the impacts of MMT®, because it was not clear at the time whether MMT® use would either be prohibited or discontinued, or both. At this time in early 2008, MMT® use is not yet prohibited, but MMT® is rarely used, if used at all in Canada.

This new study builds on the 2002 study, but adds much new data that was collected on 2000 and later model year LEVs and also early introduction of Tier 2 vehicles in the 2002-2003 timeframe. In addition, rather that evaluating the effects of discontinuing MMT® use, this new study evaluates the short-term and long-term emission inventory impacts if MMT® use becomes widespread again in Canada. This study assumes that MMT® was not in use during the 2004-2008 time period for any of the scenarios modeled.

The new data used in this study showed substantial variation in the vehicle emission system performance deterioration in response to the use of MMT® in gasoline, however, all evaluation vehicles experienced some increase in emissions when operated on MMT® containing fuel as compared to being operated on Clear fuel. Two evaluation vehicles became severely plugged before 50,000 miles [80,500 km] and required catalyst replacements.

Figure ES-1 shows the ratio of the deterioration rate on MMT® to the deterioration rate on Clear fuel for specific technology groups. These relationships were based on analysis of emissions of new data and previously collected data. The MMT®/Clear deterioration ratio is generally higher for newer technology vehicles than for the older vehicles. According to a recently released parametric study by Honda Research (SAE Paper 2007-01-1070), the higher deterioration on MMT® for newer, more advanced vehicles is generally attributable to increased use of high cell density, close-coupled catalysts on newer vehicles operating at higher temperatures. These improved catalysts and configurations on the vehicles are necessary to achieve extremely low Tier 2 and LEV II exhaust emissions standards adopted by EPA, CARB, and Environment Canada.

Figure ES-1. Deterioration Rate Ratios by Technology

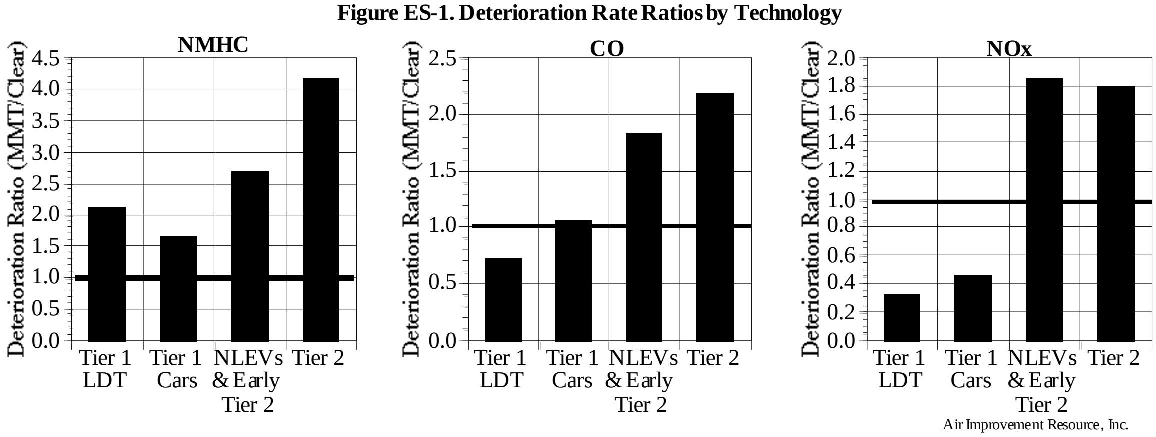


Figure ES-1 shows that on average the ratio of deterioration on MMT® to deterioration on Clear fuel has increased for NMHC, CO and NOx with more advanced technologies. Figure ES-1 does not include the effects of the catalysts that failed early because of difficulty in modeling these vehicles with catalyst replacements – if those vehicles were included (even with periodic catalyst replacements) the Tier 2 deterioration rates would be even higher. For NOx, Figure ES-1 shows that the increase in deterioration is about the same for vehicles meeting National LEV standards (2001-2003 model years) and Tier 2 vehicles (2004+ vehicles). However, for NMHC and CO, the increase in deterioration is highest on vehicles meeting the most stringent emission standards (i.e., Tier 2), and the increase in deterioration factors for NMHC (up to 4 times the Clear deterioration) is much higher than for the other two pollutants.

The MOBILE6C model was used to evaluate emission inventory impacts of the use of MMT® throughout Canada. We developed MMT® correction factors from the analysis of the data that would change the base deterioration rates of different vehicle technologies in the model. We examined emissions inventories under several cases, with and without MMT®. These cases are shown in Table ES-1 and explained below.

The baseline, called MMT-0, examines emissions without MMT® in either the pre-2004 2004-2008, or in 2008+ calendar years. MMT-1 examines emissions with just MMT® in pre-2004 calendar years. MMT-2 is the same as MMT-1 but adds MMT® use in 2008. For these three cases, we assumed that 100% of the 2001 and later vehicles experienced emission sensitivity to MMT®, and that the deterioration rates developed from evaluation vehicles, most of which were evaluated with Mn concentrations of 0.031 g Mn/ U.S. gallon [8.2 mg/L], could be applied in Canada where the average Mn concentration in the 2002-2004 period appeared to be a little lower at 0.023 g Mn/U.S. gallon [6.1 mg/L]. However, maximums of up to 0.080 g Mn/gallon [21.1 mg/L] were observed in Canada.

The next three cases (MMT-3 through MMT-5) examine different percentages of 2001 and later vehicles that are emissions-sensitive to MMT® – 80%, 50%, and 20%. MMT-6 examines the impact of lower in-use MMT® concentrations, and MMT-7 examines the impact if 10% of the fleet is plugged and requires catalyst replacements.

The without MMT® case (MMT-0) is the same as the current MOBILE6.2 baseline, and the with MMT® cases, except MMT-1, assume MMT® use starting in 2008 (unabated thereafter) with different deterioration factors for the different Groups of vehicles (Tier 1, LEV, Tier 2) based on a correction factors developed in Section 4.

Table ES-1. Summary of MMT® Modeling Runs with MOBILE6.2C					
Modeling Run	2004- MMT® Use?	2008+ MMT® Use?	% Emissions Sensitive	Mn Concentration (g/U.S.gal) [mg/L]	% Plugged
MMT-0	No	No	N/A	N/A	N/A
MMT-1	Yes	No	100%	0.031 [8.2]	None
MMT-2	Yes	Yes	100%	0.031 [8.2]	None
MMT-3	Yes	Yes	80%	0.031 [8.2]	None
MMT-4	Yes	Yes	50%	0.031 [8.2]	None
MMT-5	Yes	Yes	20%	0.031 [8.2]	None
MMT-6	Yes	Yes	80%	0.023 [6.3]	None
MMT-7	Yes	Yes	80%	0.031 [6.3]	10%

Note: This study assumes that MMT® was not in use in 2004-2008.

The first three cases (MMT-0 through MMT-2) are shown for VOC and NOx from all gasoline on-road vehicles (including heavy duty gasoline vehicles above 8500 lbs) in Canada from 2007-2020 in Figure ES-2.

Figure ES-2. Canadian Emissions from Gasoline Vehicles

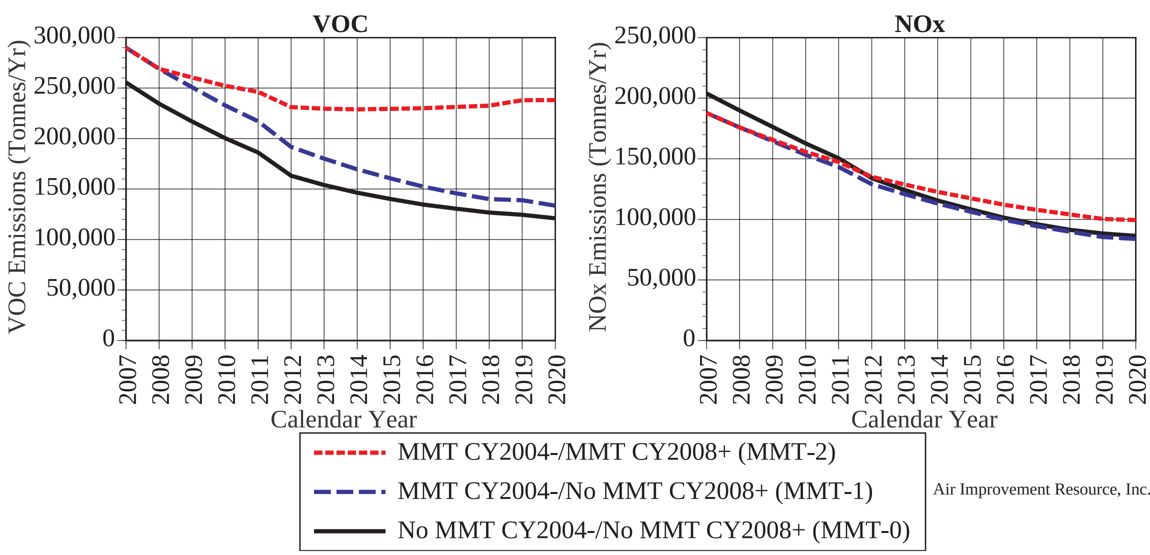


Figure ES-2 shows that VOC increases for both the MMT® CY2004-/MMT® CY2008+ case and the MMT® CY2004-/No MMT® CY2008+ cases, with the larger increases shown for the first case because MMT® use is assumed to start again in the case in 2008 (CY stands for calendar year). Since VOC is higher with MMT®, and toxics are related to exhaust VOC, then exhaust toxics such as benzene, 1,3 butadiene, acetaldehyde, formaldehyde, and acrolein will also be higher with MMT®. NOx is higher than the non-MMT® case in later years because of the effect of MMT® on NLEV and Tier 2 vehicles.

The CO emissions inventories for the different cases appear very similar to the VOC charts, except that the inventories are much higher due to the higher CO emissions in g/mi as compared to VOC. In other words, the no MMT® line is much lower than the two MMT® cases, so that CO emission inventories are much lower without MMT® than with MMT®. In 2020, CO inventories for the no MMT® case are 2 million tonnes per year lower than for the top MMT® case. The full CO emission results are shown in the main report.

Figure ES-3 shows the impact of different percentages of the 2001+ fleet displaying emissions sensitivity to MMT® (MMT-3 through MMT-5). All cases assume MMT® prior to 2004 and MMT® in 2008 and later calendar years. We show sensitivities of 20%, 50%, and 80%. In these two figures, the primary impact is on VOC and CO (CO is similar in relationship to VOC).

Figure ES-3. Canadian Emissions from Gasoline Vehicles

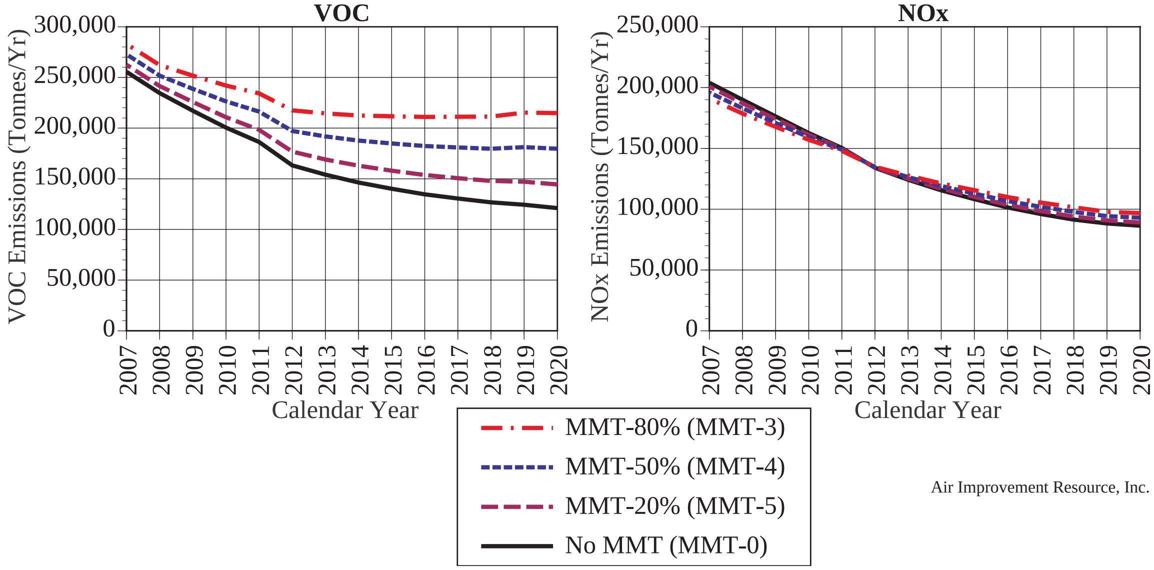
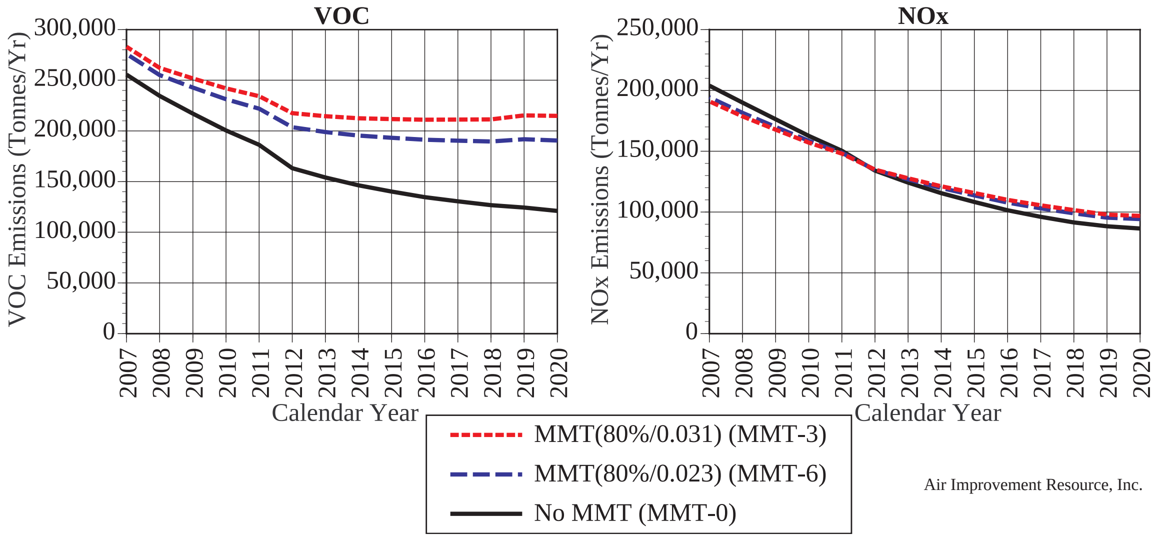


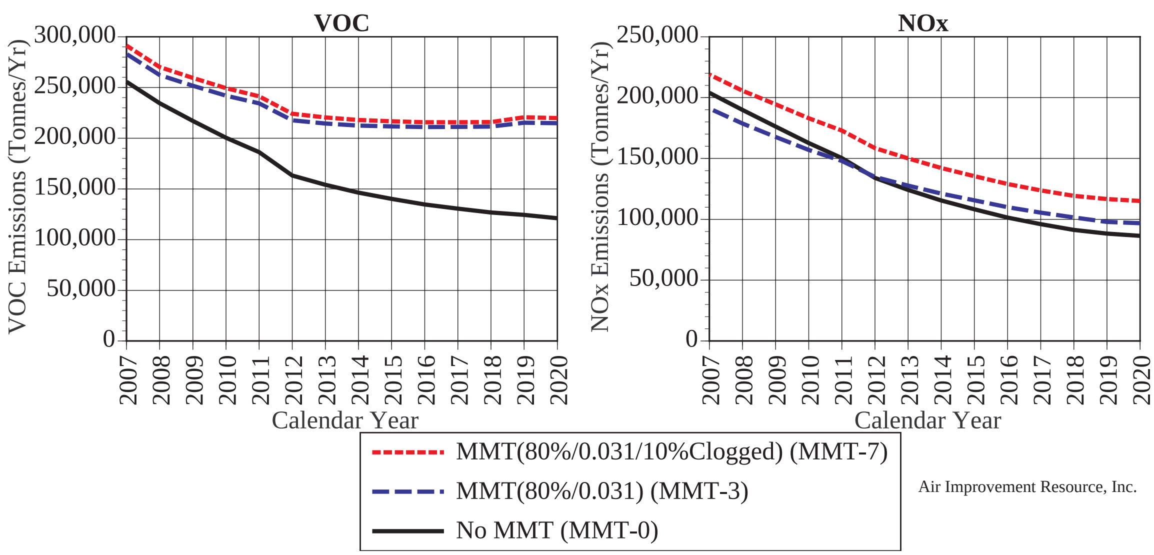
Figure ES-4 shows MMT-6, or the impact of scaling the MMT® effects proportional to the difference in Mn concentrations between most of the evaluation vehicles (0.031 g Mn/U.S. gal [8.2 mg/L]) and the average in-use Mn concentration prior to the discontinuance of MMT® in gasoline in Canada (0.023 g Mn/U.S. gal [6.1 mg/L. Both of the MMT® cases in this chart assume that 80% of the 2001+ model year fleet is emissions-sensitive to MMT®. Even if the MMT® effect is adjusted to a lower concentration of 0.023 [6.1], the effects on VOC are still very high.

ES-4. Canadian Emissions from Gasoline Vehicles



Finally, Figure ES-5 shows the impact if 10% of the fleet becomes plugged before 50,000 miles [80,500 km] and the plugged vehicles require two catalyst replacements throughout their life (MMT-7). Both of the MMT® cases assume that 80% of the 2001+ model year fleet is emissions-sensitive to MMT®, using an MMT® concentration of 0.031 g Mn/U.S. gal [8.2 mg/L]. Even if only 10% of the vehicles become plugged before 50,000 miles [80,500 km] and have catalyst replacements, there are large impacts on both VOC and NOx emission inventories.

Figure ES-5. Canadian Emissions from Gasoline Vehicles



This study evaluated emission inventory impacts if MMT® is restarted in calendar year 2008 in Canada. This analysis concludes that if MMT® use restarted in calendar year 2008 (or beyond), it would lead to widespread increases in VOC, toxics, CO, and NOx emissions throughout Canada.

In this new analysis, the total emission increases for the case with 80% emissions sensitivity, no adjustment for in-use Mn concentration, and no vehicles that are plugged are about 77% for VOC, 51% for CO, and 12% for NOx. The VOC increases in this new analysis are higher than the previous (2002) analysis, CO is about the same, and the NOx increases are lower. The reasons for these differences are directly related to the addition of new data, and the analysis of the MMT® correction factors as vehicles age. In the previous analysis, Tier 2 vehicles (based on 2 vehicles) were estimated to experience a 2.2x increase at 100,000 miles for VOC, 2.0x increase for CO, and 2.0x increase for NOx. In this new analysis, Tier 2 vehicles (based on 8 vehicles) are estimated to experience a 2.9x increase for VOC, 1.8x increase for CO, and a 1.2x increase for NOx. The lower NOx increase is due at least in part to not including two vehicles that experienced early catalyst plugging and very high deterioration – if these vehicles are included in the analysis, the new NOx deterioration rate is much higher. While there has been some change in the estimated impacts of MMT® due to the addition of new data, both studies have shown consistent increases in VOC, CO, and NOx emissions with the use of MMT®.

2.0 Introduction

The gasoline additive methylcyclopentadienyl manganese tricarbonyl, or MMT®, was in widespread use as an octane enhancer in Canada prior to 2005. The manganese in MMT® forms manganese oxides, sulfides, and phosphates during combustion, some of which deposit on the spark plugs, combustion chamber, and the exhaust system, including the catalytic converter. The remainder of manganese compounds not deposited in engine and exhaust system are emitted into the atmosphere. Automakers have long been concerned that manganese compounds can also have negative impacts on engines and emission control systems.

In 2002, AIR studied the impacts of MMT® use on on-road motor vehicles in Canada. [1] This study projected the VOC, CO, and NOx emission inventory impacts on light and heavy-duty gasoline vehicles of MMT® use out to calendar year 2020. Modeling results showed that with continued use of MMT®, VOC emissions would be between 26%-36% higher, CO emissions would be 35% higher, and NOx emissions would be 45% higher in 2020 than if MMT® were not used.

The vehicle emission impacts in the 2002 study were based on an extensive testing program conducted by the Alliance of Automobile Manufacturers, the Canadian Vehicle Manufacturers Association, and the Association of International Automobile Manufacturers. [2,3] In this program, fourteen model year 1996-1999 Tier1s, TLEVs, and LEVs, representing the latest and most stringent vehicle emission control technology available at that time, were fueled with either MMT-containing or non-MMT gasoline, and were tested at discrete mileage points using California Phase 2 gasoline. AIR developed MMT® correction factors from these data, and incorporated these correction factors into the Canadian on-road emissions model MOBILE5C, and developed inventory projections using this model.

In the spring and summer of 2004, many if not all oil companies in Canada discontinued using MMT® as an octane enhancer, even though MMT® use is not prohibited. Prior to the discontinuation of MMT® by the oil companies, automobile manufacturers were testing various vehicles on MMT® in their in-house testing programs. When MMT®'s use was discontinued, many of these manufacturers continued these testing programs for a while afterward to develop additional data on the impacts of MMT®, because it was not clear at the time whether MMT® use would either be prohibited or discontinued, or both. At this time in late 2007, MMT® use is not yet prohibited, MMT® is still rarely used, if used at all in Canada, and the government has proposed an extensive "Third-Party Review" of MMT's effects.

This new study builds on the 2002 study, but adds much new data that was collected on 2000 and later model year LEVs and also Tier 2 vehicles in the 2002-2003 timeframe. In addition, rather that evaluating the effects of discontinuing MMT® use, this new study evaluates the short- and long-term emission inventory impacts if MMT® use becomes widespread again in Canada.

This study is divided into the following sections:

- Analysis of Emissions Data on LEV and Tier 2 Vehicles
- Combining the Grouped Data for Analysis
- Modeling Methods
- Results
- Discussion

3.0 Analysis of Emissions Data on LEV and Tier 2 Vehicles

AIR's previous report discusses the emissions data collected in the Alliance/AIAM/CVMA testing program. Fourteen vehicles were tested in this testing program, which included two Tier 1 vehicles, seven Transitional Low Emission Vehicles (TLEVs) and five Low Emission Vehicles (LEVs). Four of the five LEVs were passenger cars, and one was a MDV2. No Tier 0 vehicles were tested.

AIR grouped the data from this testing program into four groups with similar numerical emission standards, as follows:

Group 1: One Tier 1 vehicle and the MDV2 LEV
Group 2: Two Tier 1 vehicles, the TLEVs, and the MDV2 LEV
Group 3: The four LEV passenger cars
Group 4: Two of the four LEV passenger cars with the lowest NOx

Group 1 was designed to approximately represent Tier 1 and LEV light duty trucks and heavy-duty vehicles. Group 2 was designed to represent Tier 1 passenger cars. Group 3 was designed to represent LEV passenger cars and LDT1s, and Group 4 was designed to represent all Tier 2 vehicles. No Tier 2 vehicles were included in this testing program because none were available, as the Tier 2 standards were still being studied when the testing program was conducted. AIR developed MMT® "correction factors" from the emissions data for these groups, incorporated these correction factors in the Canadian MOBILE model, and estimated the impacts of discontinuing MMT® use in Canada.

Since the time of the Alliance/AIAM/CVMA program, many of the individual manufacturers have continued to collect data on the adverse impacts of MMT® on catalyst systems and vehicle emissions. These include the following:

- In-use vehicles brought to dealerships by motorists for warranty service
- In-use vehicles recruited or obtained for data collection, and
- Laboratory testing programs performed to confirm in-use findings and to investigate causative factors

These data and testing programs are summarized in the main report by Sierra Research, so they will not repeated in the discussion here. However, Sierra's review found that MMT® in gasoline can cause catalyst plugging in many of the LEV and Tier 2 vehicle models, and this plugging can lead to increased backpressure, poor driveability (i.e., stumbling and hesitation), illuminated Malfunction Indicator Lights (MILs), increased emissions, and much higher warranty claims in Canada than in the U.S. for the same vehicles. The plugging is generally a function of how quickly the vehicle accumulates mileage and in some cases, how the vehicle is operated. However, Sierra concludes that based on the available data, one cannot conclusively determine what fraction of the Tier 2 fleet experiences adverse emission effects due to MMT®.[1] The reason for the inability to determine this fraction is because MMT® use was discontinued in Canada shortly after the first Tier 2 vehicles were first introduced. Consequently, many vehicles, which could have been sensitive to MMT®, simply may not have accumulated enough mileage on MMT® in order for many of these problems to surface. For example, the MOBILE model predicts that vehicles accumulate a little less than 25,000 km per year, or 50,000 km in their first two years, on average (some vehicles accumulate mileage much quicker, and some much slower). If serious catalyst plugging with MMT® does not occur in most vehicles until later, then the vehicles that accumulate mileage quickly will appear to be sensitive, and vehicles which accumulate mileage at a more normal rate my be less sensitive. If MMT® use would have continued in Canada beyond 2004, it is very possible that a much greater fraction of the fleet would be affected.

The purpose of this analysis is to update the correction factors used in the previous modeling, using all of the available data, both previous data and any new data. Not all emissions data collected by the manufacturers can be used for this purpose. The original testing program tested identical vehicles on both MMT® and Clear fuels over a long durability period (100,000 miles) [161,000 km]. Linear regressions of emissions versus mileage were then estimated for the MMT® and Clear vehicles, and odometer-related correction factors were then developed from the ratio of these regressions. Some of the new emissions tests were conducted in approximately this same manner, but other emission tests were conducted differently, as described later in this section.

AIR reviewed all of the emissions testing performed by the manufacturers, and concluded that testing conducted by three of the manufacturers – "D", "J", and "M" (as listed in the Sierra report) − could be used to develop MMT® correction factors similar to the ones that were developed from the previous testing program.[2] This does not mean that there were not adverse affects for the other manufacturers – in fact, most of the manufacturers noted adverse effects of some kind for various vehicles models.

Thus, the emissions data for LEVs and Tier 2 vehicles come from four sources:

1. The Alliance/AIAM/CVMA Testing Program
2. Additional emissions testing by Manufacturer "D"
3. Additional emissions testing by Manufacturer "J"
4. Additional emissions testing by Manufacturer "M"

The following sections discuss the individual vehicle emission results from each of these testing programs.

---

[1] All vehicles appear to be adversely impacted in some way, for example, with engine and exhaust system deposits, even though some vehicles seem to display little exhaust emission sensitivity over the range of mileages tested (they may have experienced increased emissions at later mileages).

[2] AIR is using these letters to designate manufacturers instead of naming the manufacturer to preserve the anonymity of the manufacturers. These letters are consistent with the naming convention also used by Sierra Research.

3.1 Alliance/AIAM/CVMA Testing Program

There were several LEV passenger cars tested in the Alliance/AIAM/CVMA testing program, as shown in Table 1.[3] For DCX and Ford, these are relatively light vehicles compared to the full product line for these manufacturers.

Table 1. LEV Passenger Cars Tested in the Alliance/AIAM/CVMA Program					
Make	Model	Model Year	50,000 Mile Emission Certification Standard (100,000 Mile Standard in parentheses)		
			HC	CO	NOx
Honda	Civic	1996	0.075 (0.090)	3.4 (4.2)	0.2 (0.3)
VW	Beetle	1999	0.075 (0.090)	3.4 (4.2)	0.2 (0.3)
DCX	Breeze	1998	0.075 (0.090)	3.4 (4.2)	0.2 (0.3)
Ford	Escort	1998	0.075 (0.090)	3.4 (4.2)	0.2 (0.3)

All vehicles were new at the start of the test program. Four identical vehicles of each make and model year were used in the testing. Two of each vehicle accumulated mileage on Clear gasoline, and the other two accumulated mileage on gasoline containing MMT®. The concentration of MMT® used in testing was 1/32 gram Mn per US gallon, or 0.031 g Mn/gallon [8.2 mg/L].

Prior to being used in the test program, each vehicle was tested on MMT-free certification fuel to ensure that each vehicle met its respective emission standards. After this initial testing, Clear vehicles accumulated mileage on conventional commercial fuel (with seasonal volatility and without oxygenates) with minimum 87 octane, and MMT® vehicles accumulated mileage on the same gasoline with MMT®. Mileage accumulation on the fuels was conducted using a modification of EPA's proposed Standard Mileage Accumulation (SMA) testing cycle.

The LEVs were tested at the following mileage intervals (the Honda Civics were tested only to 75,000 miles [120,700 km]):

- New
- 4,000 miles [6,400 km]
- 15,000 miles [24,100 km]
- 25,000 miles [40,200 km]
- 35,000 miles [56,300 km]
- 50,000 miles [80,500 km]
- 75,000 miles [120,700 km]
- 100,000 miles [161,000 km]

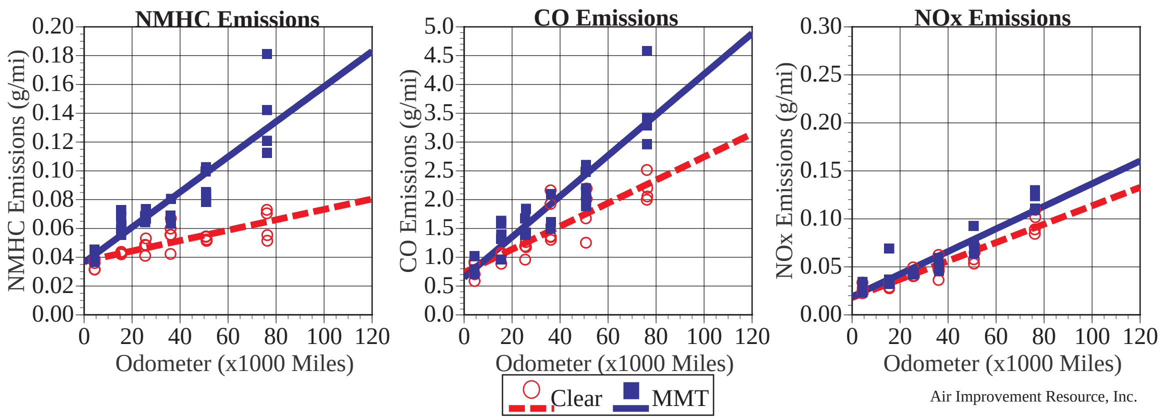
[3] One LEV MDV2 was tested in this testing program, but the emission standards for this vehicle are not comparable to the passenger car LEV emission standards, therefore, this vehicle is being omitted from the analysis.

All emission tests at these mileages for all vehicles tested at ~75-80°F [24-27°C] standard conditions were conducted with gasoline meeting California's Phase 2 specifications. Emission test procedures consisted of the 1975 Federal Test Procedure, including cold start, hot stabilized, and hot start operation, and, for Part 1 vehicles, the Highway Fuel Economy Test (HFET). A minimum of two replicate tests were conducted on each vehicle at each mileage interval, and in some cases, a third test was performed if required using an accepted protocol detailed in the study. For both phases of testing, emissions were collected on an engine-out and tailpipe basis to allow for evaluation of catalyst efficiencies and comparison of tailpipe emission trends over the mileage accumulated.

<u>Honda Civics</u>

The emissions versus mileage for NMHC, CO, and NOx for the Honda LEV Civics are shown in Figure 1 below. At zero miles, all four cars start at the same emissions. However, as they accumulate mileage, the vehicles fueled with MMT-containing fuel have higher average emissions for all three pollutants. In percentage terms, the increases in emissions are the greatest for NMHC, followed by CO, and then NOx.

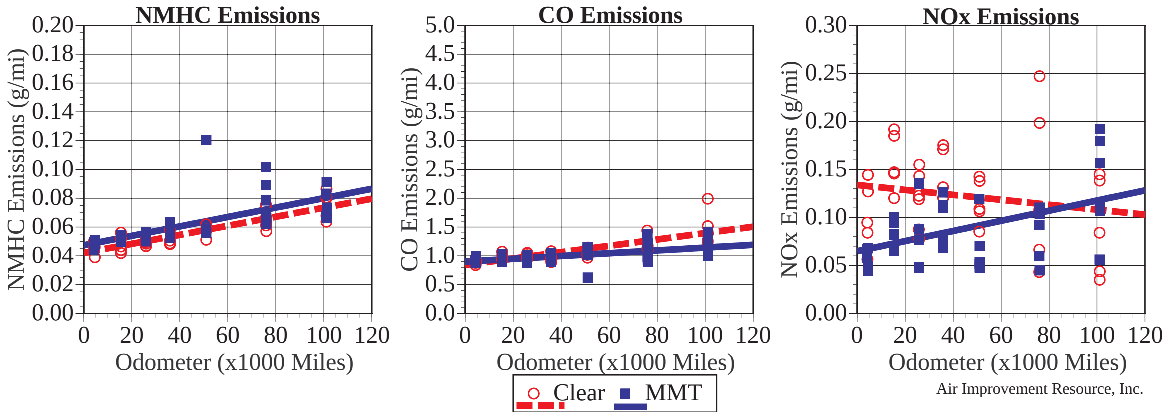
Figure 1. Civics



<u>Volkswagen Beetles</u>

The Beetles are shown in Figure 2. For NMHC and CO emissions, the emissions trend is similar between MMT® and Clear. For NOx, the emissions of the Clear vehicles appear to start slightly higher than the emissions of the MMT® vehicles, even though neither set of vehicles have accumulated mileage on their respective fuels. At the higher mileages, the emissions of the MMT® vehicles appear to increase faster than the Clear vehicles.

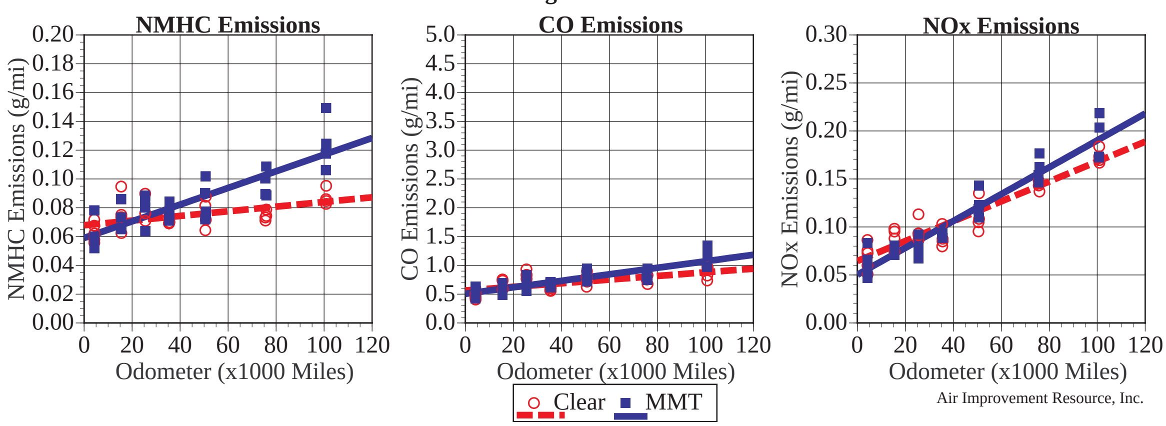
Figure 2. Beetles



Plymouth Breezes

The emissions of the Breezes are shown in Figure 3. NMHC emissions show faster deterioration for MMT® than for Clear, but the deterioration for both CO and NOx for both fuels appears to be about equivalent for the two fuels.[4]

Figure 3. Breezes



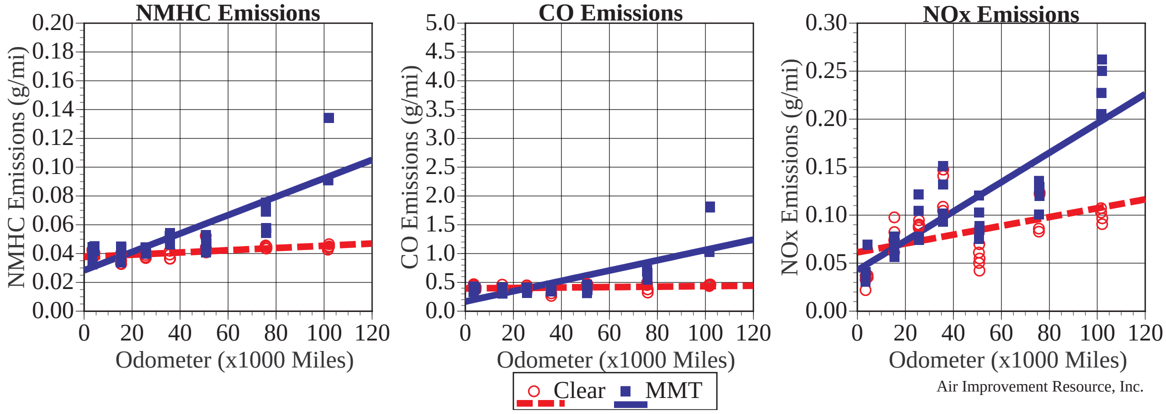
Ford Escorts

The Escorts are shown in Figure 4. For all three pollutants, the emissions of the vehicles fueled on MMT® increase much faster than the vehicles fueled on Clear fuel.

---

[4] Testing whether two regressions are the same involves trying confidence intervals around each regression, and seeing where they overlap (over the whole range, or just part of the range, or not at all?). This could be done but with these sample sizes, but the conclusions may not be very meaningful. So when evaluating trends of individual vehicles, we will rely on the data trend lines, rather than focusing on statistics.

Figure 4. Escorts

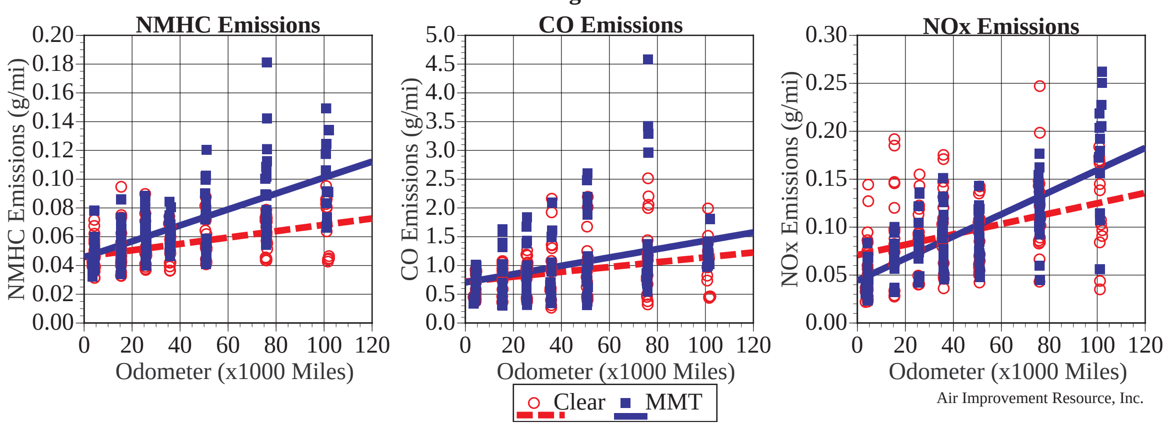


<u>Observations on All Four Vehicles</u>

Clearly the four vehicles appear to display different sensitivities to MMT® containing fuel. The Escorts appear to be the most sensitive, and the Beetles are perhaps the least sensitive. Three out of the four vehicles experienced increased NMHC emissions with MMT®. Two out of four experienced marked increases in NOx emissions with MMT®. Overall, it appears that MMT® increases deterioration for both NMHC and NOx, while differences in CO deterioration appear to be small.

The combined results for all four vehicles are shown in Figure 5.

Figure 5. All



3.2 Manufacturer "D" Emissions Data

Manufacturer D started using high-density catalytic converters on a number of vehicles in the 2003 model year. Manufacturer D started noticing significantly higher catalyst replacement rates on one of these vehicles in Canada as opposed to the U.S., referred to in this report as D-1, which was certified to Tier 2 Bin 7 levels in the U.S. and Canada (120,000 mile standards of 0.090/4.2/0.15 g/mi for NMOG/CO/NOx). This vehicle was an "early introduction" vehicle, which means it was a vehicle certified to a Tier 2 "bin" standard prior to the 2004 Tier 2 requirement, and so it had more time to accumulate mileage than typical Tier 2 vehicles introduced starting with the 2004 model year.

D initiated an emissions testing program to determine the emissions effects of the Canadian catalyst for the D-1 model. D obtained a 2001 U.S. reference vehicle and a 2003 model year Canadian reference vehicle for testing. The U.S. reference vehicle had accumulated about 100,000 miles [161,000 km] and the Canadian reference vehicle had accumulated about 115,000 miles [185,000 km].[5] The as-received catalyst systems were then removed (including the heated exhaust gas oxygen sensors and underfloor catalyst for each vehicle). D then began to test Canadian catalyst systems on the Canadian reference vehicle and U.S. catalysts on the U.S. reference vehicle. Some of the Canadian catalyst systems were tested on the US reference vehicle as well.

The Canadian catalysts were randomly obtained from Canadian dealers when catalysts were replaced under warranty by the dealers. The U.S. catalysts were taken from U.S. vehicles that were field-aged, with no known exposure to MMT®. These were vehicles that saw real on-road driving done by real customers who used them in relatively rapid mileage accumulation.

Since the Canadian catalysts were recruited from Canadian vehicles, we do not know exactly what concentration of MMT® they were fueled with, or at what frequency. Our previous report indicates that 90% of gasoline samples surveyed by the Alliance of Automobile Manufacturers in the summer of 2002 contained MMT®. Average MMT® concentrations from the Winter 1999 survey through the Winter 2002 survey indicate an average concentration of about 0.023 g Mn/U.S. gallon [6.1 mg/L] for the samples analyzed (maximum concentrations were as high as 0.080 g Mn/ U.S. gallon [21.1 mg/L], or almost 4 times the average). This average is a little lower than the concentration used in the Alliance/CVMA/AIAM test program of 0.031 g Mn/gallon [8.2 mg/L], but the maximum in-use concentrations are much higher than 0.031 [8.2 mg/L]. We address the manganese concentration differences between in-use concentration and testing concentrations in Section 5.3 of this report.

Vehicle mileage was also recorded for the vehicle each catalyst was taken from. One-by-one, the Canadian and U.S. catalysts were tested on the Canadian reference and U.S. reference vehicle, respectively. Both FTP tests and US06 tests were run on the vehicles. Certification fuel free of manganese additives (Indolene) was used to evaluate tailpipe emissions.

The emission testing results are shown in Figures 6 (FTP) and 7 (US06). The 4,000 mile [6,400 km] results are the certification results for D-1 submitted to the EPA, which represent tests on a particular certification vehicle that never was fueled with MMT®. All other data points represent the U.S. reference vehicle equipped with either a U.S. catalyst

[5] The testing was performed in 2005, so these vehicles accumulated more miles in 2-3 years than the typical vehicle would (the typical 2-3 year old vehicle would have 30,000-40,000 miles [48,300-63,400 km]).

(i.e. “Clear”), or the U.S. reference vehicle equipped Canadian catalyst (MMT®).[6] Thus, our assumption is that these are really like different vehicles, since the catalyst systems are different, even though the U.S. reference vehicle remains the same. We do not know for sure if the Canadian vehicles were fueled with MMT® containing fuel all the time, but the fact that they had to be replaced under warranty probably indicates that they were most of the time.[7]

The US06 test cycle is an aggressive cycle that features high acceleration and deceleration rates and some high speeds. It is designed basically to represent the 15% or so driving not represented completely by the FTP. The mileages of the various in-use catalysts range between 25,000 miles [40,200 km] and 100,000 miles [161,000 km]. Clearly these catalysts were used on vehicles that accumulated mileage faster than vehicles in normal use. However, there is no evidence that they were driven differently than normal vehicles, therefore, our assumption is that the emissions of vehicles that accumulated mileage at a more normal pace would be similar to these vehicles.

Figure 6

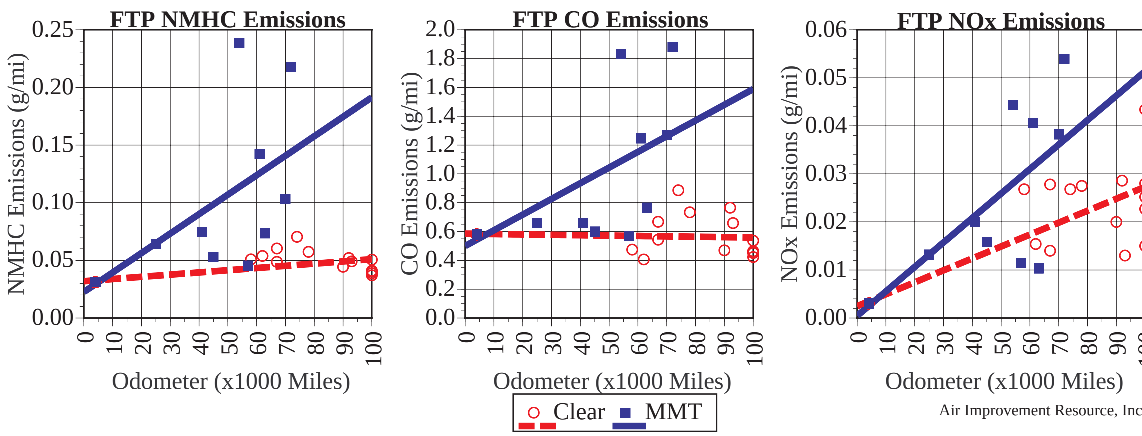


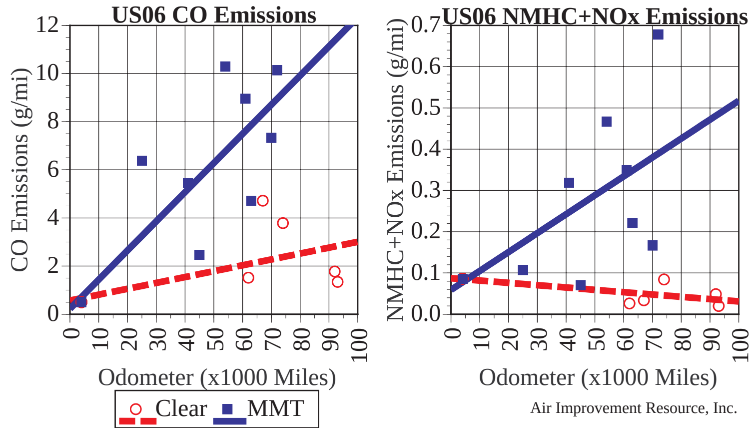
Figure 6 shows the emissions of the U.S. reference vehicle (about 100,000 miles) [161,000 km] with the Canadian (MMT®) and US (Clear) catalysts. The figure shows that that D-1 is very sensitive to MMT®, since the MMT® emissions deterioration lines are much higher than the Clear for all three pollutants.

The US06 emissions are shown in Figure 7. The left plot shows CO, and the right plot shows NMHC+NOx.[8] For all pollutants, the deterioration for the Canadian vehicles is higher than the US vehicles. The NMHC+NOx emissions on US06 at 80,000 miles

[6] The use of the U.S. reference vehicle for both catalyst systems eliminates the possible confounding influence of differences in the U.S. and Canadian reference vehicles. If, for example the Canadian vehicle had higher engine-out emissions not directly attributable to MMT, use of the Canadian reference vehicle with the Canadian catalysts could have made the MMT effect on catalysts appear worse than it really is.
[7] Our previous study indicated that greater than 90% of Canadian gasoline contained MMT before its use was essentially discontinued by the oil companies.
[8] The emissions for NMHC and NOx are shown as NMHC+NOx because that is the form of the US06 emissions standard.

[128,700 km] are projected to be about 0.4 g/mi [0.25 g/km] for Canadian vehicles, and 0.05 g/ mi [0.031 g/km] for U.S. vehicles.

Figure 7



The emissions testing done by D on Canadian D-1 catalysts is on returned catalyst systems. These may not be representative of the emissions of all D-1 vehicles, although if all D-1 vehicles continued to be operated on MMT-containing fuel, many or most of them may eventually experience catalyst problems. For this reason, we will estimate MMT® effects with and without D-1, to determine the impact of D-1 on overall Tier 2 MMT® effects. (Section 4.5)

3.3 Manufacturer "J" Emissions Data

Manufacturer J emission tested a 2002 model year mid-size SUV (J-1) for which it had found high catalyst replacement rates under warranty. This vehicle was certified to the LEV1 emission standards (100,000 mile standards of 0.090/4.2/0.3 g/mi NMOG/CO/NOx). J tested 49 vehicles total, 24 from Canada and 25 vehicles from the U.S. coming off lease from non-fleet owners, between February 1 and June 1, 2004. These were customer vehicles which were randomly selected from the J's lease return fleet. Only properly operating vehicles with no OBD codes or major emissions system repairs were included in the study.

The Canadian vehicles were fueled with Canadian fuel, most of which probably contained MMT®. However, similar to the D vehicles, we do not know exactly what the concentrations were, but based on the fuel surveys it could have seen concentrations up to 0.08 g Mn/U.S. gallon [21.1 mg/L].

All vehicles were subjected to FTP emissions testing along with catalyst flow testing to determine backpressure. Average emissions for the two samples are shown in Table 2.

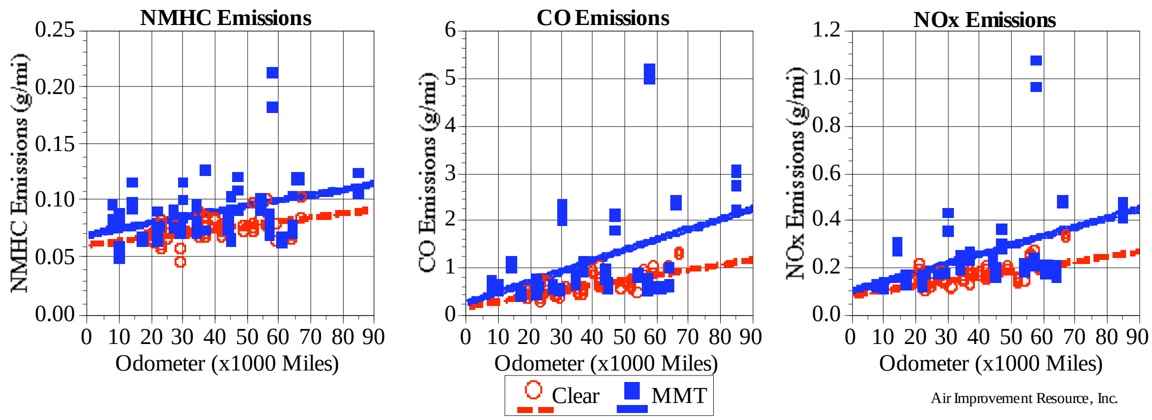
Table 2. Average FTP Results of U.S. and Canadian Fleet for Mfg J			
Pollutant	US (g/mi)	Canadian (g/mi)	Is Difference Statistically Significant?
Odometer (Km)	63,408	61,415	No
NMHC	0.076	0.090	Yes
CO	0.639	1.113	Yes
NOx	0.168	0.250	Yes

With respect to the flow testing, all of the U.S. and a portion of the Canadian vehicles had normal backpressure. However, 13 of the 24 Canadian vehicles had high exhaust system backpressure than either the U.S. or Canadian vehicles with normal backpressure. Results show that the Canadian fleet had higher emissions than the U.S. fleet, even though the average odometer level of the Canadian fleet was 7% lower than the U.S. fleet. The differences were statistically significant at the 90% level.

Chemical analysis of the material deposited on the inlet face of the Canadian catalysts indicated that it was composed of compounds containing manganese, with only trace amounts of other elements. For the sample catalysts removed from U.S. vehicles which were typically fueled with gasoline not containing MMT®, identical vehicles exhibited trace amounts to no manganese catalysts deposits.

Emissions versus mileage are shown in Figure 8. Linear regressions of emissions versus mileage show that the Canadian vehicles exposed to MMT® experience greater deterioration than the U.S. vehicles operating on clear fuel.

Figure 8



3.4 Manufacturer "M" Emissions Data

Manufacturer "M" tested 7 different models of vehicles that are popular in the Canadian market. Fourteen vehicles total accumulated mileage on one of two different fuels – one an MMT-containing fuel (0.031 g Mn/gallon) [8.2 mg/L], and the other a Clear fuel without MMT®. Vehicles were FTP tested using Clear fuel at 4,000 miles [6,500 km], 15,000 miles [24,100 km], 30,000 miles [48,300 km], 50,000 miles [80,500 km], 75,000 miles [120,700 km] and 100,000 miles [161,000 km]. Mileage accumulation for the MMT® vehicles took place on normal roads, which included both city and highway driving. Mileage accumulation for 2 of the 7 Clear vehicles (M-1 and M-7) occurred also near M's proving grounds. The catalyst aging for the other M vehicles occurred in a bench-aging process that simulates the on-road mileage accumulation.

Test results generally indicated that all seven vehicles in this program exposed to MMT® fuel developed MMT-related deposits on the primary catalyst. In most of these cases, this resulted in tailpipe emission increase for both NMHC and NOx, when compared to the results obtained from the MMT-free fuel. In some cases the catalyst surface became completely plugged at relatively low mileage intervals. Chemical analysis of the deposit material indicated that it was composed of manganese oxide, specifically Mn_3O_4, with only trace amounts of other compounds. When fueled with gasoline not containing MMT®, identical vehicles exhibited no manganese catalyst deposits.

The manufacturer points out that the results from its durability testing program do not necessarily reflect average market experience in Canada, because of fluctuations in MMT® concentrations and variability in vehicle operational patterns. Regarding the fluctuations in MMT® concentrations, we do include a sensitivity analysis of the effects of MMT® concentrations on the overall emissions impact of MMT®. Regarding the operational patterns, since the mileage accumulation for these vehicles took place on normal roads, we have no reason to believe that the mileage accumulation in the durability testing program is atypical from the standpoint of vehicles speeds and acceleration patterns. Certainly the testing vehicles accumulated mileage faster than most normal vehicles in the overall fleet, but we don't think accumulating mileage at a faster rate than normal would necessarily bias the emission result in one direction or the other. Thus, all of M's vehicles have been included in the analysis.

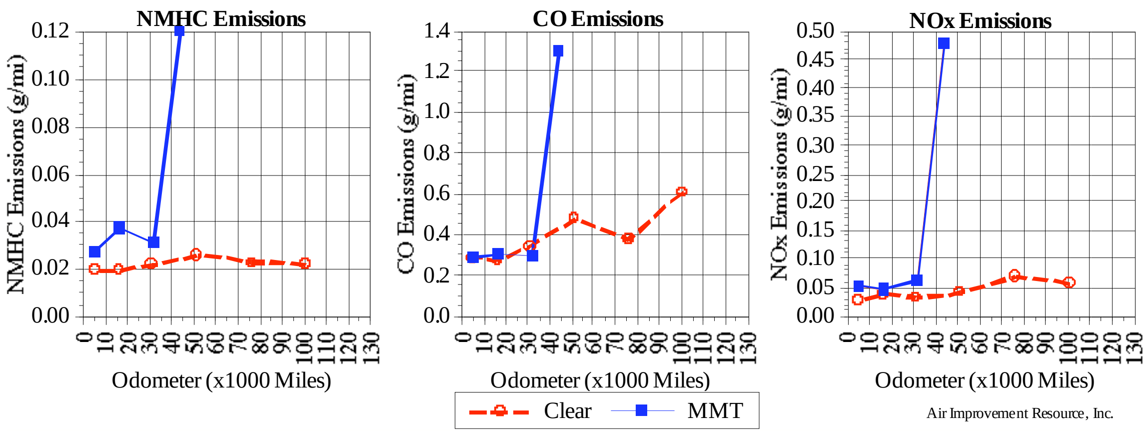
The manufacturer also points out that the testing history of the M-3 and M-4 was "problematic", in that the vehicles were removed from the durability program for a period of time to evaluate exhaust valve problems. However, the durability data for M-3 and M-4 are not significantly different from the other vehicles even though the vehicles were removed from the program for a time, therefore M-3 and M-4 have been included with the other M vehicles.

Emission results for the seven models are shown in Figures 9-14, and all of the M's vehicles are combined in Figure 15. M also performed testing at zero miles, but this has been omitted from the following analysis, because the emissions changes between zero and 4,000 miles [6,400 km] is more typical of a break-in stabilization period than the general emissions trend for a vehicle on either Clear or MMT® fuel.

Model M-1

Emissions for model M-1, a ULEV (full life emission standards of 0.055/2.1/0.30 g/mi NMOG/CO/NOx), are shown in Figure 9. The vehicle with Clear fuel shows relatively low deterioration, and was tested at the various mileage points, including 100,000 miles [161,000 km]. The MIL for the vehicle fueled with MMT® fuel turned on at 40,000 miles [64,300 km], and the driver complained of very rough vehicle operation at about the same mileage. The MIL indicated a catalyst problem, and tailpipe emissions were very high. The catalyst was replaced with a new catalyst and tailpipe emissions returned to levels which where consistent with levels seen before plugging. Examination of the used catalyst indicated the catalyst was plugged. Testing was discontinued for this vehicle on MMT® fuel.

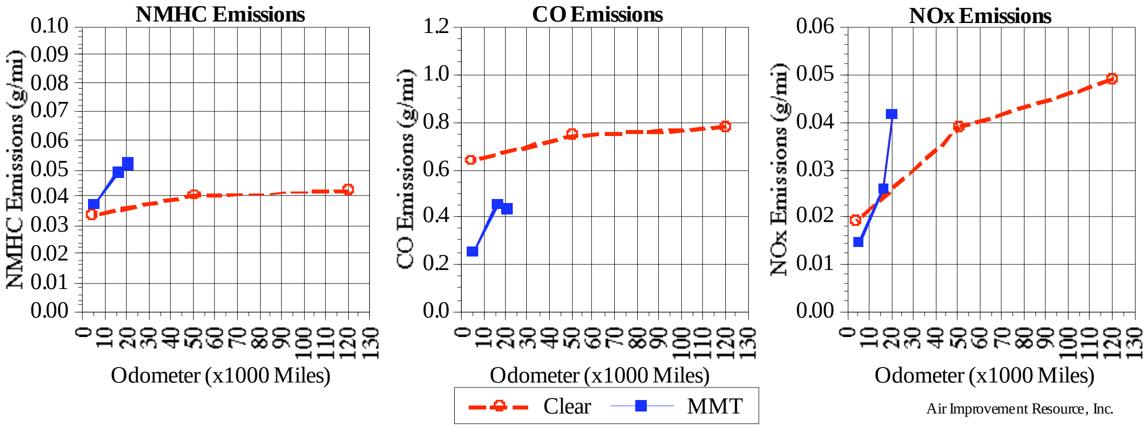
Figure 9. M-1



Model M-2

Emissions for vehicle M-2, a Tier 2 Bin 5 vehicle (with full life emission standards of 0.090/4.2/0.07 g/mi NMOG/CO/NOx), are shown in Figure 10. The vehicle operated on Clear fuel shows low deterioration for both HC and CO, but somewhat higher deterioration for NOx, with emissions at 120,000 miles [193,100 km] being 2 times the emissions at 0 miles (but still well below the 0.07 NOx emission standard at 120,000 miles). However, the vehicle operated on MMT® experienced problems at 20,000 miles. At 20,000 miles [32,200 km], the MIL had illuminated, and vehicle acceleration had degraded to the point that further mileage accumulation was not possible due to safety concerns, and the tests on the MMT® fuel were discontinued.

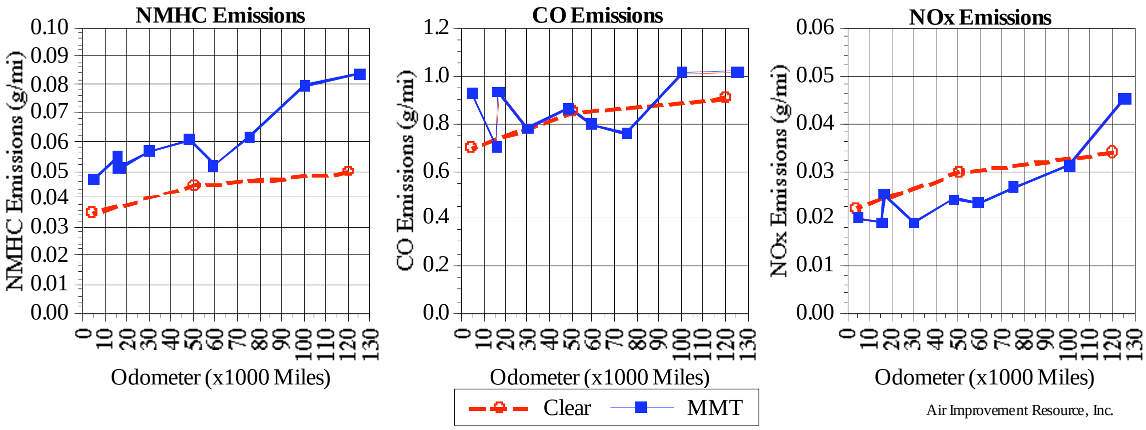
Figure 10. M-2



<u>Model M-3</u>

Emissions for Model M-3, a Tier 2 Bin 5 vehicle, are shown in Figure 11. For NMHC, the vehicle shows higher deterioration on MMT® than on Clear. For CO, there appears to be little difference in the deterioration between the two fuels. For NOx, the MMT® appears to cause higher deterioration after about 60,000 miles [96,600 km].

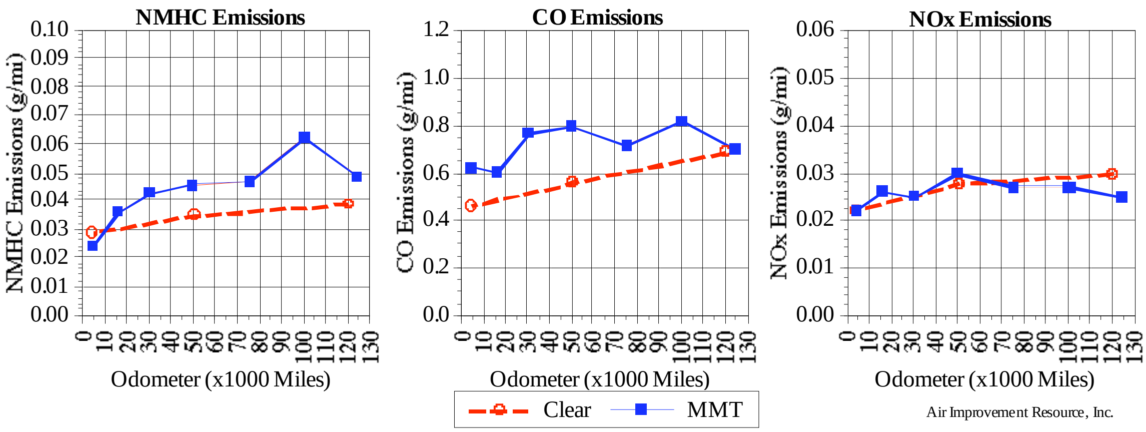
Figure 11. M-3



<u>Model M-4</u>

Emissions for Model M-4, a Tier 2 Bin 5 vehicle, are shown in Figure 12. For NMHC, the emissions of both the Clear and the MMT® vehicle start at the same point. The vehicle fueled with MMT® appears to have higher deterioration, and this deterioration starts relatively early, or around 20,000 miles [32,200 km]. For CO, the MMT® fueled vehicle starts out with higher 4,000 mile [6,400 km] emissions, and deterioration appears to be about the same as for the vehicle fueled with Clear fuel. For NO, the deterioration rates are very close, with the MMT® fueled vehicle showing a slightly smaller deterioration rate above 80,000 miles [128,700 km].

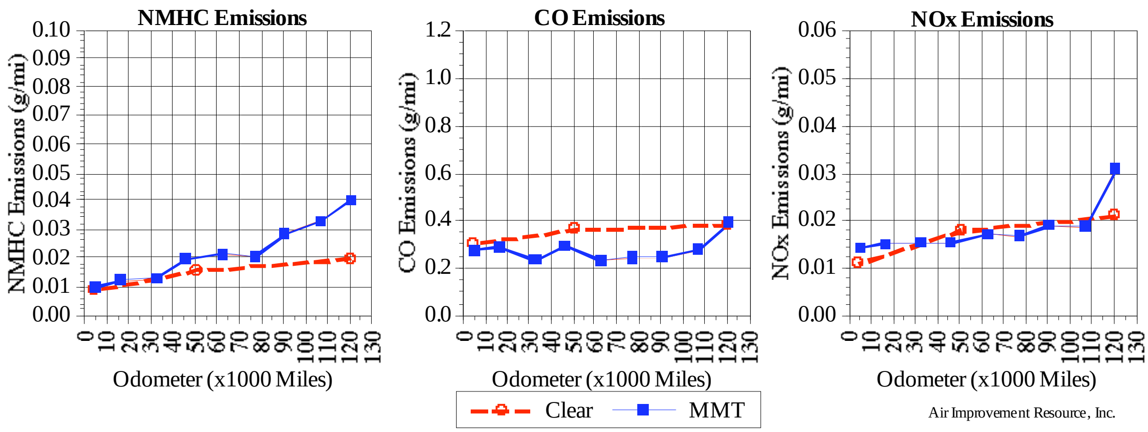
Figure 12. M-4



Model M-6

Emissions for model M-6, a Tier 2 Bin 5 vehicle, are shown in Figure 13. MMT® appears to cause an increase in NMHC emissions deterioration around 80,000 miles [128,700 km]. For CO, the MMT® line is below the Clear line for most of the mileages, but it appears to be increasing at a higher rate at the higher mileages. For NOx, it appears that MMT® causes an increase in emissions above 110,000 miles [177,000 km].

Figure 13. M-6

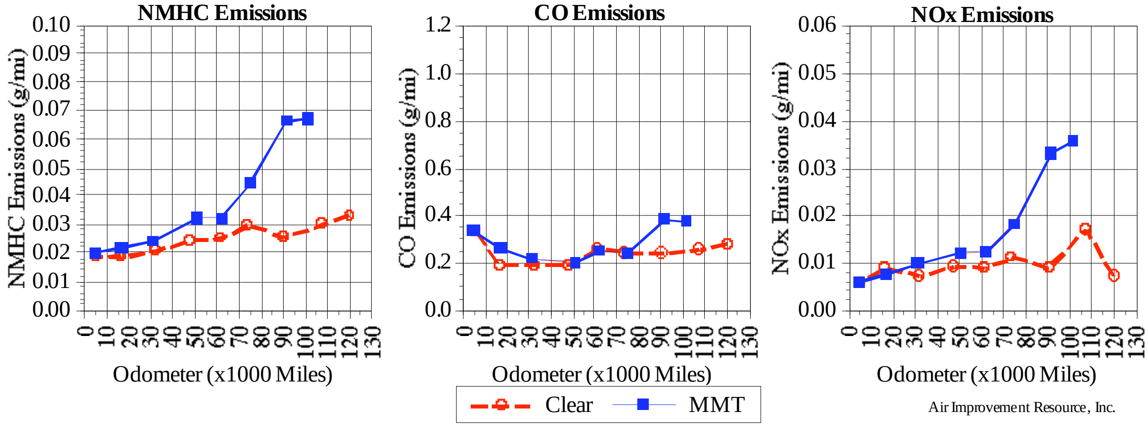


Model M-7

Emissions for Model M-7 (Tier 2 Bin 5) are shown in Figure 14. NMHC emissions deterioration for the vehicle fueled with MMT® are clearly higher than the Clear vehicle. with the acceleration in deterioration occurring between 60,000 [96,600] and 70,000 miles. There is little difference in deterioration for CO emissions, except between 70,000 [112,700 km] and 90,000 miles [144,800 km]. NOx emissions deterioration for MMT®

is also significantly higher. For both HC and NOx, the deterioration rate increases between 60,000 [96,600] and 70,000 miles [112,700 km]. For this vehicle, it appears that there is a strong MMT® effect at around 70,000 miles [112,700 km], with the largest effects on NMHC and NOx, and a lesser effect on CO.

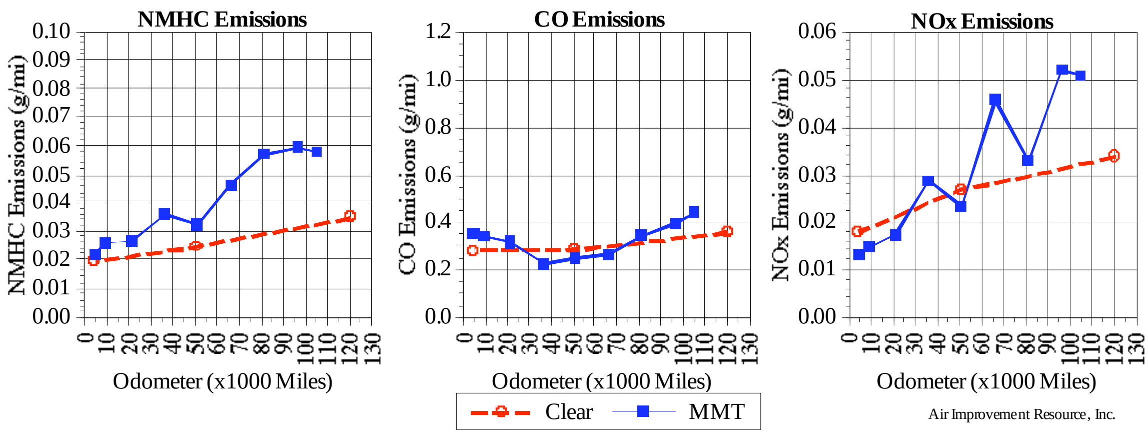
Figure 14. M-7



Model M-8

Emissions for Model M-8 (Tier 2 Bin 5) are shown in Figure 15. NMHC deterioration for the MMT® vehicle is much higher than for the Clear vehicle. Initially the CO deterioraton for the MMT® vehicle appears lower, and then it increases at about the same mileages as the NMHC and NOx deterioration. NOx deterioration for the MMT® vehicle is much higher than the Clear vehicle, especially above 50,000 miles [80,500 km].

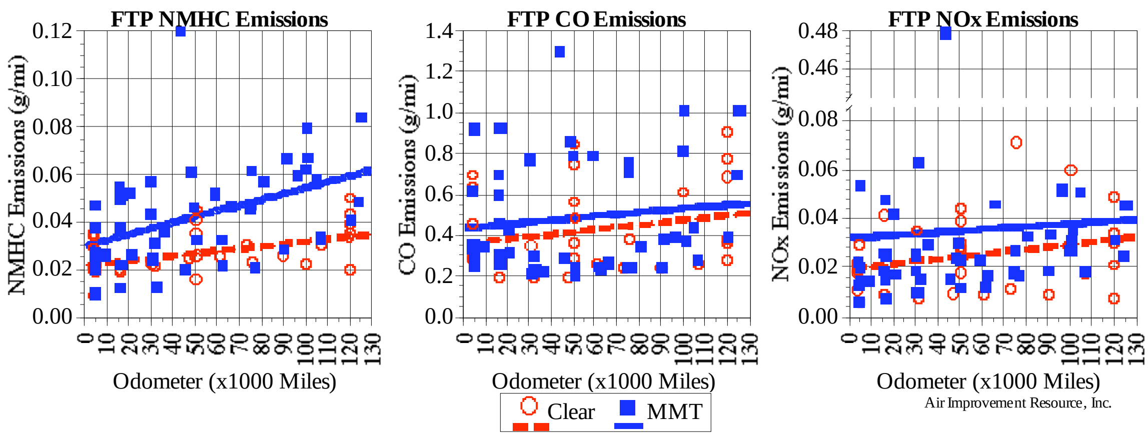
Figure 15. M-8



All Manufacturer M Vehicles Combined

Figure 16 shows all of the M vehicles combined. M-1 and M-2 are also included, even though they were tested at low mileages. For NMHC, MMT® appears to cause higher deterioration than the Clear fuel. With all data combined, there appears to be little effect of MMT® on CO emissions. For NOx, MMT® does not appear to result in higher deterioration for the M vehicles, however, this tentative conclusion is the result of including M-1 and M-2, which had very high NOx at low mileage levels, and no corresponding emissions data at higher odometer levels.

Figure 16. M-All



It is difficult to determine exactly how to include M-1 and M-2 in this analysis. Clearly these vehicles experienced driveability and emissions problems early in their lives which would have required immediate remediation (i.e., catalyst replacement). If operated again on MMT® containing fuel, they may have required 3-6 catalyst replacements over their lives. Their true emissions would be represented by a “sawtooth”, of increasing emissions, followed by catalyst replacement and a subsequent increase in emissions as the new catalyst becomes plugged again. This concept is discussed in more detail in Attachment 1. The sudden increase in emissions, accompanied by MIL illumination and driveability problems experienced with M-1 and M-2 may not be a phenomenon that is limited only to manufacturer M. And, catalyst replacements will not alter potential increases in engine-out emissions due to deposit formations.

Because it is difficult to accurately predict the emissions of vehicles M-1 and M-2 over their lives, for the primary analysis we are eliminating the M-1 and M-2 emission tests from our estimate of the emissions impact of MMT®. However, a sensitivity case will be run using the emissions predictions in Attachment 1 that shows the impact on the fleet emission inventories if 10% of the 2001 and later fleet experiences early failure like M-1 or M-2.

3.5 Method of Grouping the Data

The previous section showed that the newer vehicles display a wide variation and emission responses to MMT®. In light of recent testing and SAE Paper 2007-01-1070 released by Honda, this is not surprising. [4] Honda evaluated the impact of MMT® fuel on catalyst plugging, and found that plugging due to MMT® increased with increasing exhaust gas temperature, increased catalyst cell density, and increased angle of incidence of exhaust gas flow to the converter inlet surface. All manufacturers are using catalysts with higher cell densities to reduce emissions for Tier 2 and California LEV2 emission standards. Manufacturers are also using close-coupled catalysts to reduce cold start emissions, and these catalysts operate at higher temperatures, since they are closer to the engine. The angle of incidence of exhaust gas to catalyst inlet surface can vary considerably with different engine/catalyst configurations. But these factors explain why nearly all of the vehicles showed some emission response to MMT®, and also why there was a variation in this response.

In this new study, we are leaving the Alliance/AIAMC/CVMA vehicles in the groups that were originally used. The only vehicles we could possibly change would be the two PC LEVs that made up the original Group 4, but their very low NOx emissions indicates that they are very close to Tier 2 levels even though they were certified as LEVs. As a result, we have decided to leave them in Group 4.

The new data developed by D, J, and M are shown in Table 3.

Table 3. Characteristics of New Data						
Vehicle	Model Year	Vehicle Class	Emission Standard Type	Full Useful Life Emission Standards*		
				NMOG g/mi	CO g/mi	NOx g/mi
D-1	2003	PC	Tier 2 Bin 7	0.090	4.2	0.15
J-1	2002	LDT2	LEV1	0.090	4.2	0.30
M-1	2001	PC	ULEV1	0.055	2.1	0.30
M-2	2003	LDT1	Tier 2 Bin 5	0.090	4.2	0.07
M-3	2003	PC	Tier 2 Bin 5	0.090	4.2	0.07
M-4	2003	PC	Tier 2 Bin 5	0.090	4.2	0.07
M-6	2003	PC	Tier 2 Bin 5	0.090	4.2	0.07
M-7	2003	PC	Tier 2 Bin 5	0.090	4.2	0.07
M-8	2003	LDT2	Tier 2 Bin 5	0.090	4.2	0.07

* 100,000 miles for LEV and ULEV, 120,000 miles for Tier 2 vehicles

D-1 is a Tier 2 Bin 7 vehicle that in later model years was changed to Tier 2 Bin 5. The NOx standard is 0.15, which is significantly lower than the LEV1 or ULEV1 full useful life NOx standard of 0.30. Because of this lower NOx standard and the fact that this is a Tier 2 vehicle, we have included D-1 in Group 4. Vehicle J-1 is a LEV, so we have placed this vehicle in Group 3. Vehicle M-1 is a ULEV1 with a 0.3 useful life NOx standard, so we are placing this vehicle in Group 3. Finally, the remainder of the M vehicles (2, 3, 4, 6, 7, 8) we have placed in Group 4.

Table 4 summarizes all of the test vehicles from all programs in each Group. These vehicles are from different testing programs, and these different test programs utilized vehicles that experienced different levels of MMT®. In addition, the in-use MMT® levels in Canada could be different than the test program levels. These issues are discussed further in Section 4.2.

Table 4. Assignments of Test Vehicles in General Emission Standard Groups		
Group	Vehicles	Number of Vehicles
1	Alliance/AIAMC/CVMA: Part 1 Tier 1 S10 Blazer, Part 2 Tahoe LEV	2
2	Alliance/AIAMC/CVMA: Part 1 TLEVs, Part 1 Tier 1 Corolla, Part 2 LEV Tahoe	9
3	Alliance/AIAMC/CVMA: Part 1 and Part 2 LEVs (minus the Tahoe) New Data: J-1*	5
4	Alliance/AIAMC/CVMA: Part 1 Civic and Part 2 Escort New Data: D-1, M-3 through M-8**	9

* Vehicle M-1, which was a ULEV1 vehicle, was not included due to very early catalyst plugging and failure on MMT®

** Vehicle M-2, which was a Tier 2 vehicle, was not included due to very early catalyst plugging and failure on MMT®

4.0 Combining the Grouped Data for Analysis

Before combining the data for further emissions analysis and correction factor analysis, there are several issues that must be discussed further, as follows:

- Imbalance in amount of data for each vehicle
- Differing MMT® concentrations of test vehicles (or test catalysts, as in the case of Manufacturer D)[9]
- The MMT® tests on Vehicles M-1 and M-2, which were terminated at early mileages due to significant driveability problems
- How representative are the evaluation vehicles of the fleet as a whole?

These issues are discussed first, followed by a general discussion of the analysis of the combined data.

4.1 Imbalance in the Amount of Data for Each Vehicle

For the original Alliance/AIAM/CVMA testing program, all of the vehicles received the same number of tests at each mileage, and there were the same number of each kind of vehicle tested, so no rebalancing of that dataset was necessary. For the new data, however, there are varying numbers of vehicles and emission tests. For example, for J-1, we have 24 vehicles tested on MMT® fuel and 25 vehicles tested on Clear fuel. For the M vehicles, only 1 vehicle of each model was tested on MMT® fuel and 1 vehicle of each model was tested on Clear fuel. If we were to combine all these data without rebalancing the sample, then the emission relationships would be dominated by manufacturers D and J, where there were a significant number of tests of one particular model.

To solve this statistical imbalance problem, we developed linear regressions of emissions versus mileage for each model for both MMT® and Clear. We then estimated the emissions at each 10,000 mile [16,100 km] interval for each vehicle/fuel combination. Then, all the linear regressions for MMT® and Clear were separately combined and averaged. In this process, each vehicle/fuel combination has exactly the same weight as all the other vehicle/fuel combinations.

We considered using different types of fits to the data other than a linear regression. Some of the vehicles appeared to be represented by a log relationship or power curve, because emissions would follow the normal path of slow deterioration and then suddenly experience a rapid increase in deterioration. But many others appeared to be represented well enough by linear deterioration. For this reason, and to have a generally conservative analysis, we chose the linear regression to represent deterioration for MMT® and Clear for all vehicles, and to estimate MMT® correction factors. Slightly different MMT®

[9] The potential difference in MMT concentrations between the test vehicles and the in-use fleet is also an issue. This is discussed in the Section 5, Modeling Methods.

correction factors would probably be generated if a different emission relationship were chosen.

4.2 Differing MMT® Concentrations of Test Vehicles

The J and D vehicles accumulated mileage with in-use fuels, many of which contained MMT®, but the manufacturer M vehicles and the vehicles in the Alliance/CVMA/AIAM testing program accumulated mileage with Mn concentrations of 0.031 g/U.S. gallon [8.2 mg/L]. AIR's 2002 report indicates that the average Mn concentration of Mn containing gasolines from 2000-2002 was about 0.024 g/gallon [6.3 mg/L], but the maximum was as high as 0.080 g Mn/U.S gallon [21.1 mg/L] in premium gasoline. Given that we do not know what average these vehicles experienced, and the fact that there were only two of the vehicles that may have experienced a lower concentration, in this analysis we are assuming that the J and D vehicles experienced an average very near 0.031 g/gallon [8.2 mg/L]. If they experienced a somewhat lower average, then the MMT® effect experienced by these two vehicles, which was quite high, would be even greater.

4.3 Vehicles M-1 and M-2

As indicated in the earlier section, vehicles M-1 and M-2, which experienced very early catalyst failures due to MMT®, are not being included in the basic analysis, however, in Attachment 1 we have developed a possible method of including them in the analysis, and do perform an emissions sensitivity case assuming 10% of the fleet becomes plugged and exhibits emissions increases similar to M-1. This is discussed further in Attachment 1.

4.4 Representativeness of Test Vehicles to Whole Fleet

There could be an issue with how well the test vehicles represent the entire fleet. Manufacturers J and D tested vehicles for which there was a known problem of catalyst plugging. Manufacturer M, however, tested seven different models, and these models had varying degrees of emissions sensitivity to MMT®. Most of M's vehicles were clearly sensitive, with 2 being very sensitive. The vehicles in the earlier Alliance/CVMA/AIAM testing program showed varying degrees of sensitivity.

Another factor is that MMT's use was discontinued in Canada shortly after many manufacturers started introducing their Tier 2-like technologies. Most vehicles may not have accumulated sufficient mileage to show emissions sensitivity to MMT®.

For this emissions inventory study where we are projection inventories to calendar year 2020, we are not interested in the "early" mileage sensitivity to MMT®, but rather, the "long term" sensitivity that would be the case if the Tier 2 vehicles were fueled with MMT® containing fuel over their lifetimes. Given that we have data on only 9 different models in Group 4, and that most of these were sensitive to MMT®, we have to make some bounding assumptions about the fraction of vehicles that are more sensitive to MMT®, and conduct the inventory modeling accordingly.

For this study, we will evaluate the inventory impacts at three additional long-term sensitivity fractions – 80%, 50% and 20%. We will also assume that the vehicles that are sensitive to MMT® have the emissions sensitivity of the test data. Lastly, we will assume that only the LEVs and Tier 2 vehicles – essentially just 2001 and later vehicles – have to be adjusted for this sensitivity fraction. The earlier vehicles – Group 1 and Group 2 – will all be assumed to have the emission sensitivity as defined by the testing data. However in a projection year like 2015 or 2020, it is the Group 3 and 4 vehicles that will dominate the emission inventory analysis due to fleet penetration.

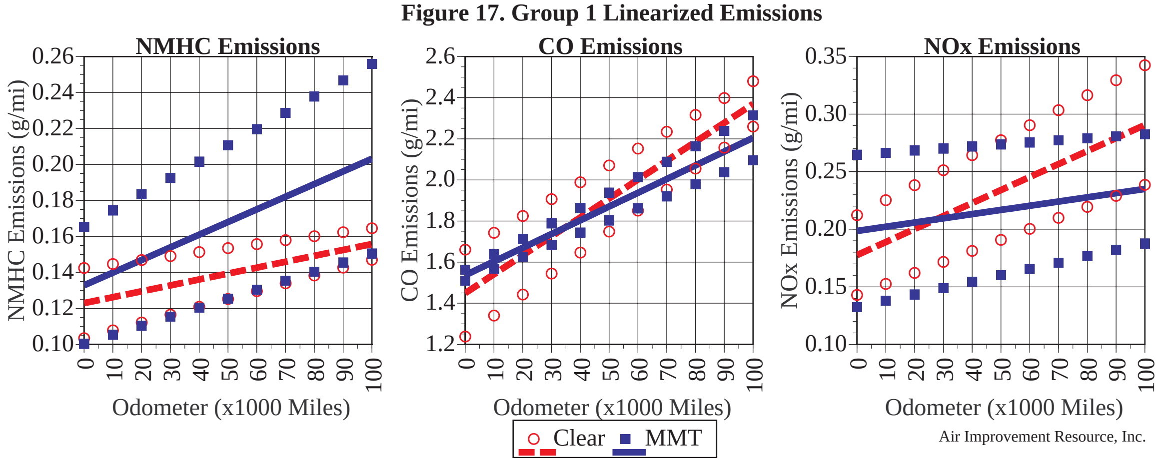
4.5 Combined Emissions Analysis

The combined emission analysis is shown in Figures 17-20 (Groups 1-4). Each set of three plots shows the predicted emissions at 10,000-mile [16,100 km] intervals for each vehicle in the group (these are the dots in each plot). These vehicle emissions prediction were determined by performing linear regression analysis of emissions versus mileage of each vehicles on each fuel, and then estimating from the regression the emissions at each 10,000-mile [16,100 km] point. Also shown in the plots is the average regression for Clear and MMT® fuels for all vehicles in the Group (these are the represented by the solid and dashed lines).

<u>Group 1 (2 vehicles)</u>

Group 1 is shown in Figure 17. The average regression shows higher emissions for MMT® than for Clear for NMHC, the fuels are about equal for CO, and for NOx MMT® results in somewhat lower emissions at higher mileages than the Clear fuel.

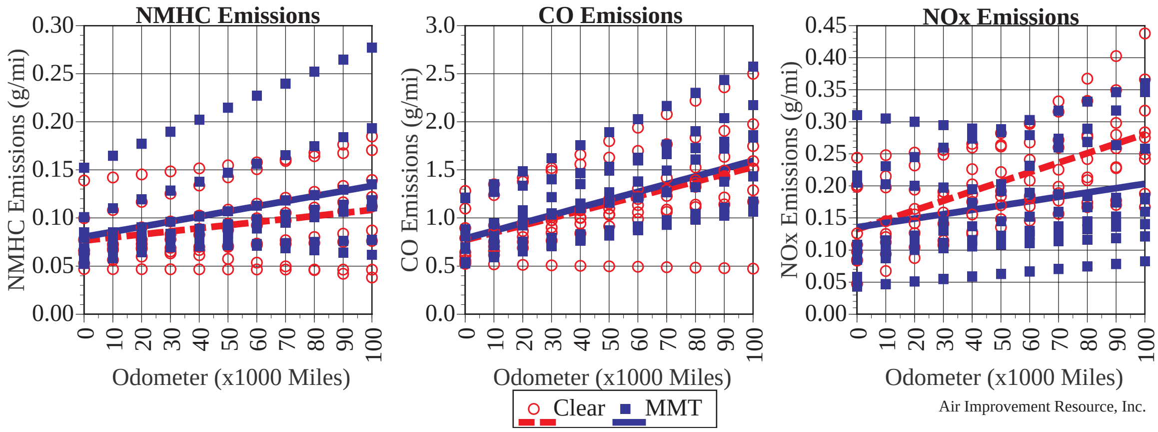
Figure 17. Group 1 Linearized Emissions



<u>Group 2 (9 vehicles)</u>

Group 2 is shown in Figures 18. MMT® results in higher NMHC emissions, no change for CO, and lower NOx.

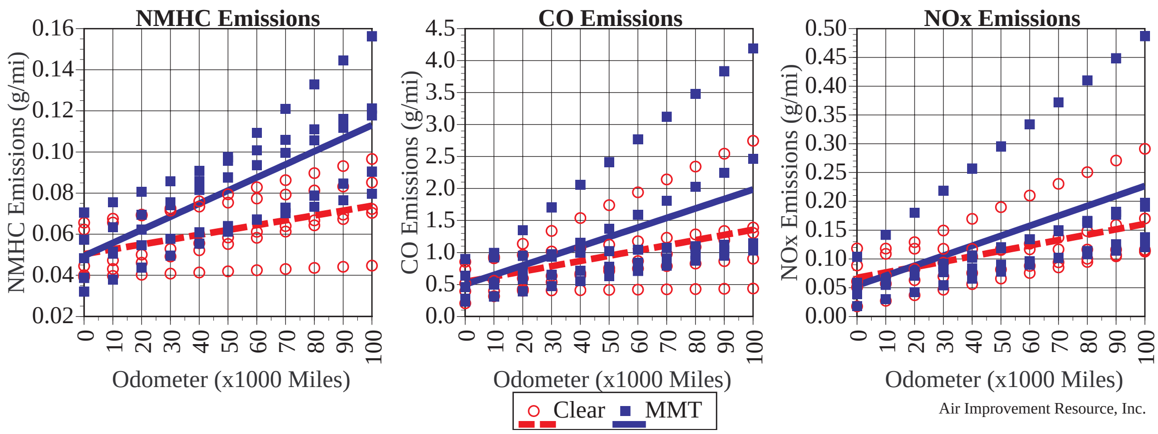
Figure 18. Group 2 Linearized Emissions



Group 3 (5 vehicles)

Group 3 is shown in Figure 19. MMT® results in higher NMHC, higher CO, and higher NOx than the Clear fuel.

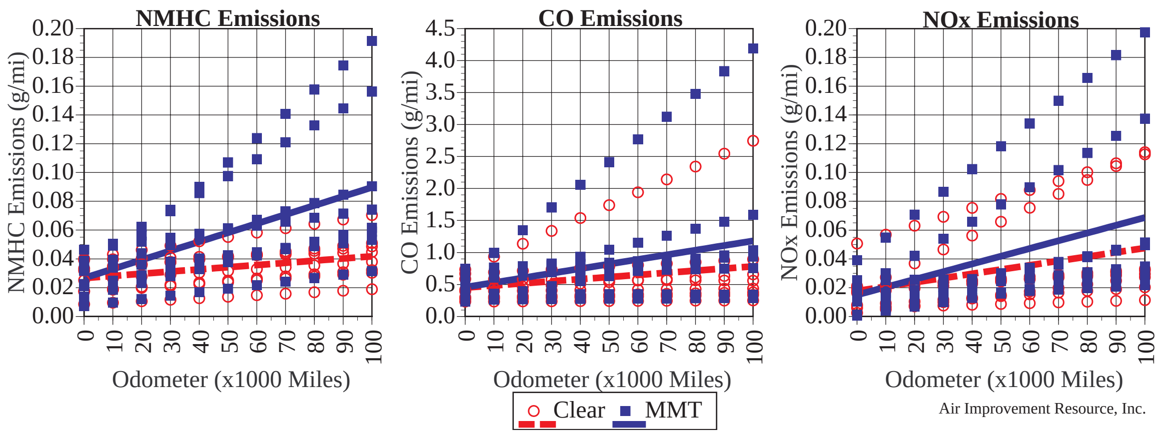
Figure 19. Group 3 Linearized Emissions



Group 4 (9 vehicles)

Group 4 emissions are shown in Figure 20. Similar to Group 3, MMT® results in higher NMHC, CO, and NOx.

Figure 20. Group 4 Linearized Emissions

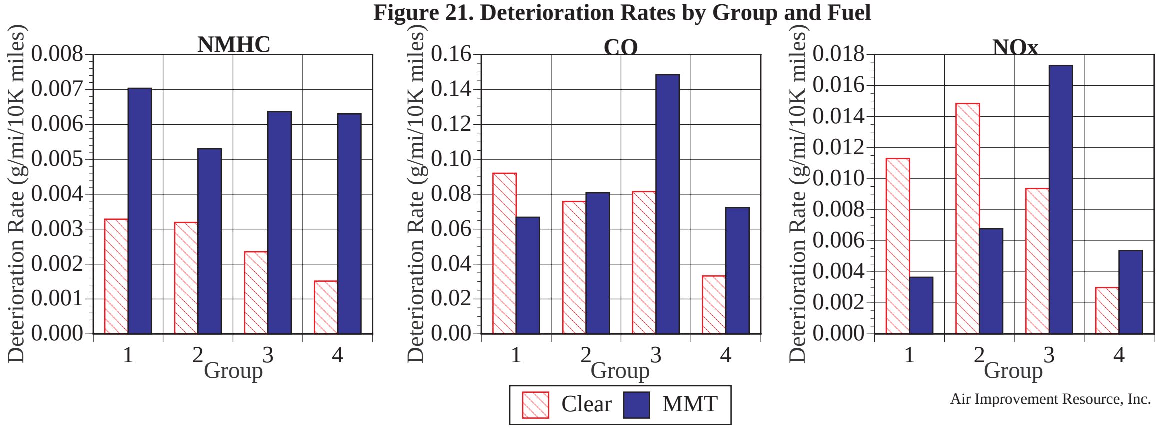


We also examined the Group 4 emissions without vehicle D-1, but there was little change from Figure 20. Therefore, for the remainder of this analysis, we leave all testing with D-1 in the database.

4.5.1 Analysis of Deterioration Rates

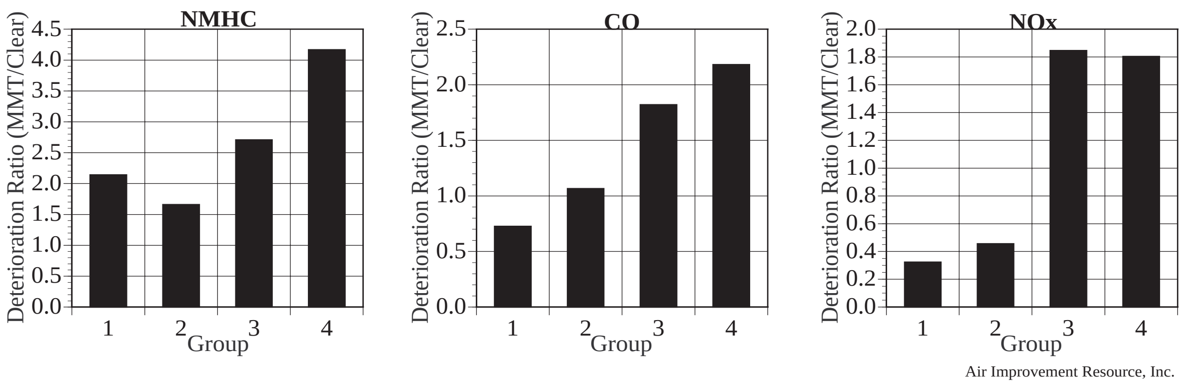
Deterioration rates by group and pollutant (in g/mi/10,000 miles) are shown in Figure 21. For NMHC on Clear fuel, deterioration rates have declined with the advance in technology, but deterioration rates for vehicles fueled with MMT® have stayed constant at higher levels. CO deterioration rates are similar to NMHC. For NOx, vehicles fueled with Clear fuels have also declined in deterioration rates. For MMT®, deterioration rates appear to have increase through Group 3, but appear to have declined for Group 4 relative to Group 3. However, we did not include in these groups two vehicles whose catalysts failed early in their life (M-1 and M-2), and whose NOx emissions increased dramatically before their catalysts failed. The MMT® deterioration rates for Group 4 are still higher than for the vehicles on Clear fuel.

Figure 21. Deterioration Rates by Group and Fuel



Deterioration rate ratios are shown in Figure 22, which estimate the ratio of deterioration on MMT® to Clear. There appears to be an upward trend in MMT®/Clear deterioration rates for all three pollutants. This is consistent with advanced technology vehicles being more sensitive to MMT® in gasoline than earlier technologies. Again, neither Group 3 nor Group 4 include the two models (M-1 and M-2) whose catalysts became plugged early in their life on MMT®.

Figure 22. Deterioration Rate Ratios by Group



4.5.2 Method of Estimating MMT®'s Impacts in MOBILE6C

In our 2002 report, we estimated MMT® correction factors versus mileage for each group by determining the log of emissions for both MMT® and Clear (by Group), developing linear regressions through the log of emissions for both MMT® and Clear, and dividing the predicted log of emissions of MMT® by the log of emissions of the Clear vehicles. This MMT® correction factor, which generally increased with increasing vehicle miles, was applied to the MOBILE5 predicted emission factors to develop emissions on MMT®.

While the above process generally worked for the vehicles tested at that time, it has a drawback when applying to newer vehicles with very low emissions. On the Clear fuel, Tier 2 vehicles can have very low NMOG and NOx emissions, and higher emissions on the MMT® fuel. When the ratio of emissions is taken, this can result in some very high MMT®/Clear ratios. And when these are applied to the heavier vehicle groups, they can result in high emissions on MMT® for the higher vehicle weight LDTs and HDGVs.

In this new analysis, we are estimating the deterioration rates for Clear and MMT® for each group as shown in Figures 17 through 20, which are also summarized for all Groups in Figure 21. Within the MOBILE6.2C model, these are first applied to MOBILE6.2 zero mile levels to estimate MMT® and Clear emissions at any mileage. MOBILE6.2 deterioration rates are not used in this process; only the MMT® and Clear deterioration rates are used. The MMT® emissions are then divided by the Clear emissions to produce a MMT®/Clear ratio. These ratios are then used to correct the MOBILE6 estimated emissions (which do use the MOBILE6.2C zero mile levels and deterioration rates), which are assumed to be on Clear, to an MMT® level. This process is illustrated in the equations below.

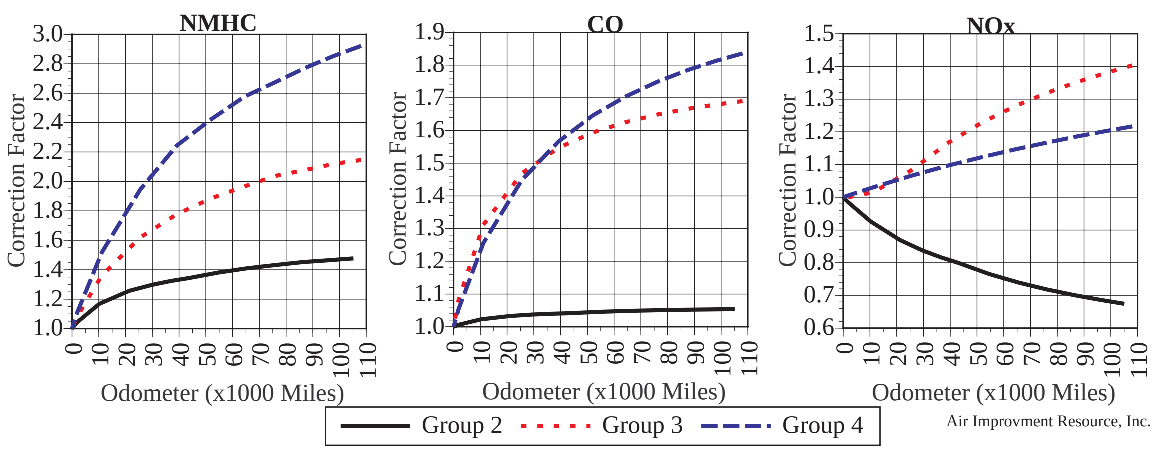
$$CF_{MMT} = [ZML_{M6C} + DR_{MMT} * miles]/[ZML_{M6C} + DR_{Clear} * miles], \text{ and}$$
$$E_{MMT} = [ZML_{M6C} + DR_{M6C} * miles] * CF_{MMT}$$

Where:

CF_{MMT} = MMT® correction factor
ZML_{M6C} = MOBILE6C zero mile level, by vehicle type and model year group
DR_{MMT} = The MMT® deterioration rate in g/mi/10K miles, by Group
DR_{Clear} = The Clear deterioration rate in g/mi/10K miles, by Group
Miles = Odometer miles of vehicle model year group
E_{MMT} = Emissions of vehicle on MMT®
DR_{M6C} = MOBILE6C deterioration rate in g/mi/10K miles

Example MMT® correction factors for PCs and LDT1s are shown below. These vehicle classes do not utilize Group 1 correction factors, so Group 1 correction factors are not shown (Table 5 shows Group assignments by vehicle class).

Figure 23. Typical LDGV MMT Correction Factors versus Group and Mileage



The figures show that Group 4 is more sensitive to MMT® than Groups 2 and 3 for HC and CO. For NOx, MMT® causes a reduction in Group 2 NOx, but increases NOx for Groups 3 and 4. It is not clear why Group 4 is less sensitive for NOx than Group 3, although they are relatively close (same for CO). Again, we must remember that two models could not even accumulate mileage satisfactorily on gasoline with MMT® without requiring catalyst replacements well under 50,000 miles.

The correction factors are used in the MOBILE5 model to correct the emissions within the model to operation on MMT® fuel.

$$EF_{MMT} = EF_{EPA} * CF_{MMT}$$

Where:

EF_{MMT} = emission factor in g/mi for a particular model year, adjusted for MMT®
EF_{EPA} = EPA emission factor for a particular model year, not adjusted for MMT®
CF_{MMT} = MMT® correction factor

Since the EPA emission factors include both on-cycle and off-cycle operation, this analysis will adjust both on-cycle and off-cycle exhaust emissions for the MMT® effect. Also, these MMT® correction factors have been developed on so-called "normal-emitting" vehicles, however the MOBILE model includes both normal emitters and high emitters. No data is available on MMT's effects on high emitting vehicles, but if most high emitting vehicles have some catalytic activity, then we would expect MMT® to have some effect even on high emitters.[10] Therefore, for this analysis, we have assumed that MMT® has the same percentage effect on both normal and high emitting vehicles.

Further explanations of the modeling methods involving the (1) corrections for combined MMT® concentration and market share to levels different than those used in the testing procedures, (2) the correction for the fraction of vehicles whose emissions are sensitive to MMT® and those that are not, and (3) the methods for estimating the MMT® correction factors in a certain implementation year, are discussed in more detail in Section 5 – Modeling Methods.

4.6 MMT® Correction Factor Mapping by Vehicle Class and Model Year Group

The different vehicle types and model years in MOBILE6.2C utilize the MMT® Groups shown in Table 5. This is the same group mapping as was used in the 2002 analysis.

Table 5. MMT® Correction Factor Mapping

Years	PC and LDT1	LDT2	LDT3	LDT4	MDPVs	HDGV
1995-2000 Tier 1	Group 2	Group 1	Group 1	Group 1	Group 1	Group 1
2001-2003 NLEV	Group 3	Group 3	Group 1	Group 1	Group 1	Group 1
2004-2006 Tier 2	Group 4	Group 4	Group 3	Group 3	Group 1	Group 1
2007+ Tier 2	Group 4	Group 4	Group 4	Group 4	Group 4	Group 3

Group 1: Alliance/AIAM/CVMA: Part 1Tier 1 S10 Blazer, Part 2 LEV Tahoe
Group 2: Alliance/AIAM/CVMA: Part 1TLEVs, Part 1 Tier 1 Corolla, Part 2 LEV Tahoe
Group 3: Alliance/AIAM/CVMA: Part 1 and Part 2 LEVs (minus Tahoe), New Data: J-1, M-1
Group 4: Alliance/AIAM/CVMA: Part 1 Civic and Part 2 Escort, New Data: D-1, M-3 through M-8

[10] Some test vehicles became higher emitters because of MMT, but the emission tests were initiated on vehicles that were not high emitters.

5.0 Modeling Methods

This section describes how the MMT® effects discussed in the previous section are implemented in the on-road emissions model, and how the emission inventories are estimated. The following subjects are addressed:

- Emission inventory scenarios modeled
- Emissions model used
- Model inputs (speeds, temperatures, fuel parameters, etc.)
- Correcting for different MMT® concentrations and market penetration
- Accounting for the fraction of Group 3 and Group 4 vehicles whose tailpipe emissions increase with MMT®

5.1 Emission Inventory Scenarios

For modeling purposes, we are assuming that MMT® use would re-commence in January of 2008, and that the average concentration and market penetration of MMT® would be the same as in the 2-3 year period before it ended, or about 0.024 g Mn/gallon [6.3 mg/L], and a market penetration of about 90% (corrections for in-use MMT® concentrations are discussed in Section 5.3).

One issue for the existing 2004 and earlier fleet is whether to try to incorporate the effects of previous MMT® use. We are not aware of any emissions test data where mileage accumulation has occurred on MMT® for a while, then stopped, then started again. In this analysis, we are assuming that the effects of previous MMT® use are not reversed, but only interrupted.

We examined emissions inventories under several cases, with and without MMT®. These cases are shown in Table 6 and explained below.

The baseline, called MMT-0, examines emissions without MMT® in either the pre-2004 calendar years, or in 2008+ calendar years. MMT-1 examines emissions with just MMT® in pre-2004 calendar years. MMT-2 is the same as MMT-1 but adds MMT® use in 2008.

The next three cases (MMT-3 through MMT-5) examine different percentages of 2001 and later vehicles that are emissions-sensitive to MMT® – 80%, 50%, and 20%. These cases assume historical MMT® use and also MMT® use restarting in 2008 (MMT-2). MMT-6 examines the impact of lower in-use MMT® concentrations, assuming 80% of 2001+ vehicles are emissions-sensitive to MMT®, and MMT-7 examines the impact if 10% of the fleet is plugged and requires catalyst replacements, assuming 80% of 2001+ vehicles are emissions-sensitive to MMT® and the average concentration is 0.031 g Mn/U.S. gallon [8.2 mg/L].

The without MMT® case (MMT-0) is the same as the current MOBILE6.2 baseline, and the with MMT® cases, except MMT-1, assumes MMT® use starting in 2008 (unabated thereafter) with different deterioration factors for the different Groups of vehicles (Tier 1, LEV, Tier 2) based on a correction factors developed in Section 4. Tier 2 and LEVs are examined with the following fraction of vehicles assumed to be sensitive: 20%, 50%, and 80%.

Table 6. Summary of MMT® Modeling Runs with MOBILE6.2C

Modeling Run	2004- MMT® Use?	2008+ MMT® Use?	% Emissions Sensitive	Mn Concentration, g/U.S.gal [mg/L]	% Plugged
MMT-0	No	No	N/A	N/A	N/A
MMT-1	Yes	No	100%	0.031 [8.2]	None
MMT-2	Yes	Yes	100%	0.031 [8.2]	None
MMT-3	Yes	Yes	80%	0.031 [8.2]	None
MMT-4	Yes	Yes	50%	0.031 [8.2]	None
MMT-5	Yes	Yes	20%	0.031 [8.2]	None
MMT-6	Yes	Yes	80%	0.023 [6.3]	None
MMT-7	Yes	Yes	80%	0.031 [8.2]	10%

5.2 Emission Model and Inputs Used

The current emission inventory modeling uses the MOBILE6.2C_PPM model, which AIR created for Environment Canada. [5] The model was run at 2 vehicle speeds and four seasons for each Province. Temperatures varied by season and Province. AIR attempted to obtain new inputs for this model that Environment Canada uses, but these were not supplied. As a consequence, we used Canadian inputs we have used in previous modeling runs for Canada and others, and adjusted them to fit the MOBILE6 model.[11] The use of the latest inputs is not critical to this analysis, as we are focusing on relative differences in cases with and without MMT®. It is not critical for the baseline inventories to be highly accurate. The MOBILE6C inputs are shown in Attachment 1.

5.3 MMT® Concentration and Market Penetration

In this study, we are assuming that all of the test data is based on 100% market penetration of MMT® with a concentration of 0.031 g Mn/U.S. gallon [8.2 mg/L]. The average in-use concentration from the last study was 0.024 g Mn/gallon [6.3 mg/L], with a market penetration of 90%. We estimated MMT® effects making two assumptions: (1) that the effect is equivalent to the test data, and (2) that the effect is proportional to the combination of the average concentration and the market penetration. We present emission inventories in this study based on the same two assumptions. The equation used

[11] In particular, MOBILE6 uses expanded vehicle classifications, so AIR developed methods of splitting the previous vehicle classes into the MOBILE6 classes.

to correct for MMT® effects for concentration is the same as in the previous study and is shown below:

$$CF_{mmt, adj} = [1+(mmt_c/0.031)*(CF_{mmt}-1)] * mmt_f + (1-mmt_f)$$

Where:

$CF_{mmt, adj}$ = adjusted mmt correction factor
mmt_c = mmt concentration, in g Mn/gal (input variable)
mmt_f = mmt penetration (fraction)
0.031 = concentration in g Mn/gal of the Part 1 and Part 2 testing programs

The above equation essentially mitigates both the positive and negative effects of MMT® in proportion to concentration and penetration. For this analysis, the market penetration is assumed to be 100%.

5.4 Fraction of Group 3 and Group 4 Vehicles that are Sensitive

Also in this study, we are assuming that not all of the group 3 and Group 4 vehicles experience tailpipe emission increases due to MMT®. They may actually all be sensitive at some mileages, but for the purposes of this inventory analysis we are estimating inventories for 3 percentages of tailpipe emissions sensitivity: 80%, 50%, and 20%. The equations for incorporating this effect are exactly analogous to the MMT® concentration and market penetration calculations, except that they only apply to Group 3 and 4 vehicles and model year groups.

5.5 Explanation of Calculations

The baseline case assumes no MMT® use in either pre-2004 or 2008+ calendar years. There are two other cases: both assume that MMT® was used in 2004 and earlier calendar years, one case assume no MMT® in 2008+ calendar years, and the other case assumes MMT® is used in 2008+ calendar years.

With these different cases, the model year emission rates of the 2004 and earlier model years and 2005 and later model years must be treated differently. The effects are explained in Table 7.

Table 7. Explanation of Effects for Different model Year Groups for Cases		
Case	2004 and earlier model year vehicles	2005 and later model year vehicles
Baseline (MMT-0)	No effect	No effect
MMT® 2004-/No MMT® 2008+ (MMT-1)	MMT® effect accumulates until calendar year 2004 and is interrupted at that point, never to resume	No effect
MMT® 2004-/MMT® 2008+ (MMT-2 to MMT-7)	MMT® effects accumulate until 2004, are interrupted in the 2004-2007 time period, and resume in 2008	MMT® effects start in calendar year 2008. 2005-2007 vehicles utilize the zero mile effect at the mileage they are at in 2008

6.0 Results

For the following results, refer to Table 6 for a detailed description of these cases. All inventories are shown in Attachment 3.

6.1 MMT-0, MMT-1, and MMT-2

Canadian VOC, CO, and NOx emission inventories from all on-road gasoline vehicles (including those above 8,500 lbs) for the three cases are shown in Figures 24-26. Emission inventories are shown in tonnes per year for 2007-2020.

VOC emission inventories for the baseline scenario with no MMT® start at about 256,000 tonnes per year in 2007, declining to 121,000 tonnes per year in 2020. The decline in VOC inventories is the result of the many control programs for light and heavy-duty gasoline vehicles and fuels, including sulfur reductions, the NLEV program implemented in 2001, the Tier 2 program implemented starting in 2004, onboard diagnostics, and other control programs. The second scenario, showing MMT® prior to 2004 and no MMT® after 2004 has higher inventories, but as the fleet turns over, the inventories approach the baseline case because older vehicles that were operated on MMT® and experienced deterioration in VOC emissions are retired from the fleet. The third and highest scenario restarts MMT® in 2008, and shows emission inventories essentially flattening out in 2012. VOC inventories in 2020 are 117,000 tonnes per year higher in 2020 than if MMT® is not restarted. In this case, essentially all the VOC benefits of lower Tier 2 standards are being negated by MMT®.

CO emissions inventories are shown in Figure 25, and the trends are very similar to VOC, except that the Baseline and MMT® 2004-/No MMT® 2008+ scenarios are equivalent in 2020.

NOx emission inventories are shown in Figure 26. For the baseline scenario, the Canadian inventory starts at about 204,000 tonnes in 2007 and declines by 58% to 86,000 tonnes per year by 2020 for the same reasons as VOC (minus the evaporative emission benefit reasons). The two MMT® cases in 2007 start at lower NOx emission inventories, because in the 2007-2011 period, the older Group 1 and 2 vehicles have a significant effect on NOx inventories, and these vehicle have a MMT® NOx benefit. As these vehicles are retired, the Group 3 and 4 vehicles dominate which have a NOx disbenefit for MMT®, and NOx emission inventories increase to above the Base scenario (the MMT® 2004-/no MMT® 2008+ scenario increases to the baseline scenario as the 2004 and earlier model year vehicle are retired).

Figure 24

Canadian VOC Emissions from Gasoline Vehicles

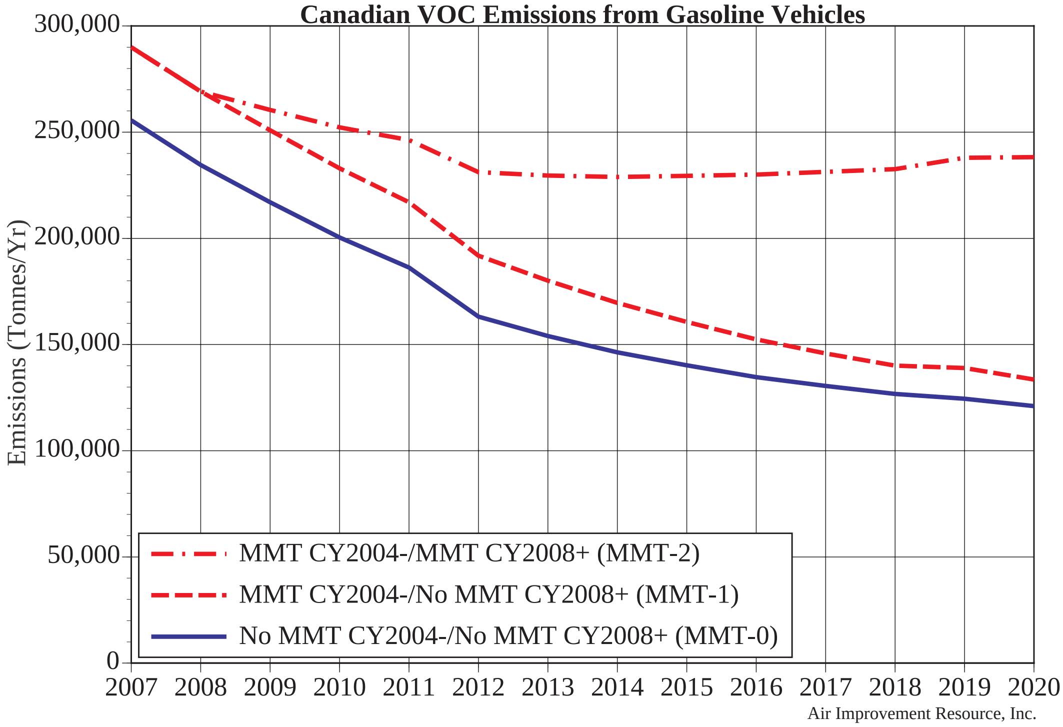


Figure 25

Canadian CO Emissions from Gasoline Vehicles

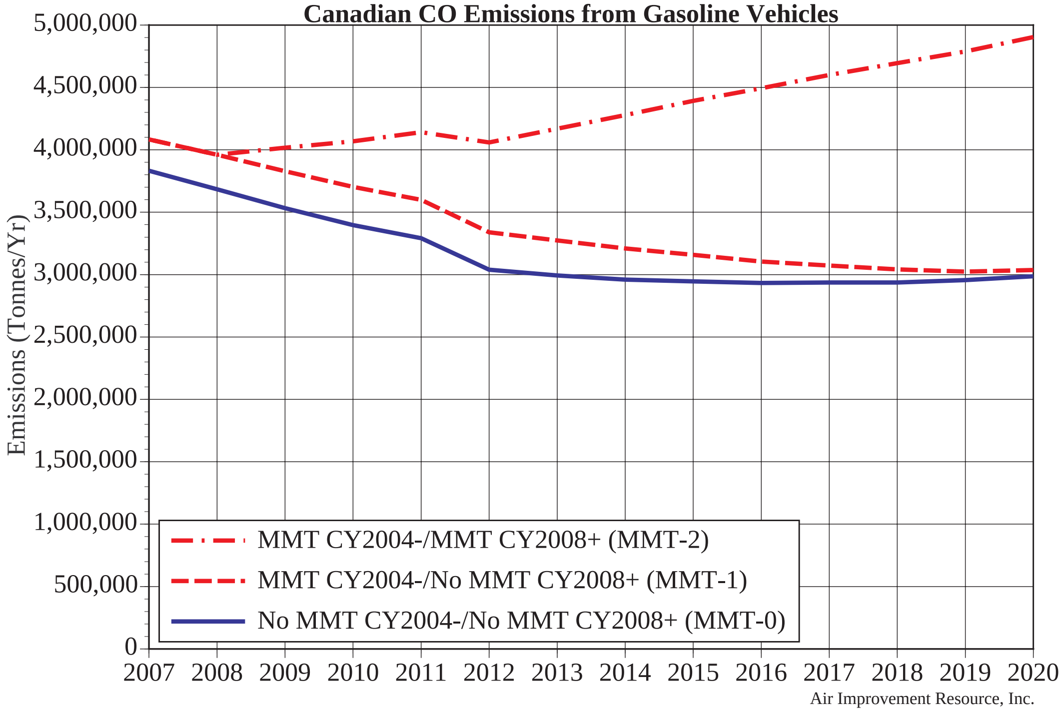
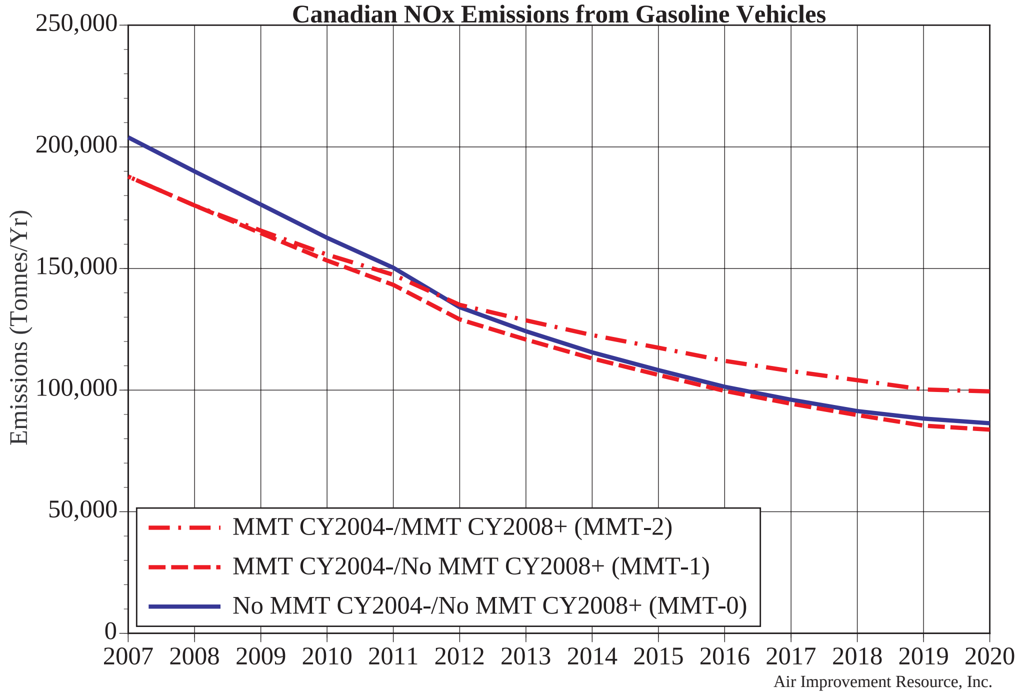


Figure 26



6.2 Sensitivity Cases (MMT-3 through MMT-7)

The sensitivity cases involve changes to two parameters: (1) varying percentages of vehicles that are assumed to display significant emission sensitivity to fueling with gasoline containing MMT®, and (2) changes in in-use MMT® concentration for 2008+, coupled with the assumption that the size of the MMT® effect is proportional to the average in-use MMT® concentration. These are discussed further below.

6.2.1 Emission Sensitivity to Fuel Containing MMT® (MMT-3 through MMT-5)

As discussed in Section 4, the various different evaluation vehicles displayed a range of tailpipe emissions sensitivity to MMT®, but all evaluation vehicles displayed some emissions sensitivity. It is difficult from the limited testing to determine the average emissions sensitivity, therefore, in this analysis we will estimate the emissions inventory impacts for a range of emissions sensitivity, specifically, 80%, 50%, and 20%. In the 80% case, we are assuming that 80% of the fleet experiences the emission sensitivity of the Group 3 and Group 4 vehicles as developed in Section 4.5, and the remaining 20% will be assumed to show no emissions sensitivity. Group 1 and 2 vehicles are always assumed to have the emissions sensitivity shown in Section 4.5. The 50% and 20% cases are analogous. We also compare the emissions inventories to the No MMT® scenario. For these three sensitivity cases, we are assuming MMT® for 2004 and earlier calendar years and MMT® for 2008 and later calendar years.

Figure 27 shows VOC emissions inventories. As the percent of Group 3 and 4 vehicles that are assumed to show emissions sensitivity to MMT® increase, the VOC emission inventories increase. The CO (Figure 28) and NOx (Figure 29) emission inventories show similar trends with increasing sensitivity.

Figure 27

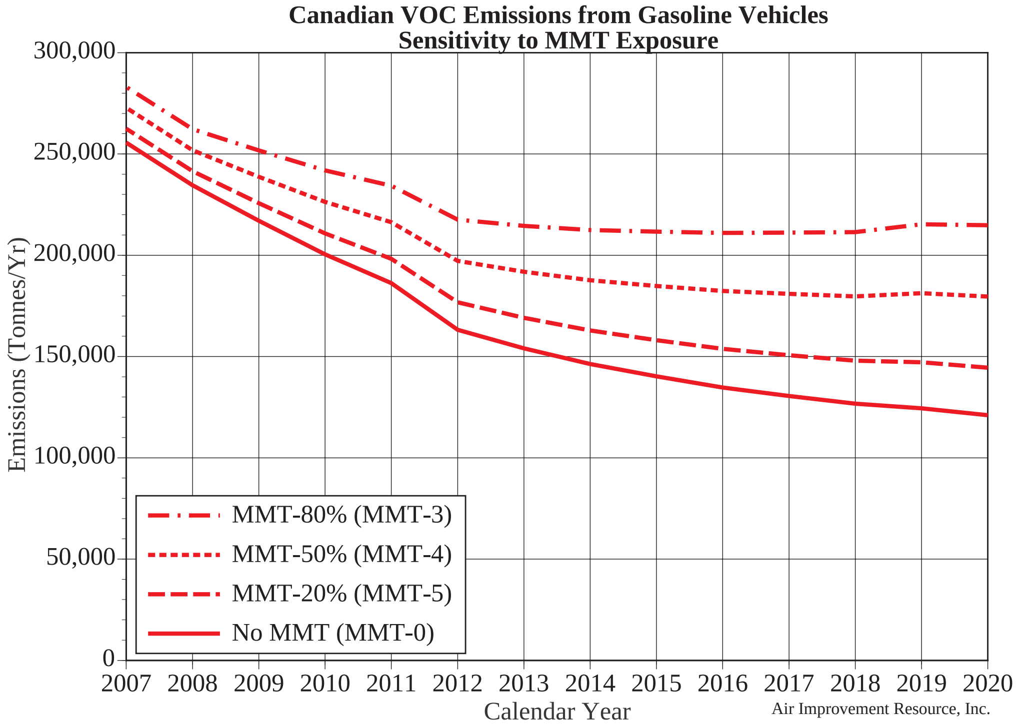


Figure 28

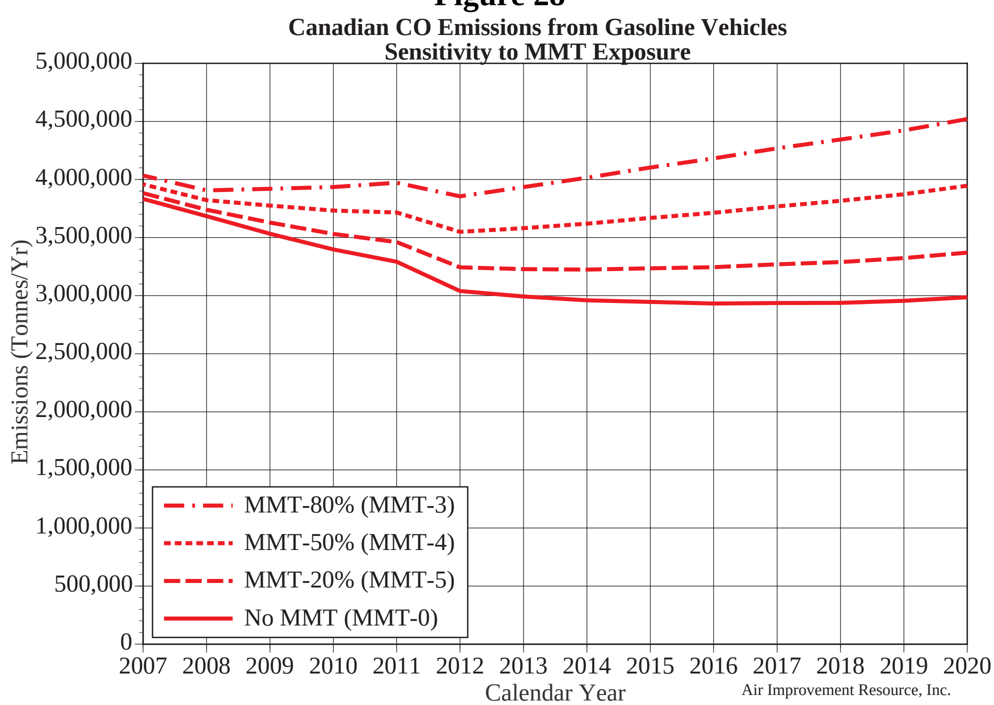
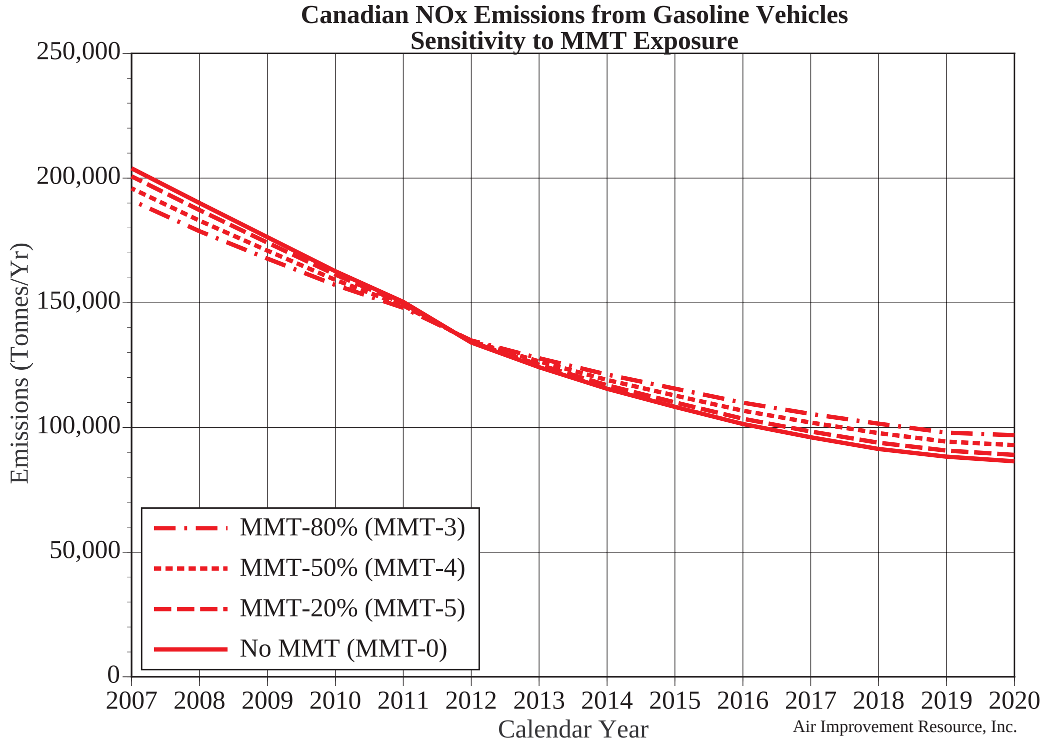


Figure 29



6.2.2 Emission Sensitivity For Differences in MMT® Concentration (MMT-6)

Figures 30-32 show emission sensitivity for different in-use MMT® concentrations. We make two assumptions in these cases: that the MMT® market penetration is near 100%, and that the percent of 2001 and later model year vehicles that experience emissions sensitivity to MMT® is 80%. We show three MMT® concentrations – 0.031 [8.2], 0.023 [6.1], and no MMT® as the Base Case. Both the 0.031 [8.2] and 0.023 [6.1] levels show a significant emissions impact on all inventories.

Figure 30

Canadian VOC Emissions from Gasoline Vehicles
Sensitivity to MMT Exposure

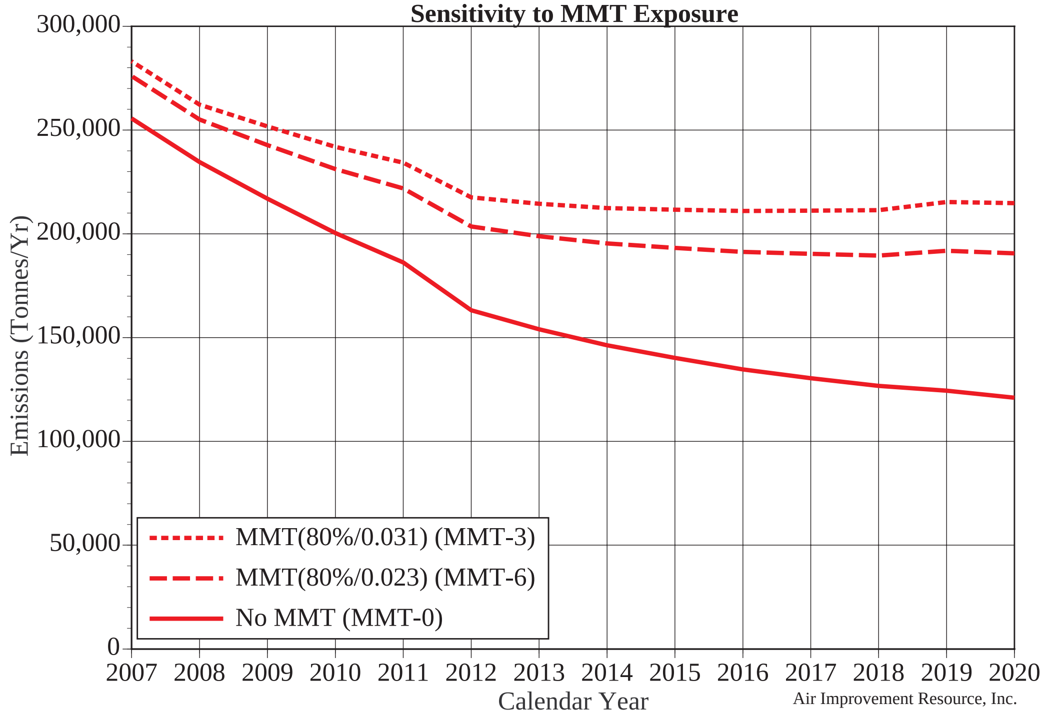


Figure 31

Canadian CO Emissions from Gasoline Vehicles
Sensitivity to MMT Exposure

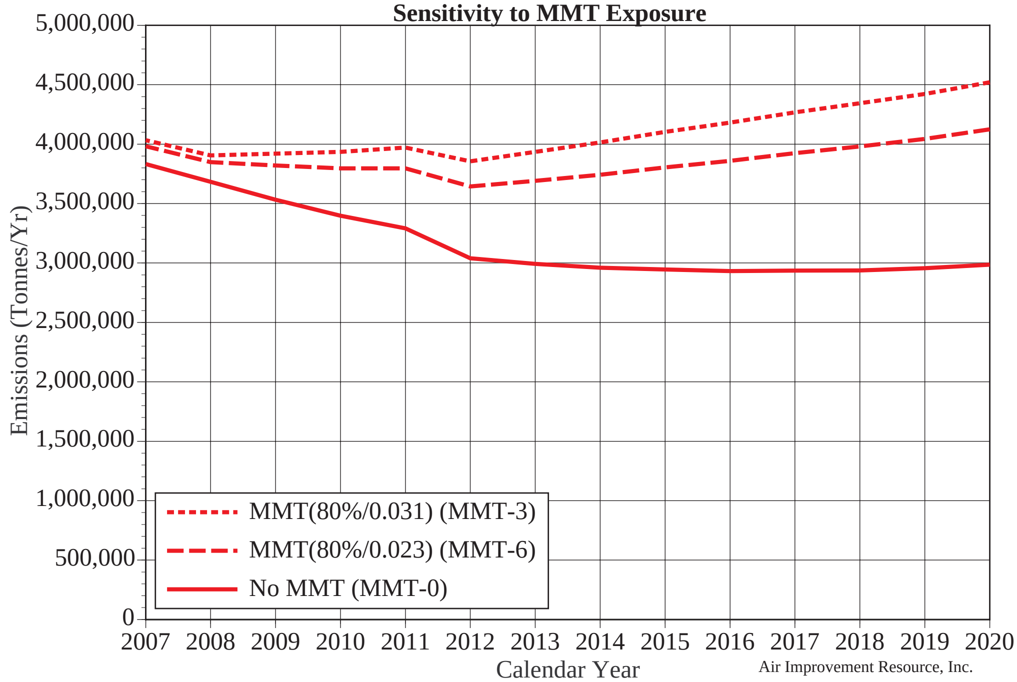
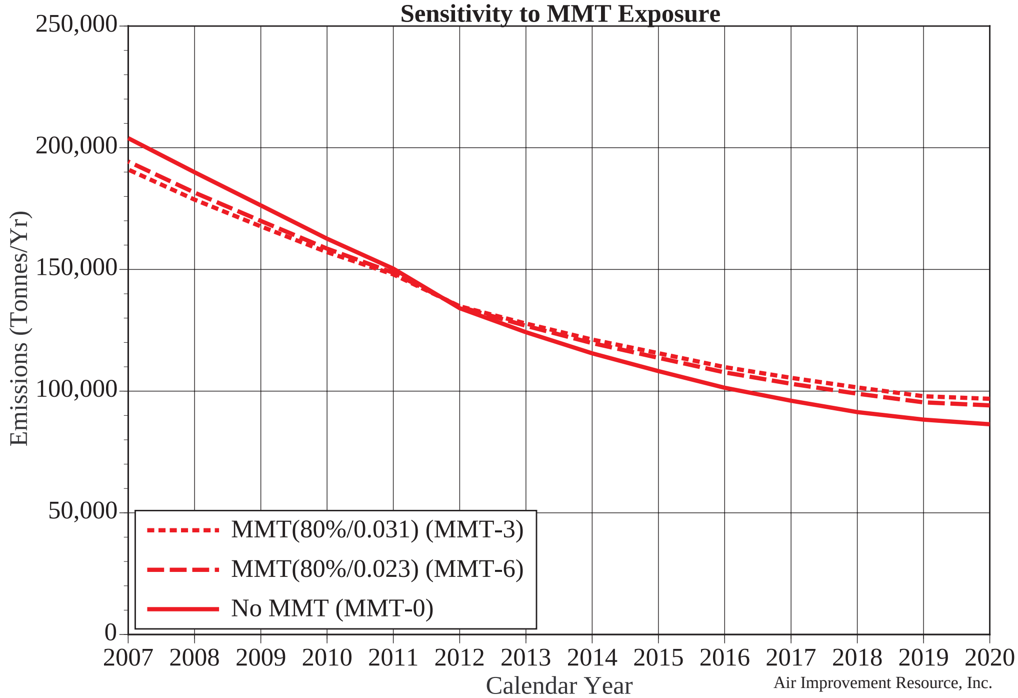


Figure 32

Canadian NOx Emissions from Gasoline Vehicles
Sensitivity to MMT Exposure



6.2.3 Emission Sensitivity to Percent of Vehicles that Plug Early (MMT-7)

In Attachment 1, we developed a possible method of modeling the emissions of vehicles that plug within the first 50,000 miles [80,500 km] and require catalyst replacement. In this section, we use this method to determine the overall fleetwide emission impact if 10% of vehicles plug early, similar to vehicle M-1.

The base case for this analysis assumes an in-use MMT® level of 0.031 [8.2 mg/l], and 80% emissions sensitivity. For the sensitivity case, we assume 70% of vehicles experience emissions sensitivity, and 10% are highly emissions sensitive (for a total of 80%) and experience emissions as described in Attachment 1. Results are shown in Figures 33-35.

VOC and NOx inventories increase somewhat due to assuming 10% of the vehicles are plugged, however, NOx inventories increase more dramatically.

Figure 33

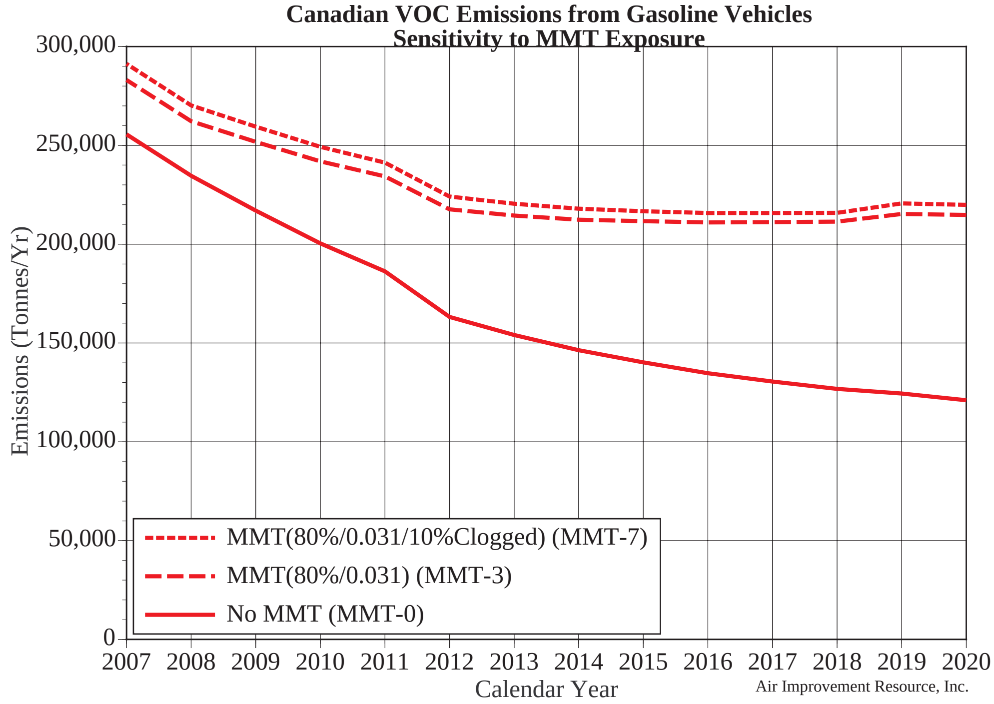


Figure 34

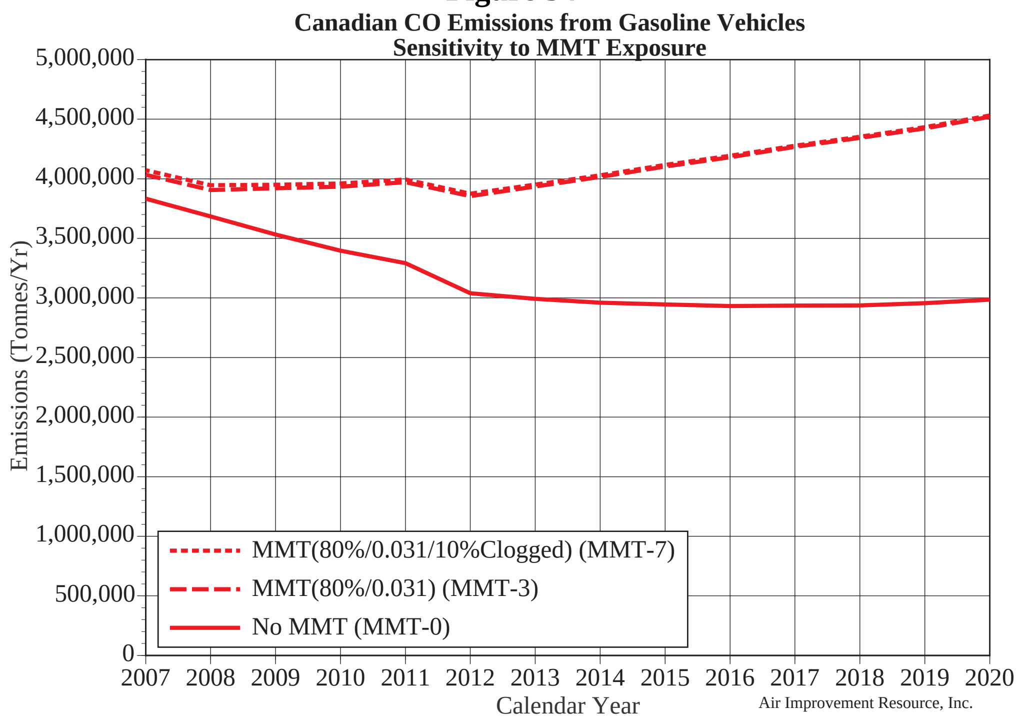
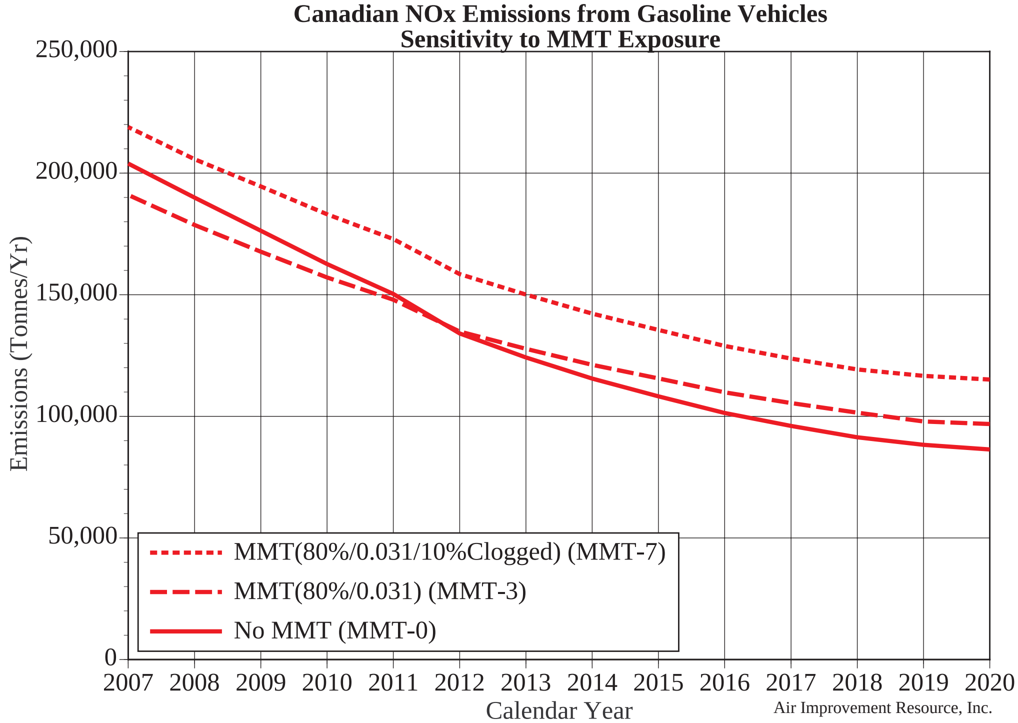


Figure 35


Canadian NOx Emissions from Gasoline Vehicles
Sensitivity to MMT Exposure
250,000
200,000
150,000
100,000
50,000
0
Emissions (Tonnes/Yr)
MMT(80%/0.031/10%Clogged) (MMT-7)
MMT(80%/0.031) (MMT-3)
No MMT (MMT-0)
2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Calendar Year
Air Improvement Resource, Inc.

7.0 Discussion

This section discusses two items – a comparison of results from the previous study by AIR to this study, and various uncertainties in this analysis.

7.1 Comparison with Previous Analysis

The results of the previous analysis conducted by AIR on a subset of the data presented in this analysis showed that in 2020, VOC emissions from gasoline on-road vehicles increased by 26-36%, CO by 35%-75%, and NOx by 45%-65%. The low end of the range of percents is for adjusting the MMT® concentration of evaluation vehicles to a lower in-use average concentration. The upper percent makes no adjustment for concentration. As noted earlier, even with an average Mn concentration of 0.023 g Mn/U.S. gallon [6.1 mg/l], maximums of up to 0.080 g Mn/gallon [21.1 mg/l] were observed.

In this new analysis, the VOC increases for the case with 80% emissions sensitivity, no adjustment for in-use Mn concentration, and no vehicles that are plugged, are about 77% for VOC, 51% for CO, and 12% for NOx. The VOC increases in this new analysis are higher than the previous analysis, CO is about the same, and the NOx increases are lower. The reasons for these differences are directly related to the MMT® correction factors as vehicles age. In the previous analysis, Tier 2 vehicles (based on 2 vehicles) experienced a 2.2x increase at 100,000 miles for VOC, 2.0x increase for CO, and 2.0x increase for NOx. In this new analysis, Tier 2 vehicles (based on 8 vehicles) are estimated to experience a 2.9x increase for VOC, 1.8x increase for CO, and a 1.2x increase for NOx.

It should be noted that for this comparison we did not include one ULEV1 vehicle and one Tier 2 vehicle whose catalysts plugged early in their life, and whose emissions increased dramatically before serious driveability problems were noted and the testing on these vehicles was discontinued. Therefore, the analysis of deterioration for the fleet of LEV and Tier 2 vehicles in this case is very conservative, and is likely higher than estimated.

The fact that the percent increases in the different emissions were not the same (i.e., HC and CO much higher than NOx) is likely due to different mechanisms that bring about the increase in emissions. Previous research has indicated that the increase in HC and CO emissions are related to valve, spark plug, and cylinder head deposits caused by MMT®, and that increases in NOx emissions are primarily due to catalyst plugging. [6,7]

7.2 Uncertainties in Analysis

Examination of the data revealed that there is a wide variation of emissions responses to MMT®, even among Tier 2 vehicles. The reasons for this high degree of variability are quite clearly explained in Honda's SAE paper 2007-01-1070, which evaluated the impacts on MMT® plugging of (1) catalytic converter placement in the exhaust stream, (2) catalytic converter cell density, and (3) exhaust system temperatures.

Uncertainties in this analysis include:

1. The extent to which the 2001 and later model year fleet will experience an emissions increase due to MMT®. All of the evaluation vehicles tested experienced some emissions increase on MMT®, and two vehicles experienced early catalyst failures on MMT®.

2. The fraction of the fleet that will experience very early plugging and catalyst failure. Two out of sixteen LEV, ULEV and Tier 2 test vehicles (13%) experienced early catalyst failure accompanied by driveability problems on MMT®.

3. The magnitude of the emission deterioration of vehicles experiencing early plugging and catalyst replacement.

4. The actual in-use concentration of Manganese in the fuel, in terms of concentration and market share.

5. How aggressively the fleet is driven in-use. The more aggressive the fleet is driven, the higher the exhaust temperatures, and the more significant MMT® plugging becomes.

6. The rate of mileage accumulation. The amount of MMT® exposure is proportional to the amount of fuel used.

In spite of the above uncertainties, it is clear from the analysis that the use of MMT® in gasoline would cause a significant number of 2001 and later LEV and Tier 2 vehicle emissions control systems to degrade with time, resulting in unnecessary catalyst replacement and much higher emissions than without MMT®.

7.0 References

1. “Effects of MMT in Gasoline on Emissions from On-Road Motor Vehicles in Canada”, Air Improvement Resource, Inc, for Canadian Vehicle Manufacturers Association and Association of International Automobile Manufacturers of Canada, November 11, 2002.

2. “The Impact of MMT on Vehicle Emissions and Durability – Part 1”, A Joint Study by the Alliance of Automobile Manufacturers, The Association of International Automobile Manufacturers and the Canadian Vehicle Manufacturers Association, July 29, 2002.

3. “The Impact of MMT on Vehicle Emissions and Durability – Part 2”, A Joint Study by the Alliance of Automobile Manufacturers, The Association of International Automobile Manufacturers and the Canadian Vehicle Manufacturers Association, July 29,2002

4. “Parametric Analysis of Catalytic Converter Plugging Caused by Manganese-based Gasoline Additives”, Shimizo and Ohtaka, Honda R&D Center, SAE 2007-01-1070.

5. “Development of the Canadian Version for the MOBILE6.2 Model”, AIR, Inc. and SENES Consultants Limited, for Environment Canada, September 2004.

6. “Effects of MMT® Fuel Additive on Emission System Components: Comparison of Clear- and MMT®-Fueled Escort Vehicles from the Alliance Study, SAE2004-01-1084, March 8-11, 2004.

7. “Effect of MMT® Fuel Additive on Emission System Components: detailed Parts Analysis from Clear- and MMT®-Fueled Escort Vehicles from the Alliance Study, 2005-01-1108, April 11-14, 2005.

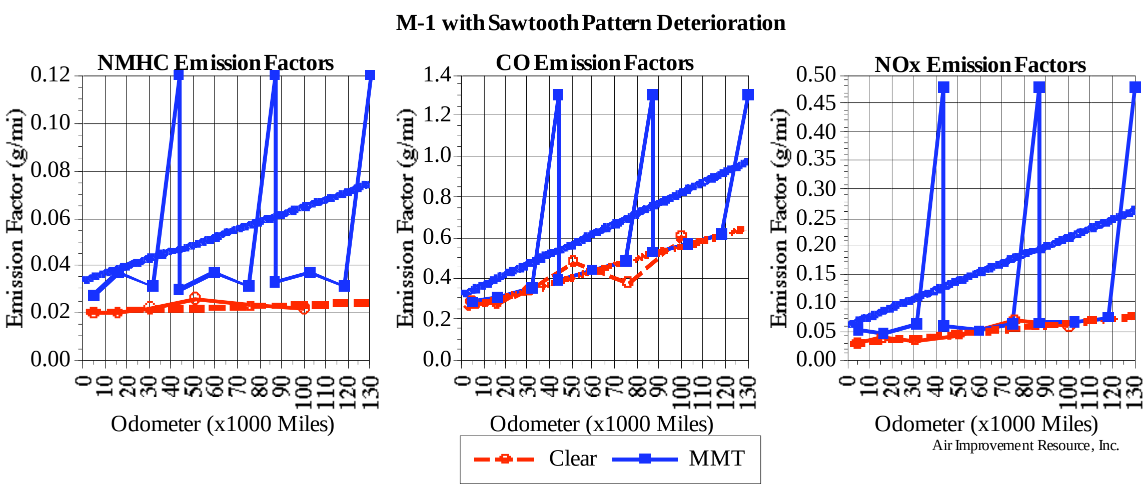
Attachment 1

Emissions Deterioration for Vehicles that are Highly Sensitive to MMT®

Vehicle M-1 experienced sudden increases in emissions, MIL illumination and driveability problems around 40,000 miles. The fault code for the OBD system indicated a catalyst problem. When the catalyst was removed, extensive manganese deposits were found. Replacing this vehicle's catalyst with a new catalyst reduced emissions and restored the driveability of the vehicle.

Vehicles are designed with highly efficient catalytic converter systems that are capable of lasting for the full useful life at a minimum (120,000 miles or about 192,000 km) without exceeding their emission standards and without a catalyst replacement, as long as the vehicle is maintained and fueled properly. Manufacturers must perform extensive durability testing in order to verify that their emission control systems meet these requirements. Durability test data is collected on vehicle models and submitted to EPA.

Vehicle M-1 appears to be highly sensitive to the presence of MMT® in gasoline. If we assume the catalytic converter only lasts about 40,000 miles [64,400 km], then the vehicle would need at least 3 catalytic converter replacements over its life if it were fueled frequently with MMT®-containing fuel, and the emission performance of the vehicle would appear as shown in the figure below.



For each pollutant, we show the deterioration for the first 40,000 miles [64,400 km] as it took place for M-1, followed by a catalyst replacement. After the catalyst replacement, we have lowered the HC, CO and NOx emissions to 10% above the 4,000 mile level [6,400 km], to account for the impact of vehicle or system aging and MMT® on engine-out deterioration. This assumption results in CO emissions for the MMT® after catalyst replacement being lower for MMT® than for Clear, because we are assuming replacement with a new, OEM catalyst.

We have assumed two catalyst replacements over the vehicle's useful life, at about 40,000 miles [64,400 km] and at about 80,000 miles [128,700 km], and have assumed that the average vehicle accumulated about 130,000 miles over its lifetime (~210,000 km), and that it is unlikely that owners would pay for a third catalyst replacement with a new OEM catalyst at 120,000 miles [193,100 km], but instead would seek other alternatives if the catalyst is significantly plugged, or retire the vehicle altogether. The average emissions deterioration therefore over the life of the vehicle is represented by the solid line (which is assumed to extend beyond 130,000 miles until scrapped through normal attrition), and the resulting deterioration for this vehicle over its lifetime is much higher on MMT® than on Clear fuel.

Since MMT® use in Canada was discontinued shortly after Tier 2 vehicles started being phased-in in Canada, we do not know what fraction of vehicles would have experienced the severity of problems as M-1. In our modeling sensitivity analysis, we show the impact of assuming 10% of vehicles would experience problems similar to vehicles M-1.

Attachment 2

MOBILE6C Modeling Inputs

Temperatures, RVP's and I/M
Speeds
VMT Weighting Factors
Seasonal Weighting Factors
Annual Vehicle Kilometers Traveled

Temperature, RVP and I/M						
Province	Season	Minimum (F)	Maximum (F)	RVP	CY	I/M?
ALB	Winter	10	32	15.5		
	Spring_Fall1	29	53	14.4		
	Spring_Fall2	38	62	11.4		
	Summer	47	72	10.4		
BCNO	Winter	35	46	15.5		
	Spring_Fall1	42	56	13.1		
	Spring_Fall2	48	63	10.9		
	Summer	54	70	10.4		
LFV	Winter	35	46	15.5		Y
	Spring_Fall1	42	56	13.1		Y
	Spring_Fall2	48	63	10.9	1996-	Y
	Spring_Fall2	48	63	10.0	1997+	Y
	Summer	54	70	9.0	1996-	Y
	Summer	54	70	8.0	1997+	Y
MAN	Winter	1	19	15.5		
	Spring_Fall1	30	51	14.4		
	Spring_Fall2	42	65	11.4		
	Summer	53	76	10.4		
NB	Winter	18	35	15.5		
	Spring_Fall1	38	56	13.1		
	Spring_Fall2	46	65	10.9		
	Summer	53	72	10.4		
NF	Winter	23	35	15.5		
	Spring_Fall1	36	50	13.8		
	Spring_Fall2	44	60	11.3		
	Summer	51	68	10.4		
NS	Winter	21	37	15.5		
	Spring_Fall1	39	57	13.1		
	Spring_Fall2	48	67	10.9		
	Summer	56	74	10.4		
NT	Winter	2	22	15.5		
	Spring_Fall1	28	52	14.4		
	Spring_Fall2	40	65	11.4		
	Summer	51	77	10.4		
ONT-9	Winter	19	34	15.5		Y
	Spring_Fall1	36	55	14.4		Y
	Spring_Fall2	46	67	11.4	1996-	Y
	Spring_Fall2	46	67	11.0	1997+	Y
	Summer	55	78	10.4	1996-	Y
	Summer	55	78	9.0	1997+	Y
ONT-B	Winter	19	34	15.5		
	Spring_Fall1	36	55	14.4		
	Spring_Fall2	46	67	11.4		
	Summer	55	78	10.4		
PEI	Winter	19	34	15.5		
	Spring_Fall1	39	55	13.1		
	Spring_Fall2	48	65	10.9		
	Summer	56	73	10.4		
QUE-9	Winter	15	30	15.5		
	Spring_Fall1	36	53	14.4		
	Spring_Fall2	47	66	11.4	1996-	
	Spring_Fall2	47	66	11.0	1997+	
	Summer	57	77	10.4	1996-	
	Summer	57	77	9.0	1997+	
QUE-B	Winter	15	30	15.5		
	Spring_Fall1	36	53	14.4		
	Spring_Fall2	47	66	11.4		
	Summer	57	77	10.4		
SASK	Winter	2	22	15.5		
	Spring_Fall1	28	52	14.4		
	Spring_Fall2	40	65	11.4		
	Summer	51	77	10.4		
YT	Winter	35	46	15.5		
	Spring_Fall1	42	56	13.1		
	Spring_Fall2	48	63	10.9		
	Summer	54	70	10.4		

Speeds	
City	20.4 mph
Highway	41.4 mph

VMT Weighting				
Season	Length	Factor	Weight	Normalized
Winter	5	0.893	0.3721	0.3721
Spring	2	0.958	0.1597	0.1597
Autumn	2	1.105	0.1842	0.1842
Summer	3	1.136	0.2840	0.2840
Total	12		0.9999	1.0000

Class Weighting		
Class	City	Highway
LDGV	0.57	0.43
LDGT1	0.57	0.43
LDGT2	0.45	0.55
HDGV	0.36	0.64
LDDV	0.57	0.43
LDDT	0.53	0.47
HDDV	0.36	0.64
MC	0.60	0.40

Annual Vehicle Kilometers Traveled

Class	CY	AB	BC-LFV	LFV	MB	NB	NF	NS	NT	ON-QWC ON	PE	QC-QWC QC	QWC ON	QWC QC	SK	YT
LDGV	1995	18,049,346	7,607,071	10,379,541	7,016,644	5,563,536	2,735,966	5,295,961	132,002	6,462,523	944,408	9,316,741	67,531,819	42,269,747	5,341,299	166,113
	1996	19,418,542	7,746,698	10,570,057	6,615,851	5,623,132	2,765,273	5,352,690	141,625	6,514,486	954,524	8,823,627	68,074,822	40,032,507	5,730,708	169,162
	1997	19,766,311	7,982,849	10,892,275	6,716,281	5,546,827	2,727,749	5,280,055	147,285	6,664,936	941,571	8,565,086	69,646,986	38,859,513	5,959,731	174,319
	1998	22,815,274	7,409,914	10,110,529	6,823,310	5,658,346	2,782,590	5,386,210	134,487	7,063,453	960,502	8,777,241	73,811,393	39,822,053	5,441,856	161,808
	1999	22,672,056	7,358,882	10,040,898	6,729,163	5,653,494	2,780,204	5,381,591	132,133	7,127,425	959,678	8,684,244	74,479,894	39,400,130	5,346,607	160,694
	2000	22,403,679	7,230,693	9,865,989	6,674,255	5,671,106	2,788,865	5,398,357	129,517	7,142,963	962,668	8,535,800	74,642,255	38,726,644	5,240,756	157,894
	2001	22,396,201	7,141,183	9,743,857	6,642,630	5,546,755	2,727,713	5,279,986	127,476	7,143,572	941,559	8,394,212	74,648,623	38,084,264	5,158,161	155,940
	2002	22,594,168	7,129,008	9,727,244	6,616,105	5,466,197	2,688,097	5,203,303	127,058	7,221,178	927,884	8,384,998	75,459,584	38,042,461	5,141,260	155,674
	2003	22,890,775	7,129,939	9,728,514	6,634,205	5,422,447	2,666,582	5,161,657	127,734	7,345,529	920,458	8,429,581	76,759,024	38,244,730	5,168,610	155,694
	2004	23,264,112	7,129,454	9,727,852	6,687,360	5,396,209	2,653,679	5,136,681	129,255	7,501,264	916,004	8,510,312	78,386,416	38,611,008	5,230,161	155,684
	2005	23,828,875	7,169,023	9,781,843	6,799,283	5,408,807	2,659,875	5,148,673	131,925	7,709,078	918,142	8,636,533	80,558,022	39,183,668	5,338,216	156,548
	2006	24,039,798	7,201,292	9,825,873	6,874,133	5,412,557	2,661,719	5,152,242	133,927	7,797,602	918,779	8,780,974	81,483,082	39,838,990	5,419,210	157,252
	2007	24,248,915	7,225,166	9,858,448	6,967,921	5,417,851	2,664,322	5,157,282	136,370	7,885,633	919,678	8,934,101	82,402,986	40,533,722	5,518,058	157,774
	2008	24,567,091	7,273,349	9,924,191	7,098,412	5,445,225	2,677,784	5,183,340	139,497	7,996,749	924,324	9,116,993	83,564,123	41,363,500	5,644,589	158,826
	2009	24,859,085	7,315,718	9,982,002	7,236,091	5,466,181	2,688,089	5,203,287	142,769	8,101,706	927,882	9,304,748	84,660,891	42,215,335	5,776,992	159,751
	2010	25,175,446	7,373,803	10,061,256	7,384,026	5,491,826	2,700,701	5,227,699	146,280	8,207,915	932,235	9,494,644	85,770,755	43,076,889	5,919,061	161,019
	2011	25,661,230	7,470,727	10,193,506	7,499,005	5,555,919	2,732,220	5,288,710	149,049	8,366,503	943,115	9,708,127	87,427,963	44,045,455	6,031,095	163,136
	2012	26,166,871	7,581,291	10,344,366	7,615,559	5,621,609	2,764,524	5,351,240	151,950	8,531,792	954,266	9,931,721	89,155,194	45,059,894	6,148,474	165,550
	2013	26,678,265	7,702,874	10,510,261	7,729,776	5,682,975	2,794,701	5,409,654	154,815	8,696,236	964,682	10,157,335	90,873,590	46,083,497	6,264,433	168,205
	2014	27,187,849	7,837,561	10,694,036	7,839,490	5,742,673	2,824,059	5,466,482	157,617	8,863,611	974,816	10,388,326	92,622,615	47,131,494	6,377,799	171,146
	2015	27,696,057	7,986,722	10,897,560	7,949,506	5,801,926	2,853,198	5,522,885	160,400	9,038,284	984,874	10,627,063	94,447,913	48,214,636	6,490,431	174,403
	2016	28,207,908	8,144,297	11,112,565	8,053,869	5,861,907	2,882,694	5,579,981	163,122	9,218,681	995,056	10,870,884	96,333,018	49,320,843	6,600,567	177,844
	2017	28,719,855	8,306,185	11,333,454	8,155,586	5,919,961	2,911,244	5,635,243	165,761	9,403,055	1,004,911	11,118,606	98,259,682	50,444,749	6,707,353	181,379
	2018	29,243,280	8,474,459	11,563,058	8,255,842	5,978,820	2,940,189	5,691,271	168,393	9,594,547	1,014,902	11,373,847	100,260,723	51,602,769	6,813,821	185,054
	2019	29,777,488	8,647,621	11,799,329	8,352,496	6,036,595	2,968,600	5,746,267	171,012	9,792,883	1,024,709	11,636,886	102,333,287	52,796,169	6,919,815	188,835
	2020	30,307,833	8,819,077	12,033,275	8,446,059	6,090,940	2,995,325	5,797,999	173,549	9,994,131	1,033,934	11,900,836	104,436,287	53,993,700	7,022,484	192,579
LDGT1	1995	5,738,455	3,464,802	2,911,083	2,111,014	1,667,425	1,265,721	1,900,728	82,967	1,338,780	341,216	2,262,117	17,732,975	8,007,806	2,014,503	228,178
	1996	5,833,354	3,607,568	3,031,032	2,172,567	1,672,750	1,269,764	1,906,798	82,835	1,385,657	342,305	2,847,168	18,353,890	10,078,861	2,011,294	237,580
	1997	5,980,125	3,763,751	3,162,255	2,184,643	1,676,739	1,272,792	1,911,346	82,512	1,440,989	343,122	3,000,609	19,086,796	10,622,039	2,003,445	247,865
	1998	5,702,650	4,710,734	3,957,898	2,313,436	1,697,760	1,288,749	1,935,308	89,293	1,486,269	347,423	2,518,129	19,686,551	8,914,079	2,168,086	310,230
	1999	5,934,172	4,925,412	4,138,268	2,391,438	1,763,410	1,338,583	2,010,143	91,318	1,528,943	360,858	2,598,916	20,251,801	9,200,060	2,217,257	324,367
	2000	6,069,888	5,065,143	4,255,668	2,461,313	1,825,967	1,386,069	2,081,453	92,279	1,549,122	373,659	2,638,794	20,519,087	9,341,228	2,240,594	333,570
	2001	6,240,989	5,227,949	4,392,456	2,528,960	1,894,573	1,438,147	2,159,659	93,740	1,579,769	387,698	2,687,859	20,925,026	9,514,916	2,276,058	344,291
	2002	6,472,117	5,423,953	4,557,136	2,594,108	1,964,308	1,491,081	2,239,150	96,121	1,625,685	401,969	2,759,058	21,533,211	9,766,958	2,333,871	357,199
	2003	6,697,213	5,610,821	4,714,140	2,653,648	2,035,641	1,545,230	2,320,464	98,434	1,674,270	416,566	2,826,869	22,176,741	10,007,005	2,390,037	369,506
	2004	6,911,798	5,777,735	4,854,378	2,706,394	2,106,016	1,598,650	2,400,686	100,631	1,721,712	430,967	2,887,120	22,805,149	10,220,291	2,443,396	380,498
	2005	7,137,689	5,958,898	5,006,589	2,767,556	2,182,735	1,656,887	2,488,139	103,026	1,773,149	446,667	2,949,391	23,486,462	10,440,726	2,501,546	392,429
	2006	7,348,170	6,141,225	5,159,779	2,829,293	2,258,693	1,714,546	2,574,726	105,376	1,827,895	462,211	3,008,316	24,211,601	10,649,321	2,558,590	404,436
	2007	7,529,542	6,306,633	5,298,752	2,890,009	2,325,717	1,765,423	2,651,127	107,674	1,881,196	475,926	3,063,057	24,917,608	10,843,099	2,614,395	415,329
	2008	7,710,005	6,489,167	5,452,115	2,952,673	2,396,171	1,818,903	2,731,439	110,024	1,939,167	490,343	3,118,931	25,685,468	11,040,894	2,671,461	427,350
	2009	7,870,001	6,662,665	5,597,885	3,011,380	2,463,227	1,869,805	2,807,878	112,250	1,996,859	504,066	3,170,464	26,449,639	11,223,318	2,725,494	438,776
	2010	8,000,537	6,845,555	5,751,548	3,071,291	2,526,984	1,918,202	2,880,556	114,476	2,053,157	517,113	3,219,133	27,195,341	11,395,605	2,779,556	450,820
	2011	8,147,153	7,030,166	5,906,655	3,146,219	2,594,103	1,969,151	2,957,065	116,926	2,114,364	530,848	3,274,822	28,006,066	11,592,741	2,839,047	462,978
	2012	8,307,481	7,215,345	6,062,240	3,226,467	2,663,735	2,022,008	3,036,440	119,580	2,180,517	545,097	3,337,548	28,882,296	11,814,788	2,903,475	475,173
	2013	8,475,200	7,393,036	6,211,534	3,305,947	2,733,728	2,075,139	3,116,227	122,272	2,250,072	559,420	3,403,055	29,803,599	12,046,679	2,968,851	486,875
	2014	8,652,167	7,564,814	6,355,860	3,384,935	2,802,421	2,127,283	3,194,531	125,041	2,322,398	573,477	3,470,426	30,761,599	12,285,170	3,036,066	498,188
	2015	8,841,116	7,735,395	6,499,179	3,463,887	2,868,044	2,177,096	3,269,335	127,793	2,396,677	586,906	3,540,129	31,745,481	12,531,919	3,102,885	509,421
	2016	9,045,391	7,894,298	6,632,687	3,540,981	2,934,212	2,227,324	3,344,762	130,601	2,473,010	600,446	3,611,213	32,756,553	12,783,551	3,171,064	519,886
	2017	9,264,986	8,047,197	6,761,151	3,620,332	3,001,313	2,278,259	3,421,252	133,495	2,551,630	614,177	3,684,639	33,797,931	13,043,475	3,241,338	529,955
	2018	9,505,001	8,200,378	6,889,853	3,700,690	3,070,487	2,330,769	3,500,105	136,546	2,634,592	628,333	3,762,791	34,896,810	13,320,133	3,315,431	540,043
	2019	9,763,111	8,354,019	7,018,939	3,780,368	3,141,860	2,384,946	3,581,464	139,741	2,721,914	642,938	3,846,077	36,053,444	13,614,961	3,393,002	550,161
	2020	10,031,663	8,502,904	7,144,031	3,861,509	3,213,232	2,439,124	3,662,822	143,030	2,811,899	657,544	3,931,569	37,245,355	13,917,599	3,472,855	559,966
LDGT2	1995	5,589,646	2,026,431	1,702,581	1,175,290	687,169	419,293	651,703	0	527,959	134,611	528,156	6,993,144	1,869,650	1,824,371	0
	1996	5,682,084	2,109,929	1,772,735	1,209,560	689,363	420,632	653,785	0	546,445	135,040	664,752	7,238,007	2,353,197	1,821,465	0
	1997	5,825,048	2,201,275	1,849,483	1,216,283	691,007	421,635	655,344	0	568,266	135,362	700,578	7,527,034	2,480,017	1,814,358	0
	1998	5,554,769	2,755,129	2,314,824	1,287,987	699,670	426,921	663,560	0	586,122	137,059	587,929	7,763,552	2,081,245	1,963,460	0
	1999	5,780,287	2,880,686	2,420,315	1,331,415	726,726	443,430	689,219	0	602,951	142,359	606,791	7,986,463	2,148,015	2,007,989	0
	2000	5,912,484	2,962,409	2,488,978	1,370,317	752,506	459,160	713,669	0	610,909	147,410	616,102	8,091,870	2,180,975	2,029,124	0
	2001	6,079,148	3,057,629	2,568,980	1,407,979	780,780	476,412	740,483	0	622,995	152,948	627,557	8,251,955	2,221,527	2,061,241	0
	2002	6,304,282	3,172,264	2,665,295	1,444,249	809,518	493,948	767,738	0	641,102	158,578	644,181	8,491,798	2,280,374	2,113,598	0
	2003	6,523,542	3,281,556	2,757,121	1,477,398	838,916	511,885	795,618	0	660,262	164,336	660,013	8,745,579	2,336,420	2,164,462	0
	2004	6,732,561	3,379,177	2,839,141	1,506,764	867,918	529,582	823,124	0	678,971	170,018	674,080	8,993,397	2,386,217	2,212,785	0
	2005	6,952,595	3,485,133	2,928,164	1,540,815	899,535	548,874	853,109	0	699,256	176,211	688,619	9,262,079	2,437,684	2,265,447	0
	2006	7,157,618	3,591,769	3,017,758	1,575,187	930,839	567,974	882,797	0	720,845	182,343	702,377	9,548,043	2,486,387	2,317,107	0
	2007	7,334,287	3,688,510	3,099,039	1,608,990	958,460	584,828	908,993	0	741,865	187,754	715,158	9,826,463	2,531,630	2,367,645	0
	2008	7,510,069	3,795,267	3,188,735	1,643,878	987,495	602,545	936,529	0	764,726	193,442	728,203	10,129,275	2,577,811	2,419,325	0
	2009	7,665,917	3,896,739	3,273,990	1,676,563	1,015,130	619,407	962,738	0	787,478	198,855	740,235	10,430,632	2,620,402	2,468,259	0
	2010	7,793,067	4,003,705	3,363,861	1,709,917	1,041,405	635,439	987,657	0	809,679	204,002	751,598	10,724,705	2,660,628	2,517,219	0
	2011	7,935,881	4,111,677	3,454,578	1,751,633	1,069,066	652,317	1,013,890	0	833,817	209,421	764,600	11,044,421	2,706,655	2,571,094	0
	2012	8,092,052	4,219,981	3,545,574	1,796,310	1,097,762	669,827	1,041,105	0	859,905	215,042	779,245	11,389,970	2,758,498	2,629,442	0
	2013	8,255,421	4,323,905	3,632,890	1,840,560	1,126,607	687,427	1,068,462	0	887,334	220,693	794,540	11,753,293	2,812,640	2,688,647	0
	2014	8,427,800	4,424,372	3,717,301	1,884,536	1,154,916	704,701	1,095,310	0	915,857	226,238	810,270	12,131,089	2,868,322	2,749,518	0
	2015	8,611,849	4,524,138	3,801,123	1,928,492	1,181,960	721,202	1,120,958	0	945,149	231,536	826,544	12,519,090	2,925,933	2,810,031	0
	2016	8,810,826	4,617,074	3,879,207	1,971,414	1,209,229	737,841	1,146,820	0	975,252	236,878	843,140	12,917,815	2,984,683	2,871,775	0
	2017	9,024,727	4,706,499	3,954,340	2,015,592	1,236,882	754,714	1,173,046	0	1,006,256	242,295	860,284	13,328,491	3,045,370	2,935,417	0
	2018	9,258,518	4,796,089	4,029,613	2,060,330	1,265,390	772,109	1,200,082	0	1,038,973	247,879	878,531	13,761,843	3,109,964	3,002,517	0
	2019	9,509,935	4,885,948	4,105,111	2,104,690	1,294,804	790,057	1,227,978	0	1,073,409	253,641	897,976	14,217,971	3,178,800	3,072,767	0
	2020	9,771,522	4,973,025	4,178,272	2,149,865	1,324,217	808,004	1,255,873	0	1,108,896	259,403	917,937	14,688,011	3,249,459	3,145,083	0
HDGV	1995	893,377	305,432	256,620	231,986	107,948	68,902	101,913	4,485	66,297	32,888	114,374	878,145	404,881	430,869	26,416
	1996	938,315	325,123	273,164	259,016	114,392	73,015	107,997	4,429	67,718	34,852	113,969	896,969	403,447	425,564	28,119
	1997	1,031,088	358,215	300,968	259,339	120,582	76,966	113,840	4,842	80,039	36,737	125,929	1,060,168	445,783	465,208	30,981
	1998	1,041,548	353,510	297,015	256,737	140,180	89,476	132,344	5,589	72,204	42,709	137,995	956,383	488,495	536,946	30,574
	1999	1,080,309	361,741	303,930	257,455	145,638	92,959	137,496	5,731	73,564	44,371	145,317	974,402	514,417	550,607	31,286
	2000	1,118,206	369,178	310,179	257,677	150,660	96,164	142,237	5,862	74,755	45,901	152,389	990,172	539,453	563,193	31,929
	2001	1,139,997	371,525	312,151	252,826	151,262	96,549	142,805	5,896	74,747	46,085	154,810	990,073	548,020	566,487	32,132
	2002	1,161,158	373,695	313,974	248,295	151,938	96,980	143,444	5,929	74,786	46,291	157,103	990,589	556,138	569,611	32,320
	2003	1,182,498	375,446	315,445	244,982	152,783	97,520	144,242	5,963	74,924	46,548	159,551	992,412	564,805	572,925	32,471
	2004	1,203,948	376,854	316,628	242,340	153,980	98,283	145,371	6,011	75,361	46,913	162,406	998,203	574,911	577,491	32,593
	2005	1,223,155	378,824	318,283	240,401	155,437	99,214	146,747	6,054	76,074	47,357	165,606	1,007,652	586,237	581,686	32,764
	2006	1,238,955	381,111	320,205	239,407	157,312	100,410	148,517	6,100	76,951	47,928	169,002	1,019,265	598,260	586,024	32,962
	2007	1,251,103	383,153	321,920	239,490	159,461	101,782	150,547	6,152	77,977	48,583	172,479	1,032,855	610,568	591,091	33,138
	2008	1,259,333	386,490	324,724	239,293	161,745	103,240	152,703	6,195	79,075	49,279	175,970	1,047,393	622,928	595,187	33,427
	2009	1,266,244	389,795	327,500	239,412	164,112	104,751	154,938	6,241	80,252	50,000	179,492	1,062,981	635,393	599,602	33,712
	2010	1,268,967	393,399	330,529	239,575	166,575	106,323	157,263	6,293	81,537	50,750	183,156	1,080,006	648,363	604,583	34,024
	2011	1,272,819	397,319	333,823	240,082	169,121	107,948	159,666	6,353	82,954	51,526	186,940	1,098,782	661,759	610,380	34,363
	2012	1,280,445	401,928	337,695	241,789	171,997	109,784	162,381	6,430	84,500	52,402	190,859	1,119,259	675,633	617,739	34,762
	2013	1,292,308	407,246	342,163	244,358	175,108	111,770	165,319	6,525	86,176	53,350	194,916	1,141,453	689,995	626,951	35,222
	2014	1,307,378	413,100	347,081	247,525	178,432	113,891	168,456	6,634	87,971	54,363	199,068	1,165,228	704,694	637,409	35,728
	2015	1,327,275	419,858	352,759	251,203	181,861	116,080	171,694	6,751	89,770	55,407	203,162	1,189,059	719,187	648,587	36,313
	2016	1,350,851	426,753	358,553	255,621	185,445	118,368	175,078	6,877	91,584	56,499	207,211	1,213,083	733,518	660,750	36,909
	2017	1,376,982	434,150	364,768	260,147	189,074	120,684	178,504	7,008	93,416	57,605	211,273	1,237,352	747,897	673,311	37,549
	2018	1,406,408	441,939	371,312	264,831	192,840	123,088	182,060	7,143	95,301	58,752	215,406	1,262,327	762,530	686,296	38,222
	2019	1,438,855	450,500	378,505	269,752	196,746	125,581	185,747	7,284	97,236	59,942	219,625	1,287,951	777,466	699,799	38,963
	2020	1,473,614	459,317	385,912	274,975	200,799	128,168	189,574	7,431	99,226	61,177	223,910	1,314,314	792,634	713,912	39,725

Class	CY	AB	BC-LFV	LFV	MB	NB	NF	NS	NT	ON-QWC ON	PE	QC-QWC QC	QWC ON	QWC QC	SK	YT
LDDV	1995	109,508	85,569	89,330	55,790	58,324	7,452	75,521	1,513	20,412	8,970	153,887	518,293	608,209	35,565	1,678
	1996	117,815	87,140	90,970	52,603	58,949	7,532	76,330	1,623	20,576	9,066	145,742	522,461	576,018	38,158	1,709
	1997	119,925	89,796	93,743	53,402	58,149	7,430	75,294	1,688	21,051	8,943	141,472	534,527	559,140	39,683	1,761
	1998	138,423	83,352	87,015	54,253	59,318	7,579	76,808	1,541	22,310	9,123	144,976	566,488	572,989	36,235	1,634
	1999	137,554	82,777	86,416	53,504	59,267	7,573	76,742	1,514	22,512	9,115	143,440	571,618	566,918	35,600	1,623
	2000	135,926	81,336	84,910	53,068	59,452	7,596	76,981	1,484	22,561	9,144	140,988	572,864	557,228	34,896	1,595
	2001	135,880	80,329	83,859	52,816	58,148	7,430	75,293	1,461	22,563	8,943	138,649	572,913	547,985	34,346	1,575
	2002	137,081	80,192	83,716	52,605	57,304	7,322	74,199	1,456	22,808	8,813	138,497	579,137	547,383	34,233	1,572
	2003	138,881	80,202	83,727	52,749	56,845	7,263	73,605	1,464	23,201	8,743	139,234	589,110	550,294	34,415	1,573
	2004	141,146	80,197	83,722	53,172	56,570	7,228	73,249	1,481	23,693	8,700	140,567	601,600	555,564	34,825	1,573
	2005	144,573	80,642	84,186	54,062	56,702	7,245	73,420	1,512	24,349	8,721	142,652	618,267	563,804	35,545	1,581
	2006	145,852	81,005	84,565	54,657	56,741	7,250	73,471	1,535	24,629	8,727	145,038	625,366	573,233	36,084	1,588
	2007	147,121	81,273	84,846	55,403	56,797	7,257	73,543	1,563	24,907	8,735	147,567	632,426	583,229	36,742	1,594
	2008	149,051	81,815	85,411	56,440	57,084	7,294	73,915	1,598	25,258	8,779	150,588	641,338	595,169	37,585	1,604
	2009	150,823	82,292	85,909	57,535	57,303	7,322	74,199	1,636	25,589	8,813	153,689	649,755	607,426	38,466	1,614
	2010	152,742	82,945	86,591	58,711	57,572	7,356	74,547	1,676	25,925	8,854	156,826	658,273	619,822	39,412	1,626
	2011	155,690	84,036	87,729	59,625	58,244	7,442	75,417	1,708	26,426	8,958	160,352	670,992	633,759	40,158	1,648
	2012	158,757	85,279	89,028	60,552	58,933	7,530	76,309	1,741	26,948	9,064	164,045	684,248	648,355	40,940	1,672
	2013	161,860	86,647	90,455	61,460	59,576	7,612	77,142	1,774	27,467	9,163	167,771	697,436	663,084	41,712	1,699
	2014	164,952	88,162	92,037	62,333	60,202	7,692	77,952	1,806	27,996	9,259	171,587	710,860	678,163	42,467	1,729
	2015	168,035	89,840	93,789	63,207	60,823	7,771	78,757	1,838	28,548	9,354	175,530	724,869	693,748	43,217	1,762
	2016	171,141	91,612	95,639	64,037	61,452	7,852	79,571	1,869	29,117	9,451	179,557	739,336	709,665	43,950	1,796
	2017	174,247	93,433	97,540	64,846	62,061	7,930	80,359	1,899	29,700	9,545	183,649	754,123	725,837	44,661	1,832
	2018	177,422	95,326	99,516	65,643	62,678	8,008	81,158	1,930	30,304	9,640	187,865	769,481	742,499	45,370	1,869
	2019	180,664	97,274	101,549	66,412	63,283	8,086	81,942	1,960	30,931	9,733	192,210	785,387	759,671	46,076	1,907
	2020	183,881	99,203	103,563	67,156	63,853	8,159	82,680	1,989	31,567	9,820	196,569	801,527	776,902	46,759	1,945
LDDT	1995	1,296,392	886,421	279,840	281,549	142,173	37,364	152,356	2,960	291,456	21,382	540,254	1,043,847	1,038,728	553,183	39,566
	1996	1,451,900	1,023,006	322,959	364,176	152,336	40,035	163,246	3,111	300,018	22,910	546,725	1,074,512	1,051,169	581,412	45,663
	1997	1,605,778	1,130,404	356,865	339,046	167,625	44,053	179,631	3,380	330,725	25,209	604,697	1,184,490	1,162,630	631,612	50,457
	1998	1,336,805	949,628	299,794	405,235	135,881	35,710	145,613	3,379	316,686	20,435	528,776	1,134,208	1,016,659	631,401	42,388
	1999	1,412,060	976,274	308,206	429,574	137,021	36,010	146,835	3,571	323,591	20,607	534,975	1,158,938	1,028,579	667,362	43,577
	2000	1,478,489	1,001,287	316,103	452,118	137,756	36,203	147,623	3,744	329,308	20,717	538,881	1,179,412	1,036,088	699,701	44,693
	2001	1,546,700	1,027,677	324,434	474,900	138,860	36,493	148,806	3,914	335,497	20,883	542,954	1,201,578	1,043,920	731,414	45,871
	2002	1,609,422	1,051,911	332,084	496,522	140,069	36,811	150,101	4,065	341,577	21,065	546,612	1,223,356	1,050,952	759,569	46,953
	2003	1,664,725	1,074,430	339,194	516,471	141,251	37,121	151,367	4,198	347,059	21,243	549,593	1,242,990	1,056,685	784,582	47,958
	2004	1,712,535	1,095,592	345,874	533,806	142,426	37,430	152,626	4,307	352,319	21,420	552,508	1,261,827	1,062,288	804,899	48,903
	2005	1,753,200	1,113,013	351,374	548,980	143,440	37,697	153,713	4,389	357,327	21,572	554,869	1,279,764	1,066,827	820,270	49,680
	2006	1,786,791	1,127,234	355,864	561,984	144,225	37,903	154,555	4,445	361,888	21,690	556,850	1,296,097	1,070,636	830,586	50,315
	2007	1,813,317	1,139,285	359,668	572,939	144,867	38,072	155,242	4,480	366,178	21,787	558,632	1,311,462	1,074,064	837,243	50,853
	2008	1,833,339	1,150,591	363,237	582,014	145,481	38,233	155,901	4,496	370,363	21,879	560,661	1,326,450	1,077,964	840,100	51,358
	2009	1,848,733	1,158,863	365,849	589,595	146,059	38,385	156,520	4,499	374,320	21,966	562,667	1,340,624	1,081,821	840,785	51,727
	2010	1,860,905	1,164,677	367,684	596,089	146,634	38,536	157,136	4,496	378,145	22,053	565,075	1,354,323	1,086,450	840,201	51,986
	2011	1,874,241	1,173,691	370,530	604,281	147,612	38,793	158,184	4,498	382,807	22,200	569,137	1,371,022	1,094,260	840,629	52,389
	2012	1,886,958	1,181,404	372,965	612,714	148,697	39,078	159,346	4,507	387,601	22,363	573,890	1,388,189	1,103,400	842,208	52,733
	2013	1,899,842	1,189,553	375,538	620,963	149,930	39,402	160,668	4,521	392,343	22,548	578,982	1,405,172	1,113,189	844,830	53,097
	2014	1,912,621	1,197,587	378,074	628,988	151,313	39,766	162,151	4,541	397,205	22,756	584,512	1,422,586	1,123,821	848,501	53,455
	2015	1,925,617	1,208,007	381,364	637,221	152,767	40,148	163,708	4,566	402,206	22,975	590,446	1,440,498	1,135,231	853,298	53,921
	2016	1,939,002	1,218,162	384,569	645,318	154,159	40,514	165,200	4,599	407,199	23,184	596,646	1,458,379	1,147,152	859,457	54,374
	2017	1,952,762	1,229,885	388,270	653,255	155,414	40,844	166,545	4,635	412,181	23,373	602,962	1,476,223	1,159,295	866,225	54,897
	2018	1,967,238	1,242,041	392,108	661,338	156,702	41,182	167,925	4,675	417,325	23,567	609,558	1,494,647	1,171,977	873,630	55,440
	2019	1,982,309	1,255,708	396,422	669,188	158,011	41,526	169,328	4,718	422,640	23,763	616,435	1,513,683	1,185,200	881,707	56,050
	2020	1,997,794	1,269,806	400,873	677,127	159,334	41,874	170,745	4,765	428,171	23,962	623,593	1,533,490	1,198,962	890,388	56,679
HDDV	1995	6,638,361	4,121,803	1,301,239	1,810,349	1,595,760	561,705	1,278,439	48,964	2,811,512	246,381	3,422,980	10,069,408	6,581,247	2,200,820	154,571
	1996	6,972,283	4,387,541	1,385,131	2,021,282	1,691,014	595,235	1,354,752	48,361	2,871,782	261,088	3,410,858	10,285,263	6,557,941	2,173,725	164,536
	1997	7,661,648	4,834,119	1,526,114	2,023,810	1,782,513	627,442	1,428,057	52,867	3,394,287	275,215	3,768,783	12,156,613	7,246,111	2,376,219	181,283
	1998	7,739,366	4,770,624	1,506,069	2,003,500	2,072,236	729,424	1,660,168	61,019	3,062,004	319,948	4,129,884	10,966,542	7,940,387	2,742,649	178,902
	1999	8,027,386	4,881,700	1,541,136	2,009,103	2,152,919	757,825	1,724,806	62,571	3,119,695	332,405	4,349,037	11,173,163	8,361,746	2,812,426	183,068
	2000	8,308,990	4,982,065	1,572,820	2,010,839	2,227,149	783,954	1,784,275	64,002	3,170,183	343,866	4,560,693	11,353,985	8,768,690	2,876,712	186,831
	2001	8,470,912	5,013,734	1,582,818	1,972,980	2,236,045	787,085	1,791,403	64,376	3,169,868	345,239	4,633,121	11,352,856	8,907,945	2,893,541	188,019
	2002	8,628,151	5,043,018	1,592,063	1,937,620	2,246,042	790,604	1,799,412	64,731	3,171,520	346,783	4,701,754	11,358,773	9,039,904	2,909,497	189,117
	2003	8,786,719	5,066,645	1,599,522	1,911,767	2,258,538	795,002	1,809,423	65,108	3,177,357	348,712	4,775,024	11,379,679	9,180,777	2,926,425	190,003
	2004	8,946,107	5,085,647	1,605,521	1,891,151	2,276,225	801,228	1,823,593	65,626	3,195,895	351,443	4,860,466	11,446,074	9,345,053	2,949,747	190,716
	2005	9,088,823	5,112,228	1,613,912	1,876,017	2,297,765	808,810	1,840,849	66,103	3,226,148	354,769	4,956,225	11,554,423	9,529,165	2,971,172	191,713
	2006	9,206,232	5,143,104	1,623,660	1,868,260	2,325,486	818,568	1,863,058	66,596	3,263,330	359,049	5,057,867	11,687,590	9,724,589	2,993,329	192,870
	2007	9,296,496	5,170,651	1,632,357	1,868,909	2,357,261	829,753	1,888,515	67,172	3,306,840	363,955	5,161,925	11,843,422	9,924,659	3,019,211	193,903
	2008	9,357,652	5,215,687	1,646,574	1,867,371	2,391,021	841,636	1,915,561	67,637	3,353,387	369,167	5,266,421	12,010,128	10,125,568	3,040,136	195,592
	2009	9,409,006	5,260,283	1,660,653	1,868,301	2,426,015	853,954	1,943,596	68,139	3,403,294	374,570	5,371,803	12,188,869	10,328,184	3,062,688	197,265
	2010	9,429,236	5,308,922	1,676,008	1,869,575	2,462,418	866,768	1,972,761	68,705	3,457,800	380,191	5,481,456	12,384,083	10,539,010	3,088,127	199,089
	2011	9,457,861	5,361,830	1,692,711	1,873,533	2,500,053	880,015	2,002,912	69,364	3,517,914	386,001	5,594,703	12,599,382	10,756,747	3,117,738	201,073
	2012	9,514,528	5,424,029	1,712,347	1,886,854	2,542,567	894,980	2,036,972	70,200	3,583,476	392,566	5,711,998	12,834,192	10,982,266	3,155,325	203,405
	2013	9,602,678	5,495,786	1,735,000	1,906,898	2,588,565	911,171	2,073,823	71,247	3,654,532	399,667	5,833,425	13,088,679	11,215,729	3,202,379	206,096
	2014	9,714,657	5,574,787	1,759,941	1,931,612	2,637,689	928,463	2,113,178	72,436	3,730,653	407,252	5,957,691	13,361,306	11,454,651	3,255,799	209,059
	2015	9,862,502	5,665,986	1,788,732	1,960,312	2,688,385	946,308	2,153,794	73,706	3,806,952	415,079	6,080,217	13,634,570	11,690,227	3,312,894	212,479
	2016	10,037,692	5,759,041	1,818,109	1,994,791	2,741,367	964,958	2,196,241	75,088	3,883,869	423,260	6,201,381	13,910,044	11,923,185	3,375,019	215,969
	2017	10,231,863	5,858,864	1,849,623	2,030,112	2,795,017	983,842	2,239,221	76,515	3,961,567	431,543	6,322,938	14,188,320	12,156,899	3,439,182	219,712
	2018	10,450,510	5,963,978	1,882,807	2,066,666	2,850,691	1,003,439	2,283,825	77,991	4,041,528	440,139	6,446,653	14,474,700	12,394,761	3,505,505	223,654
	2019	10,691,616	6,079,508	1,919,279	2,105,069	2,908,422	1,023,761	2,330,076	79,526	4,123,567	449,053	6,572,924	14,768,524	12,637,538	3,574,480	227,986
	2020	10,949,897	6,198,484	1,956,840	2,145,826	2,968,346	1,044,854	2,378,084	81,129	4,207,974	458,305	6,701,162	15,070,827	12,884,098	3,646,565	232,448
MC	1995	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	1996	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	1997	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	1998	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	1999	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2000	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2001	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2002	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2003	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2004	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2005	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2006	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2007	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2008	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2009	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2010	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2011	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2012	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2013	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2014	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2015	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2016	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2017	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2018	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2019	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090
	2020	89,991	62,984	85,939	26,874	26,375	18,272	32,886	4,055	24,677	3,912	33,790	257,865	153,303	12,257	2,090

Attachment 3

Emission Inventories

Canadian Emissions from Gaoline Vehicles (Tonnes/Yr)

Figs 24-26	No MMT CY2004-/No MMT CY2008+ (MMT-0)			MMT CY2004-/No MMT CY2008+ (MMT-1)			MMT CY2004-/MMT CY2008+ (MMT-2)		
CY	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**
2007	255,606	3,832,496	203,921	289,976	4,083,619	187,826	289,976	4,083,619	187,826
2008	234,575	3,683,633	189,941	269,128	3,961,103	175,871	269,128	3,961,103	175,871
2009	216,977	3,532,550	176,286	250,888	3,828,107	164,535	260,453	4,017,017	165,551
2010	200,404	3,397,052	162,637	232,989	3,702,437	153,294	252,279	4,068,627	155,718
2011	186,234	3,291,544	150,336	217,043	3,598,635	143,276	246,328	4,141,181	147,396
2012	163,172	3,039,197	134,057	191,808	3,338,963	129,049	231,193	4,059,048	135,069
2013	154,027	2,992,547	124,202	180,089	3,273,247	120,773	229,563	4,169,992	128,681
2014	146,328	2,959,758	115,498	169,598	3,209,448	113,008	228,940	4,278,722	122,646
2015	140,204	2,945,895	108,237	160,630	3,157,847	106,259	229,447	4,392,658	117,397
2016	134,696	2,932,234	101,408	152,454	3,104,903	99,664	230,069	4,493,348	112,038
2017	130,487	2,936,236	96,047	145,843	3,072,442	94,372	231,313	4,600,260	107,827
2018	126,757	2,937,108	91,359	140,086	3,042,396	89,725	232,572	4,695,323	104,094
2019	124,457	2,955,933	88,283	138,924	3,023,393	85,363	237,979	4,788,455	100,279
2020	121,062	2,986,274	86,402	133,553	3,037,283	83,769	238,237	4,903,985	99,479

Canadian Emissions from Gaoline Vehicles (Tonnes/Yr)

Figs 27-29	No MMT (MMT-0)			MMT-80% (MMT-3)			MMT-20% (MMT-5)			MMT-50% (MMT-4)		
CY	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**
2007	255,606	3,832,496	203,921	289,976	4,083,619	187,826	289,976	4,083,619	187,826	272,780	3,958,156	195,866
2008	234,575	3,683,633	189,941	262,228	3,905,675	178,687	241,479	3,738,945	187,129	251,844	3,822,271	182,916
2009	216,977	3,532,550	176,286	251,757	3,920,159	167,706	225,675	3,629,168	174,145	238,721	3,774,742	170,908
2010	200,404	3,397,052	162,637	241,914	3,934,253	157,083	210,791	3,531,471	161,252	226,340	3,732,672	159,181
2011	186,234	3,291,544	150,336	234,299	3,971,225	147,970	198,241	3,461,453	149,746	216,278	3,716,200	148,865
2012	163,172	3,039,197	134,057	217,594	3,855,069	134,870	176,775	3,243,210	134,258	197,193	3,549,151	134,578
2013	154,027	2,992,547	124,202	214,455	3,934,410	127,777	169,136	3,228,187	125,109	191,800	3,581,274	126,455
2014	146,328	2,959,758	115,498	212,405	4,014,980	121,203	162,843	3,223,595	116,927	187,629	3,619,360	119,060
2015	140,204	2,945,895	108,237	211,613	4,103,192	115,565	158,073	3,235,148	110,062	184,835	3,669,214	112,812
2016	134,696	2,932,234	101,408	211,006	4,181,051	109,904	153,758	3,244,518	103,524	182,373	3,712,937	106,726
2017	130,487	2,936,236	96,047	211,149	4,267,304	105,457	150,645	3,268,977	98,386	180,916	3,768,163	101,944
2018	126,757	2,937,108	91,359	211,418	4,343,619	101,546	147,924	3,288,512	93,885	179,664	3,816,254	97,727
2019	124,457	2,955,933	88,283	215,305	4,421,671	97,907	147,154	3,322,436	90,707	181,231	3,872,207	94,299
2020	121,062	2,986,274	86,402	214,816	4,520,278	96,870	144,499	3,369,730	89,026	179,632	3,945,086	92,936

Canadian Emissions from Gaoline Vehicles (Tonnes/Yr)

Figs 30-32	No MMT (MMT-0)			MMT(80%/0.031) (MMT-3)			MMT(80%/0.023) (MMT-6)		
CY	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**
2007	255,606	3,832,496	203,921	283,101	4,033,504	191,031	275,997	3,981,619	194,356
2008	234,575	3,683,633	189,941	262,228	3,905,675	178,687	255,080	3,848,286	181,581
2009	216,977	3,532,550	176,286	251,757	3,920,159	167,706	242,781	3,820,079	169,912
2010	200,404	3,397,052	162,637	241,914	3,934,253	157,083	231,190	3,795,665	158,522
2011	186,234	3,291,544	150,336	234,299	3,971,225	147,970	221,893	3,795,766	148,589
2012	163,172	3,039,197	134,057	217,594	3,855,069	134,870	203,555	3,644,445	134,661
2013	154,027	2,992,547	124,202	214,455	3,934,410	127,777	198,857	3,691,409	126,870
2014	146,328	2,959,758	115,498	212,405	4,014,980	121,203	195,360	3,742,779	119,742
2015	140,204	2,945,895	108,237	211,613	4,103,192	115,565	193,189	3,804,497	113,671
2016	134,696	2,932,234	101,408	211,006	4,181,051	109,904	191,310	3,858,831	107,719
2017	130,487	2,936,236	96,047	211,149	4,267,304	105,457	190,340	3,923,825	103,031
2018	126,757	2,937,108	91,359	211,418	4,343,619	101,546	189,562	3,980,614	98,926
2019	124,457	2,955,933	88,283	215,305	4,421,671	97,907	191,859	4,043,615	95,426
2020	121,062	2,986,274	86,402	214,816	4,520,278	96,870	190,606	4,124,250	94,169

Canadian Emissions from Gaoline Vehicles (Tonnes/Yr)

Figs 33-35	No MMT (MMT-0)			MMT(80%/0.031) (MMT-3)			MMT(80%/0.031/10%Clogged) (MMT-7)		
CY	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**	**VOC**	**CO**	**NOx**
2007	255,606	3,832,496	203,921	283,101	4,033,504	191,031	291,277	4,072,499	218,897
2008	234,575	3,683,633	189,941	262,228	3,905,675	178,687	270,167	3,945,913	205,687
2009	216,977	3,532,550	176,286	251,757	3,920,159	167,706	259,486	3,949,782	194,500
2010	200,404	3,397,052	162,637	241,914	3,934,253	157,083	249,277	3,960,401	183,085
2011	186,234	3,291,544	150,336	234,299	3,971,225	147,970	241,240	3,994,040	172,880
2012	163,172	3,039,197	134,057	217,594	3,855,069	134,870	224,064	3,874,888	158,475
2013	154,027	2,992,547	124,202	214,455	3,934,410	127,777	220,441	3,951,528	150,046
2014	146,328	2,959,758	115,498	212,405	4,014,980	121,203	217,930	4,029,537	142,238
2015	140,204	2,945,895	108,237	211,613	4,103,192	115,565	216,687	4,116,082	135,503
2016	134,696	2,932,234	101,408	211,006	4,181,051	109,904	215,769	4,192,557	128,966
2017	130,487	2,936,236	96,047	211,149	4,267,304	105,457	215,732	4,277,728	123,759
2018	126,757	2,937,108	91,359	211,418	4,343,619	101,546	215,863	4,353,141	119,258
2019	124,457	2,955,933	88,283	215,305	4,421,671	97,907	220,593	4,433,387	116,645
2020	121,062	2,986,274	86,402	214,816	4,520,278	96,870	219,874	4,530,725	115,120