Tier 2/LEV II Emission Control Technologies for Light-Duty Gasoline Vehicles

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Executive Summary

In response to continued public health concerns associated with ground level ozone and toxic hydrocarbon components of vehicle exhaust, the U.S. Environmental Protection Agency and California Air Resources Board established the Tier 2 and LEV II emission regulations, respectively, for light-duty vehicles in the late 1990s that began implementation starting with the 2004 model year. These regulatory programs established a single set of fuel neutral, vehicle emission certification categories that auto manufacturers can select from for the broad weight range of light-duty cars and trucks that make-up the light-duty vehicle segment (up to 8500 lbs. GVW for all light-duty cars and trucks, and up to 10,000 lbs. GVW for passenger carrying trucks). The Tier 2 and LEV II requirement established significantly lower levels of hydrocarbon and NOx emission levels with extended durability requirements (e.g., 120,000 miles) compared to the previous emission regulations for light-duty cars and trucks. Manufacturers must comply with not only the selected certification category emission limits but also meet fleet average emission limits: an oxides of nitrogen (NOx) emission fleet average in the case of Tier 2 and a non-methane organic gas (NMOG) emission fleet average in the case of LEV II. As part of these light-duty rulemaking efforts, both California and the EPA also established limits on gasoline fuel sulfur levels, a known catalyst deactivation agent. California's 15 ppm average gasoline sulfur level requirement began in 2004 and EPA's 30 ppm average gasoline sulfur level phase-in began in 2005.

To achieve the emission requirements of the Tier 2 and LEV II programs, a systems engineering and optimization effort is required combining advanced engines, advanced engine control strategies, with advanced emission control technologies. Interest in high performance emission systems, along with the interest in lowering future light-duty vehicle emission standards, drove the development of advanced emission controls during the late 1980s and 1990s. The results of these developments are a number of key emission control technologies that manufacturers will rely on heavily for Tier 2/LEV II compliance. Included in these key technologies are close-coupled converters, high cell density substrates, and advanced three-way catalysts. The maximum performance benefits for each of these advanced emission technologies result from combining these technologies with optimized engine operating strategies and high quality fuels and lubricants that are compatible with these high emission conversion efficiency components.

Close-coupled converters facilitate the fast converter heat-up necessary to significantly reduce emissions within seconds after the engine is started. Tier 1 compliant light-duty vehicles, for example, are characterized by high cold-start emissions, especially with respect to hydrocarbons. Converter locations close to the exit of the exhaust manifold ensure the efficient and quick transfer of combustion heat to the catalyst, resulting in fast dynamic light-off and the resulting high catalytic efficiencies necessary to reduce cold-start emissions. Engine cold-start strategies aimed at accelerating converter heat-up, including spark retard during engine start and lean air/fuel engine start strategies, are used to complement and enhance the performance of close-coupled converters during the first few critical seconds following engine start.

High cell density ceramic and metallic substrates provide significant increases in substrate geometric surface area versus standard designs used in Tier 1 and earlier model light-duty vehicles. Larger substrate geometric surface area translates into more efficient contact between the exhaust gas constituents and active catalyst components displayed on the substrate channel walls. The result is more emission conversion efficiency per unit volume of substrate as cell densities are increased. Increasing the substrate channel density also results in smaller channel flow dimensions, which in turn improves mass transfer between the flowing exhaust gas and active catalyst sites on the walls of the substrate. Manufacturers have also developed high cell density substrate designs that utilize thinner ceramic or metallic walls separating flow channels. In this way, the overall mass of a given sized substrate is reduced relative to older designs with lower cell density and thicker wall dimensions. The resulting lower thermal mass is able to heat-up quicker during critical start-up operations and contribute to improved performance during cold and warm-start driving modes, making these advanced high cell density substrates ideal for close-coupled converter applications.

Through the use of advanced, thermally stable support and promoter materials, improved precious metal impregnation strategies, and sophisticated catalyst coating architectures, the performance of today's advanced three-way catalysts are far beyond performance levels used with Tier 1 light-duty vehicles. These advanced three-way catalysts offer improved light-off properties, wider air/fuel windows of operation, higher NOx conversion efficiencies, and improved long term durability in higher temperature operating environments. These improvements have been extended to catalysts that utilize one or more of the preferred catalytically active precious metals used in automotive catalysts (i.e., Pt, Pd, Rh). Additional system performance benefits have been achieved by combining advanced three-way catalysts with advanced engine controls that, for example, closely control the input air/fuel ratio at the catalyst inlet.

Numerous published studies have reported on the characteristics and performance benefits of these new generations of advanced emission control technologies and the synergies realized by combining these technologies with advanced engine operating strategies. MECA completed a study in 1998 that demonstrated the ability of advanced catalysts, high cell density substrates, close-coupled converters, and other technologies combined with appropriate engine controls and low sulfur gasoline to achieve Tier 2, Bin 5 and LEV II LEV emission levels on four different Tier 1 certified light-duty vehicles, including two passenger cars and two trucks (with simulated high mileage emission systems aged using an accelerated engine dynamometer schedule). A second MECA study completed in 2006 demonstrated similar advanced emission control technologies on two large light-duty trucks. In this program, these SUV-class light-duty trucks achieved exhaust emissions significantly below LEV II ULEV standards with engine-aged emission systems.

The current large volume demand for high performance emission technologies and the future forecasts for growth of these advanced technologies around the globe in light-duty vehicle applications are clear indications that the emission performance benefits associated with advanced emission control technologies are an integral part of the systems approach required to bring light-duty vehicles in compliance with extremely low emission standards like the EPA Tier 2 and California LEV II programs.

1.0 Introduction

Light-duty motor vehicle tailpipe emission regulations have been pushed to lower levels in many world markets since the late 1990s in response to public health concerns. At the forefront of these new waves of regulatory programs aimed at significantly reducing emissions from light-duty vehicles are the U.S. Environmental Protection Agency's (EPA) Tier 2 and the California Air Resource Board's (ARB) Low Emission Vehicle II (LEV II) programs. California acted first, adopting their LEV II program in late 1998, followed by EPA finalizing the Tier 2 regulations in December 1999. In a parallel or slightly delayed timeframe relative to these U.S. initiatives, Europe (Euro 3 and Euro 4 regulations), Japan (Japan Low Emission Vehicle regulations), and Korea (Korea Low Emission Vehicle regulations) also established new, more severe light-duty emission regulations.

All of these new light-duty emission programs require significant reductions in hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NOx) emissions relative to vehicle emission requirements associated with the regulations that precede each of these new emission programs (e.g., EPA's Tier 1 or California LEV I regulations). An important input into each of these regulatory processes was the ability of emission control technologies to meet these increasingly tighter tailpipe emission standards in a cost effective manner.

This paper reviews details of the Tier 2 and LEV II programs, and highlights emission control technologies that will be an integral part of the overall engineered systems approach necessary for the wide weight-range of light-duty vehicles to comply with Tier 2/LEV II tailpipe emission levels. In particular the discussion will focus on advanced three-way catalysts (TWCs) and advanced substrates designed to achieve the high conversion efficiencies of regulated pollutants over extended vehicle mileage associated with meeting Tier 2/LEV II regulations.

Full useful life tailpipe emission standards for the fully phased-in Tier 2 and LEV II programs are summarized in Tables 1 and 2, respectively. Each of these programs provides auto manufacturers with several different certification categories to choose from for their light-duty vehicle fleet. The concept of multiple certification categories was first introduced with ARB's LEV I program in the 1994 model year with Transitional Low Emission Vehicle (TLEV), Low Emission Vehicle (LEV), and Ultra-Low Emission Vehicle (ULEV) certification options that varied by vehicle weight class (e.g., passenger car and light-duty truck weight classes). The EPA Tier 1 light-duty emission regulations also have weight class specific emission regulations but only one set of emission standards for each gasoline vehicle weight class. The Tier 2/LEV II programs have several common features that are also significant changes from either Tier 1 or LEV I requirements: 1) fuel neutral requirements (emission standards are equivalent for gasoline and diesel-fueled vehicles); 2) 120,000 mile full useful life durability; and 3) a single set of standards that does not vary with light-duty vehicle weight class (up to 8500 lb. gross vehicle weight [GVW] for all passenger cars and light-duty trucks; up to 10,000 lb. GVW for medium-duty passenger vehicles [MDPVs]). Treating passenger cars and light-duty trucks on an equivalent emissions basis is an important focus for both the Tier 2 and LEV II programs.

Table 1. California LEV II 120,000 mile tailpipe emission limits

Certification Level	*NMOG (g/mi)*	*CO (g/mi)*	*NOx (g/mi)*
LEV-2	0.090	4.2	0.07
LEV-2/LDT2*	0.090	4.2	0.10
ULEV-2	0.055	2.1	0.07
SULEV	0.010	1.0	0.02

* the LEV-2/LDT2 certification category is limited to no more than 4% of the LDT2 light-duty truck production for a given manufacturer

Table 2. EPA Tier 2 120,000 mile tailpipe emission limits

Certification Level	*NMOG (g/mi)*	*CO (g/mi)*	*NOx (g/mi)*
Bin 1	0.0	0.0	0.0
Bin 2	0.010	2.1	0.02
Bin 3	0.055	2.1	0.03
Bin 4	0.070	2.1	0.04
Bin 5	0.090	4.2	0.07
Bin 6	0.090	4.2	0.10
Bin 7	0.090	4.2	0.15
Bin 8	0.125	4.2	0.20

The LEV II regulations maintain hydrocarbon emission levels established in the LEV I program but significantly reduce NOx emission requirements compared to LEV I requirements. For example, LEV 2 and ULEV 2 certification categories require 0.07 g/mi NOx emissions after 120,000 miles of operation compared to 0.30 g/mi NOx for LEV I and ULEV I categories after 100,000 miles. This represents more than a 70% reduction with respect to NOx emissions for these LEV II categories relative to the LEV I levels.

The Tier 2 program draws from both the California LEV I and LEV II programs in significantly tightening both HC and NOx tailpipe emissions relative to Tier 1 regulations that were first implemented with the 1994 model year. In the Tier 2 program, certification categories are labeled as numbered “bins” rather than with specific titles as in the LEV I and LEV II programs. Table 3 provides a comparison of Tier 2, Bin 5 120,000 mile emission standards versus full useful life (either 100,000 miles or 120,000 miles depending on vehicle weight) gasoline passenger car and light-duty truck emission levels required under the Tier 1 program. Bin 5 is chosen in this comparison since the NOx limits associated with Bin 5 are equivalent to the corporate fleet average NOx requirement that is also required as a part of the Tier 2 regulatory program (The fleet average requirements of both the LEV II and Tier 2 programs are discussed later in this section.). Tier 2, Bin 5 emissions performance provides anywhere from 70% to 84% lower hydrocarbon tailpipe emissions and from 90% to 95% lower tailpipe NOx emissions than hydrocarbon or NOx levels associated with the Tier 1 limits.

Manufacturers are provided additional certification flexibilities under the Tier 2 program through the choice of eight different "bins," each with their associated tailpipe emission requirements. Several of these bins are intentionally equivalent to LEV II certification categories (with respect to NMOG [non-methane organic gas] and NOx emission limits) in an effort to harmonize some aspects of the Tier 2 program with California's LEV II program. For example, Bin 5 is equivalent to the LEV II category and Bin 2 NMOG and NOx limits are equivalent to the SULEV category. In both the Tier 2 and LEV II programs manufacturers, besides certifying vehicles in one of the available categories detailed in Tables 1 and 2, must also meet a corporate average emission requirement for the entire fleet of vehicles sold in a given model year.

In the California program this corporate average emission requirement is based on non-methane organic gas (NMOG) emissions, while NOx emissions are used for fleet averaging in the federal Tier 2 program. Fleet average NMOG emissions have been set by ARB on a declining scale for each model year to gradually force manufacturers to produce more and more of their California vehicles in the lower emission certification categories. For example, the fleet average NMOG requirement for vehicles up to 3750 lb. loaded vehicle weight (LVW) is 0.053 g/mi NMOG (based on the 50,000 mile emission requirements) in model year 2004, declining to 0.035 g/mi (based on the 50,000 mile emission requirements) in model year 2010. In comparison, the fully phased-in Tier 2 program has a single 0.07g/mi fleet average NOx requirement (based on full useful life limits) for all light-duty vehicles produced by a given manufacturer that fall under the Tier 2 requirements (The Tier 2 NOx fleet average requirement is fully phased-in with model year 2009 vehicles.). In each case vehicles certified to categories above the average NMOG or NOx fleet average requirement must be compensated by production of vehicles certified to emission categories below the fleet average.

Table 3. Tier 2, Bin 5 vs. Tier 1 light-duty gasoline tailpipe emission limits (full useful life)

Certification Level	*NMOG or NMHC (g/mi)*	*CO (g/mi)*	*NOx (g/mi)*
Tier 2, Bin 5	0.09	4.2	0.07
Tier 1, 0-3750 lb. LVW (GVWR up to 6000 lb.)	0.31	4.2	0.60
Tier 1, 3751-5750 lb. LVW (GVWR up to 6000 lb.)	0.40	5.5	0.97
Tier 1, 3751-5750 lb. LVW (GVWR > 6000 lb.)	0.46	6.4	0.98
Tier 1, > 5750 lb. LVW (GVWR > 6000 lb.)	0.56	7.3	1.53

Implementation of both the Tier 2 and LEV II programs begins with model year 2004. Phase-in for the LEV II program is complete in model year 2007 while the Tier 2 program is not fully phased-in until model year 2009. The Tier 2 program has additional flexibilities associated with its phase-in such as interim certification bins and higher fleet average NOx requirements as a function of vehicle weight in the early implementation phases of the program. Complete details of the Tier 2 program are available from the EPA website: www.epa.gov/otaq/tr2home.htm. Similarly more complete information regarding the ARB LEV II regulations is available at: www.arb.ca.gov/msprog/levprog/levii/levii.htm.

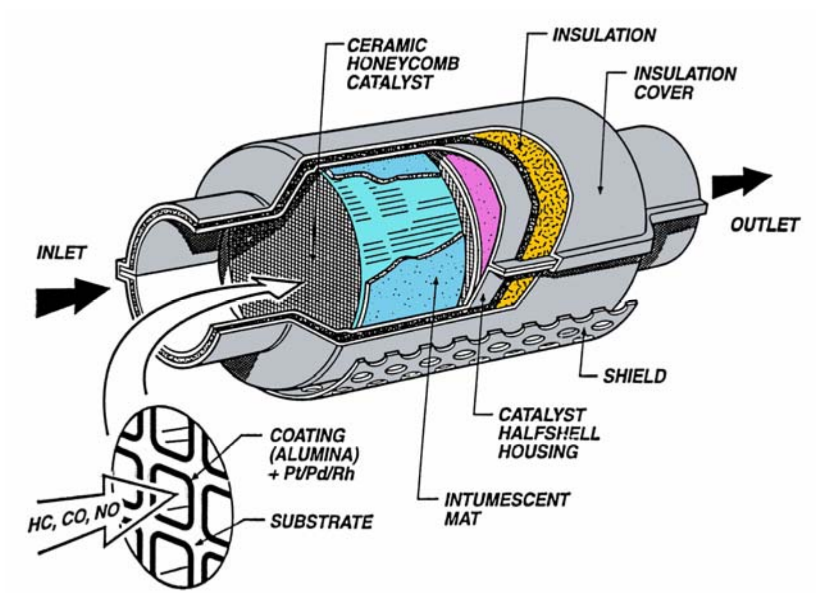
Reaching the tailpipe emission levels associated with the Tier 2 and LEV II regulations summarized in Tables 1 and 2 requires a concerted systems approach that includes the use of advanced spark ignited engines, advanced engine control strategies, clean fuels, clean lubricants, and advanced emission control technologies. Both ARB and EPA have included the clean fuel component in their regulatory efforts with respect to gasoline sulfur levels. The negative impacts of fuel sulfur levels on three-way catalyst performance have been well documented. ARB established a 30 ppm sulfur average for gasoline as a part of their California Phase II reformulated gasoline requirements. This sulfur level will be further reduced to an average of 15 ppm sulfur starting in 2004 with the introduction of California Phase III reformulated gasoline regulations (In fact, most gasoline in California is already produced to the Phase III specifications.). Similarly, the EPA included gasoline sulfur level regulations as an integral part of their Tier 2 regulatory package with the phase-in of 30 ppm average S levels beginning in 2005. Lubricant constituents such as phosphorus and inorganic elements such as Zn and Ca have also been shown to act as catalyst poisons or catalyst masking agents driving lubricant producers to optimize lubricant formulations to insure adequate engine lubrication characteristics with minimal impacts on catalyst performance and driving engine designers to minimize engine oil consumption characteristics of advanced engines. Clean fuels and clean lubricants are a necessary pre-requisite for maintaining the high performance levels of the advanced engine and emission systems required for Tier 2/LEV II compliance.

In the following sections, the characteristics and performance of important emission control technologies such as advanced catalysts and substrates are summarized. Examples are included of the combination of these and other advanced emission control components with advanced engines, calibration strategies, and low sulfur fuel to meet the tailpipe emission targets needed to comply with Tier 2 and LEV II regulations. The paper includes an extensive reference list of SAE technical papers published by automobile manufacturers, emission control technology developers and others from 1998 through early 2003 that have documented the performance characteristics of advanced TWCs and advanced substrate designs aimed at Tier 2 and LEV II light-duty vehicle applications.

2.0 Emission Control Technologies for Light-Duty Gasoline Vehicles

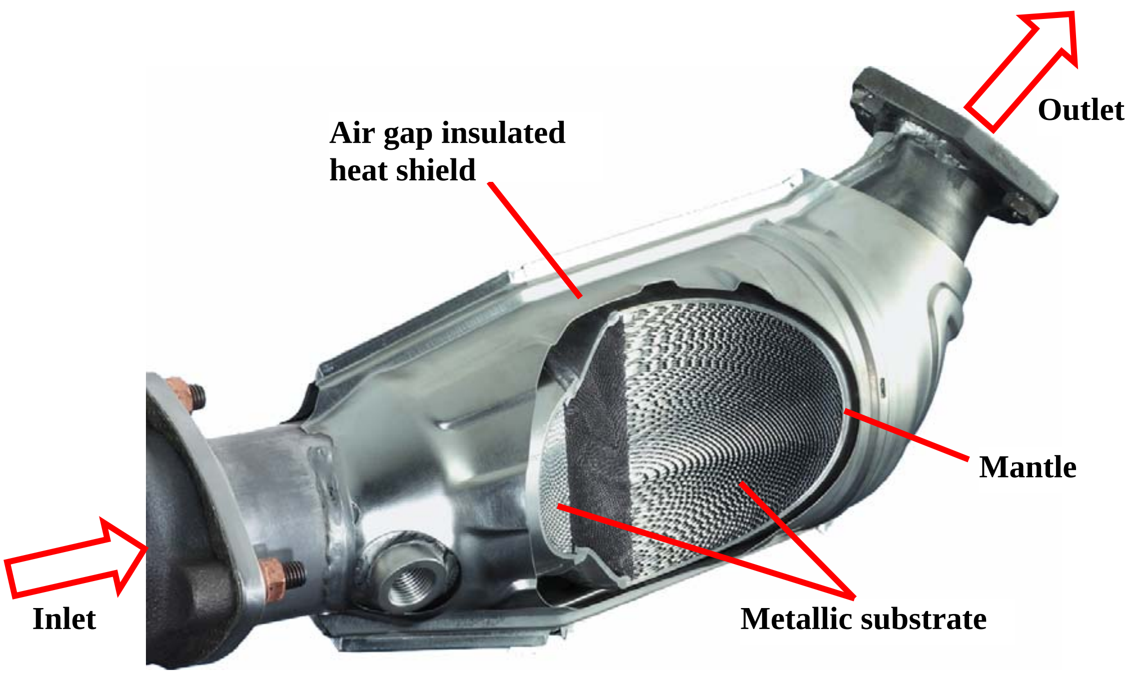
The three-way catalytic converter (TWC) has been the primary emission control technology on light-duty gasoline vehicles since the early 1980s. The use of TWCs, in conjunction with an oxygen sensor-based closed-loop fuel delivery system, allows for simultaneous conversion of the three criteria pollutants, hydrocarbons, CO, and NOx, produced during the combustion process of an internal combustion, spark ignited engine. The conversion of these three pollutants is maximized by controlling operation of the gasoline-fueled engine near the stoichiometric air/fuel (A/F) condition through the use of the oxygen sensor control loop. Figures 1 and 2 depict a cut-away drawing and a cut-away photo of typical three-way catalytic converters, one with ceramic substrates and one with metallic substrates. The active catalytic materials are present as a thin coating of precious metals (e.g., Pt, Pd, Rh), and oxide-based inorganic promoters and support materials on the internal walls of the honeycomb substrate. The substrate typically provides a large number of parallel flow channels to allow for sufficient contacting area between the exhaust gas and the active catalytic materials without creating excess pressure losses.

Figure 1. Three-way catalytic converter with ceramic substrates



Catalytic materials are typically applied by contacting the substrate with a water-based slurry containing the active inorganic catalyst materials. The coated substrate is contained within an outer metal-based shell that facilitates connection of the converter to the vehicle's exhaust system through flanges or welds. The honeycomb-based substrates are typically either ceramic or metal foil-based. Cordierite, a magnesium alumino-silicate compound, is the preferred ceramic substrate material due to its low coefficient of thermal expansion, good mechanical strength characteristics, and good coating adhesion properties. The ceramic substrate is formed as a single body using an extrusion process followed by high temperature firing. Metal-foil based substrates are made from thin ferritic-based specialty stainless steel foils brazed together to form the parallel flow passages. The ferritic foil alloy provides good oxidation resistance in the exhaust environment, good mechanical strength, and an oxidized surface that promotes good adhesion of the catalytic coating to the foil. In the case of ceramic substrates, a special oxide fiber-based mounting material is used between the substrate and the metal outer shell to hold the substrate in place, provide thermal insulation, and cushion the ceramic body against the shell. The outer metal shell or mantle is an integral part of the metal substrate production scheme and no additional mounting materials are generally required. As shown in Figures 1 and 2, in some cases the converter housing or "can" can be surrounded by a second metal shell with an annular gap between these two metal shells. This type of arrangement provides additional heat insulation to the converter. The annular region between the two shells may be left as an air gap or filled with an insulating material such as an inorganic fiber-based material.

Figure 2. Three-way catalytic converter with metallic substrates



Although the primary components and function of a three-way catalytic converter has remained relatively constant during its more than twenty years of use on light-duty gasoline vehicles, each of the primary converter components (catalytic coating, substrate, mounting materials) has gone through a continuous evolution and redesign process aimed at improving the overall performance of the converter while maintaining a competitive cost effectiveness of the complete assembly. A similar re-engineering effort has occurred with other exhaust system components such as exhaust manifolds and exhaust pipes that complements improvements in catalytic converter technology. The focus of these manifold and other exhaust component improvements has been exhaust system thermal management and heat conservation through the use of low thermal mass, air gap insulated components. A large driver in the continuous improvement processes for both catalytic converters and exhaust system components has been the introduction of increasingly more severe emission requirements such as the Tier 2 and LEV II programs discussed in the introduction. The performance-based catalytic converter re-engineering effort has had three main focuses: wide application of close-coupled converters mounted near the exhaust manifold of engines, the development of high cell density substrates, and the design of advanced, high performance TWCs for both close-coupled and underfloor converter applications. Each of these technologies is discussed in some detail in the following sections.

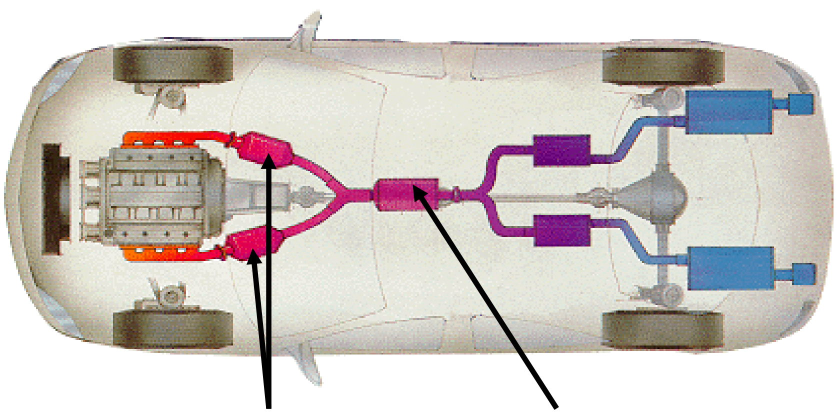
2.1 Close-Coupled Converters

Achieving high conversion efficiencies for both HC and NOx emissions during normal vehicle operation represented by the FTP driving cycle, for example, has focused attention on cold-start performance of catalytic converters for both Tier 2 and LEV II light-duty applications. LEV I hydrocarbon emission requirements introduced by California in 1994 provided the first regulatory driver that placed importance on cold-start emissions. Numerous studies published in the late 1980s and 1990s have discussed the high percentage of FTP driving cycle emissions associated with the early stages of vehicle operation following a cold engine start situation (references include: 2, 3, 12, 22-24, 29-31, 38, 39, 41, 45, 52, 54-56, 66, 69, 75, 78, 80, 83, 88-90). This is especially true for 1990s vintage vehicles sold in the U.S. designed to comply with less severe Tier 1 emissions standards. Hydrocarbon tailpipe emission profiles during FTP testing of Tier 1 vehicles are generally dominated by emissions emitted during the first one to two minutes of operation after the cold-start. This large fraction of cold-start emissions in Tier 1 vehicles stemmed from significant fuel enrichment used by auto manufacturers to facilitate engine start under cold conditions and significant delays in converter warm-up to catalyst operating temperatures required for high conversion efficiencies (e.g., 350^{o}C or higher). Heat-up delays were usually associated with relatively long distances and the associated poor heat transfer between the converter location and the engine exhaust ports. NOx emission profiles also have a component related to cold-start operation but are generally distributed more uniformly through the FTP driving cycle on Tier 1 certified vehicles due to NOx emission events associated with vehicle accelerations and decelerations.

To more effectively deal with cold-start emissions, converter volumes have been moved closer to the engine exhaust ports to minimize exhaust system heat losses and accelerate the heat-up of catalysts during the critical time following engine start. Converters located near the engine exhaust valves (e.g., at the exit of the exhaust manifold) are referred to as close-coupled converters (or sometimes light-off converters or pre-converters). LEV I and ULEV I compliant light-duty vehicles introduced in the mid-1990s were the first significant applications of exhaust systems featuring close-coupled catalytic converters. In some applications (typically smaller displacement engines), a vehicle may have all or a large fraction of the required catalyst volume located close to the engine exhaust manifold. In other applications (typically larger displacement engines), the exhaust system will include smaller volume converters located close to the engine followed by a larger converter volume located further downstream in the exhaust in an underfloor location. In these multiple converter exhaust schemes, the size of the close-coupled converter is balanced between thermal mass (minimal catalyzed substrate mass for faster heat-up), diagnostic (adequate oxygen storage capacity), and durability considerations (sufficient volume to maintain required performance over extended mileage).

In larger engines, dual exhaust system configurations are often used with parallel systems for each cylinder bank (in the case of V-type engine designs) or groups of cylinders (in the case of in-line engine designs). These parallel systems may each incorporate close-coupled and underfloor converters or parallel close-coupled converters that lead into a y-pipe and a single underfloor converter. A schematic of an exhaust system layout featuring dual close-coupled converters flowing into a single underfloor converter is shown in Figure 3. Due to their close orientation to the engine, the close-coupled converter(s) can reach temperatures required for high conversion efficiencies of hydrocarbons, CO, and NOx in 30 seconds or less following engine start, compared to heat-up times of 60 seconds or more associated with underfloor-only converter systems.

Figure 3. Exhaust system with close-coupled converters



Fast dynamic converter heat-up, a requirement for low cold-start emissions, is also facilitated by advanced cold-start engine calibration strategies. These strategies include retardation of the engine spark, reduced idle speed, use of secondary air injection, and/or lean start strategies. Numerous examples of these cold-start strategies have been described in the literature (references include: 2, 3, 5, 18, 22-24, 28, 34, 46, 52, 56, 69, 80) and are a key part of the systems approach required to achieve high conversion efficiencies for HC and NOx at the early stages following engine start. Each of these engine start-up strategies seeks to maximize conditions at the close-coupled converter that accelerate its heat-up following engine start (e.g., additional unburned fuel to combust over the catalyst, minimized total exhaust flow during initial engine idle, slight excess of oxygen to combustibles in the exhaust to promote full oxidation at the catalyst). Examples of some of these cold-start strategies were included in a MECA test program summarized in Section 3.0.

Rapid converter heat-up also has placed greater emphasis on exhaust system thermal management. Efficient transfer of heat generated during the combustion process to the catalytic converter with minimal heat losses to the surrounding environment is facilitated by insulated exhaust manifolds and insulated exhaust pipes (2, 3, 21-24, 52, 54, 84). The preferred method of insulation is through the use of low thermal mass, air gap components. Insulated manifolds and pipes featuring dual wall construction separated by air gaps have been developed to improve light-duty vehicle cold-start and warm-start emission performance. These air gap components generally make use of a thin, low thermal mass, durable inner wall to facilitate fast heat-up characteristics. An air gap between the thin inner wall and a thicker outer wall provides insulation to minimize heat losses between the engine and the converter(s). These air gap exhaust components provide significant reductions in converter heat-up during the FTP test protocol, which in turn provides significant reductions in cold-start and warm-start vehicle emissions.

Placement of catalytic converters closer to the engine results in dramatic reductions in cold-start emissions of all criteria pollutants (especially hydrocarbon and CO emissions that are most associated with cold engine start conditions). The close-coupled converter environment also raises converter maximum operating temperatures relative to underfloor environments. This, in turn, has placed added demands on the thermal durability of catalysts and other converter components used in these more severe close-coupled converter applications. In particular, fiber-based mounting materials and packaging assemblies used with ceramic substrates have been re-engineered and optimized to meet these more severe thermo-mechanical environments, as well as the longer durability requirements associated with the Tier 2 and LEV II emission regulations. Similarly, metal substrate construction methods and brazing schemes have also been optimized for the high mechanical loads and high temperatures encountered in close-coupled applications. A discussion of high temperature catalyst designs is presented in a subsequent section of this paper.

2.2 High Cell Density Substrates

Tier 1 compliant vehicles have generally relied on substrate designs that utilize straight flow channeled monoliths with square cross-sectional channel openings. Channel sizes that equate to 400 channels or cells per square inch of frontal area (designated as 400 cpsi) became an industry standard for many applications in the late 1980s and 1990s. In Tier 1 applications of ceramic substrate designs with 400 cpsi, ceramic substrate wall thickness was typically 0.0065 in or 6.5 mils, with some limited usage of 400 cpsi substrates with 8 mil walls. Limited applications of ceramic monoliths with triangular shaped cells have also been used for Tier 1 applications with cell densities of 236 cpsi or 300 cpsi (wall thickness of 6.5-11.5 mils). Metal substrates were also introduced with channel densities of up to 400 cpsi but with thinner metal foil walls that were typically 50 microns (approximately 2 mils) in thickness. These standard metal substrate designs typically utilize sinusoidally corrugated metal foils layered between flat foils to produce parallel flow channels.

Interest in automotive emission systems with high conversion efficiencies and improved cold-start performance to meet more severe emission requirements, such as Tier 2, LEV I and LEV II standards, encouraged the development of a new generation of both ceramic and metallic substrate designs that offer significantly higher cell densities (more flow channels per cross-sectional area) and thinner walls separating flow channels. These two key substrate characteristics provide increased geometric surface area per unit volume of monolith for efficient distribution of the active catalytic coating, relatively small flow channels (or more precisely, relatively small values for the channel hydraulic diameter) for good heat and mass transfer characteristics, and reduced substrate thermal mass for faster heat-up during emission critical cold-start events. Figure 4 provides a comparison of relative specific geometric areas and bulk densities of ceramic substrates with progressively higher cell densities and thinner wall thickness.

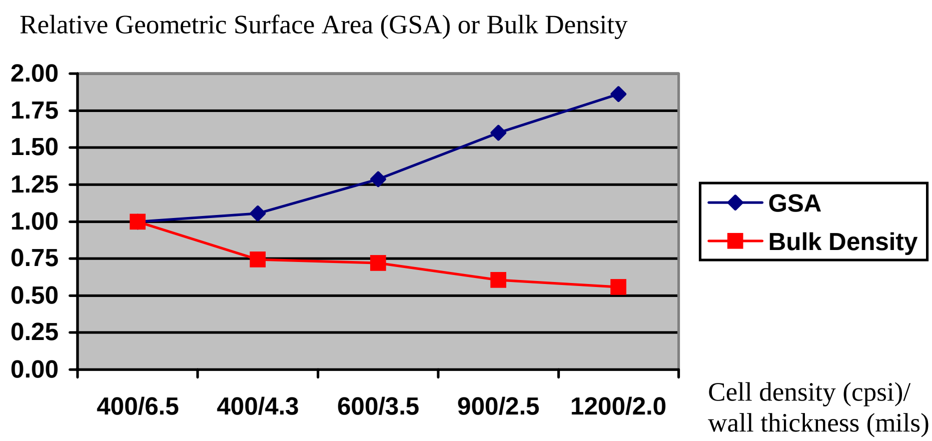


Figure 4. Relative geometric area and bulk density of ceramic substrates

As discussed in the many references associated with these high cell density substrates, substrate geometric surface area is an important physical property in heterogeneous catalysis associated with the effective mass transfer of reactants present in the exhaust stream of an engine (e.g., HCs, CO, NOx, H_2O, and O_2) to the solid surfaces that contain the active catalytic sites (references include: 1, 9, 11-16, 18, 26, 29, 30, 35, 39, 42-45, 52, 56, 60-66, 70, 78-81, 88). Increasing this specific geometric area provides for more efficient contact between the reactants and the active catalyst sites and, in turn, a higher overall conversion efficiency of these reactants in a given volume of catalyzed monolith. Increasing cell density at a constant monolith wall thickness provides increased geometric surface area but results in higher bulk density or thermal mass due to the resulting higher fraction of walls per given cross-sectional area (or, stated in another way, higher cell density at a constant wall thickness lowers the fraction of the frontal area open to the flow of exhaust gas). To compensate for this bulk density effect, substrate manufacturers have successfully developed high cell density products with significantly thinner walls than the "standard products" used primarily in Tier 1 applications. For example, ceramic substrates with 6.5 mil walls offered in "standard products" have been reduced to wall thickness in the range of 1.5-3.5 mils in high cell density substrates. Similarly, metal substrates utilize 50 micron foils in "standard products" with high cell density products typically constructed with foil thickness ranging from 20-40 microns (approximately 0.8-1.6 mils). Thinning the monolith walls provides significant reductions in the thermal mass/bulk density of high cell density products. This low thermal mass characteristic enables catalyst-coated substrates to heat-up more quickly than heavier, "standard" wall thickness substrates. Fast dynamic heat-up of converters is key to achieving low tailpipe emissions during the critical cold-start and warm-start periods associated with normal driving operations, and required to comply with Tier 2 and LEV II emission regulations. To further illustrate the properties and benefits associated with thin wall, high cell density substrates, results from three recent SAE technical papers are briefly discussed below.

Hughes and Witte (12) completed a comprehensive study of the impacts of high cell density substrates on light-duty vehicle emission performance in both the FTP and US06 test cycles. Their study made use of ceramic substrates covering a range of cell densities, including the "standard" ceramic substrate product with 400 cpsi/6.5 mil wall thickness, used in many Tier 1 applications, and high cell density, thin wall ceramic substrates such as 600 cpsi substrates with 3.5 and 4.5 mil wall thickness, and 900 cpsi substrates with 2.5 mil wall thickness. Table 4 summarizes ceramic substrates used in this study along with their accompanying properties including specific geometric surface area (GSA) and bulk density.

Table 4. Ceramic substrate properties for standard and high cell density products [from Hughes and Witte (12)]

Cell Density (cpsi)	**400**	**400**	**600**	**600**	**900**
Wall Thickness (mils)	**6.5**	**4.5**	**4.5**	**3.5**	**2.5**
Open Frontal Area (%)	75.7	82.8	80.0	83.6	85.6
Geometric Surface Area (m^2/liter)	2.74	2.87	3.45	3.53	4.37
Bulk Density (g/liter)	401	279	324	267	267

The performance of these substrates was investigated by catalyzing each substrate with an identical advanced Pd/Rh TWC (100 g/ft^3 total precious metal loading with Pd/Rh = 14/1; all substrates coated with a total coating weight of 140 g/liter of substrate), aging the converters containing these catalyzed substrates using a Ford accelerated aging protocol, and performing triplicate FTP and US06 drive cycle tests on each aged converter. The Ford accelerated aging protocol was performed on an engine dynamometer and simulated approximately 50,000 miles of actual service life. FTP and US06 chassis dynamometer tests were run using a 2.0 liter, 4 cylinder, 4 valve test vehicle with a single aged converter mounted at the exit of the exhaust manifold in a close-coupled location on the test vehicle. Catalyzed monolith volumes of both 1.0 liter (50% of engine swept volume) and 0.5 liters (25% of engine swept volume) were evaluated on the test vehicle using both drive cycles.

Figures 5 and 6 summarize NMHC and NOx average emission performance, respectively, of aged converters evaluated on the test vehicle during FTP evaluations as a function of substrate type (cell density and wall thickness). Emissions data are included in these figures for both the 1.0 liter catalyzed volume and 0.5 liter catalyzed volume converters, appropriately weighted for each of the three phases of the FTP driving cycle (cold-start (Bag 1), hot transient (Bag 2), and hot-start (Bag 3)). These data clearly show the significant decrease in both NMHC and NOx emissions that result from the use of high cell density/thin wall substrates relative to the base case 400 cpsi/6.5 mil wall standard. Lower emissions of NMHC and NOx emissions are evident in each phase (or "bag") of the FTP drive cycle: cold-start phase (phase 1 or "bag" 1), warmed-up transient phase (phase 2 or "bag" 2), and warm-start phase (phase 3 or "bag" 3). These reduced tailpipe emissions stem from the higher geometric surface area of these advanced substrates, the smaller hydraulic diameter of each coated channel, and the lower thermal mass of the higher cell density substrates. Thermal mass is proportional to the substrate bulk density values shown in Table 4 (thermal mass = [substrate bulk density] x [substrate volume] x [substrate mass specific heat capacity]).

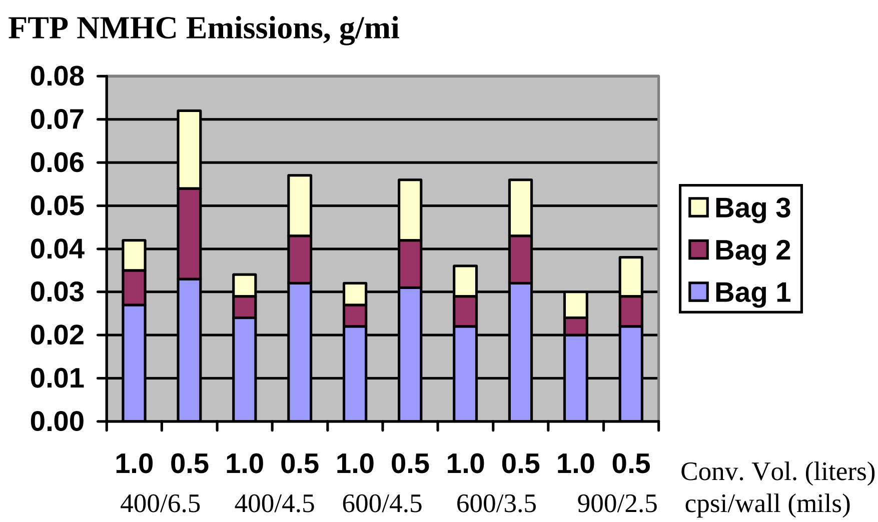


Figure 5. NMHC FTP emissions for substrates with varying cell density and wall thickness [see (12) for details]

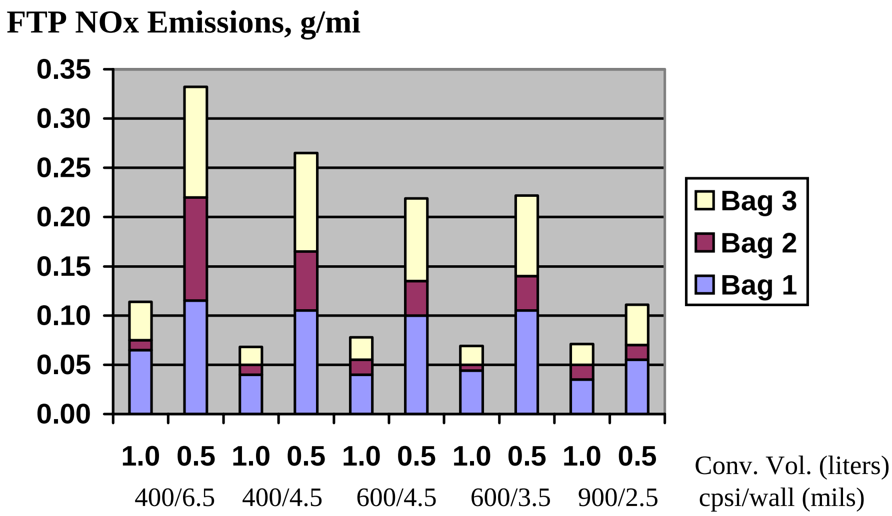


Figure 6. NOx FTP emissions for substrates with varying cell density and wall thickness [see (12) for details]

Emission results presented by Aoki et al. (15) also detail the performance of advanced high cell density ceramic substrates with respect to FTP NMHC emissions on a late model, 4 cylinder test vehicle. This study evaluated engine-aged converters with equivalent volume (substrate dimensions of 106 mm dia. X 114 mm long) and equivalent precious metal loading (150 g/ft^3 advanced trimetal [Pt/Pd/Rh] catalyst) on a vehicle with a 2.3 liter engine (vehicle calibrated for ULEV I performance with lean start strategy; converter inlet approximately 1.1 m downstream of the engine's exhaust valves). Converters were aged for 50 h using an accelerated engine aging protocol with a maximum catalyst temperature of 850^oC. Aged converters with substrate cell densities from 300 to 1200 cpsi and varying wall thickness were evaluated on the test vehicle using the FTP drive cycle. Figure 7 compares the NMHC FTP emissions measured on the test vehicle for the various aged converters versus the specific geometric surface area of the substrates evaluated by this program. In this figure each ceramic substrate design is denoted by its cell density (cpsi) and wall thickness in mils (e.g., 600/3.5). The results show a strong relationship between NMHC emissions and substrate geometric surface area with higher substrate geometric surface area contributing to lower NMHC emissions in the FTP test cycle, a result consistent with the results shown in Figures 5 and 6. The results from Aoki et al. also show a relatively large benefit in emission performance for 600 cpsi substrates relative to 300 and 400 cpsi substrate designs. Smaller relative emission benefits were achieved in this study for additional increases in cell density beyond 600 cpsi (e.g., 900 cpsi and 1200 cpsi substrate designs). The relative magnitudes of the emission benefits shown in Figures 5-7 for different substrate cell density and wall thickness options will be impacted by the vehicle application environment including the number and location of catalysts in the exhaust system and the engine calibration strategy employed on the test vehicle. These optimization parameters again emphasize the overall systems design philosophy that needs to be employed to achieve the required emission performance with the most cost effective system design.

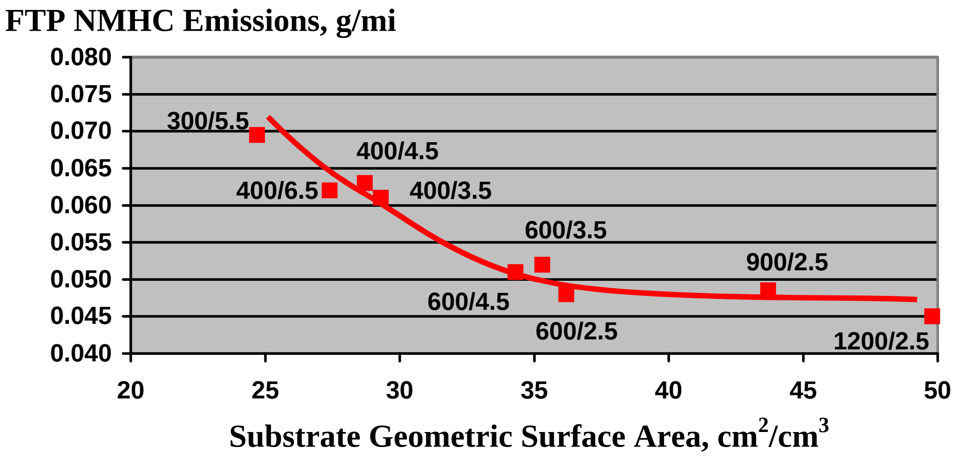


Figure 7. NMHC FTP emissions vs. substrate geometric surface area [see (15) for details]

Results presented by Marsh et al. (27) show similar trends in reducing HC and NOx emissions with advanced high cell density metal substrates during FTP emission tests utilizing a 2.4 liter, 5 cylinder test vehicle. In this study cell densities as high as 1600 cpsi were evaluated for their impacts on emissions performance. Physical properties for the metallic substrates evaluated in this study are summarized in Table 5 below, including values of the flow channel hydraulic diameter. As in the study by Hughes and Witte, converters were evaluated on the test vehicle using the same volumetric precious metal and total catalyst loading of an advanced TWC on each metallic substrate. Converters were located near the exit of the exhaust manifold on the 5 cylinder engine. FTP HC and NOx emissions reported by Marsh et al. for these various high cell density metallic substrate-based catalysts are detailed in Figures 8 and 9, respectively. Similar to the results reported by Hughes and Witte, FTP HC and NOx emissions were reduced in this study by utilizing higher cell density, thinner wall metal substrates. Improvements in HC emissions were most strongly impacted by the combined increase in cell density with thinner walls between channels since this substrate design strategy lowers thermal mass and increases geometric area (e.g., moving from 600 cpsi/30 micron wall to 1000 cpsi/20 micron wall), critical properties for maximizing converter heat-up and mass transfer characteristics during the HC intensive cold-start period. Further increases in cell density at constant wall thickness (e.g., 1000, 1200, 1600 cpsi with 20 micron wall thickness) equates to higher thermal mass substrates with poorer heat-up characteristics during the cold-start phase of the FTP test cycle. The additional geometric area of these highest cell density designs helped to compensate for the higher thermal mass but no net benefit in cold-start HC performance was realized. NOx benefits were shown in each case as cell densities increased, largely due to more effective contacting efficiency between the exhaust gas constituents and the active catalyst coating present on the walls of the substrate. Somewhat higher pressure drop of these substrates with increasing cell density may also have contributed to some reductions in engine-out NOx levels in certain driving modes due to increased levels of internal exhaust gas recirculation within the engine's combustion chambers.

Table 5. Metallic substrate properties for high cell density products
[from Marsh et al. (27)]

Cell Density (cpsi)	**600**	**800**	**1000**	**1200**	**1600**
Wall Thickness (mils)	**30**	**25**	**20**	**20**	**20**
Hydraulic Diameter (mm)	0.85	0.75	0.66	0.60	0.52
Geometric Surface Area (m^2/liter)	3.77	4.32	4.88	5.36	6.08
Thermal Mass (J/K)	689	681	641	680	750

Results like those shown in Figures 5 through 9 and the many other studies aimed at understanding the impacts of advanced substrate properties such as cell density, hydraulic diameter, and thermal mass have allowed researchers and design engineers to develop sophisticated mathematical models that accurately predict the performance of catalytic converters during vehicle operation including performance during the FTP test protocol (13-15, 26, 27, 39, 42, 49). These models generally include mathematical descriptions of the heat and mass transfer processes that occur within catalytic converters. Becker et al.(26) used a modeling approach to predict the emission performance of a variety of substrate types and designs. In their work they report that the catalytic performance of these substrates could be strongly correlated with key substrate physical properties: higher catalytic efficiency was proportional to substrate geometric surface area, and inversely proportional to bulk density and substrate channel hydraulic diameter. Large geometric surface area in combination with small channel diameters provide good heat and mass transfer characteristics, while low substrate bulk density results in fast dynamic converter heat-up properties.

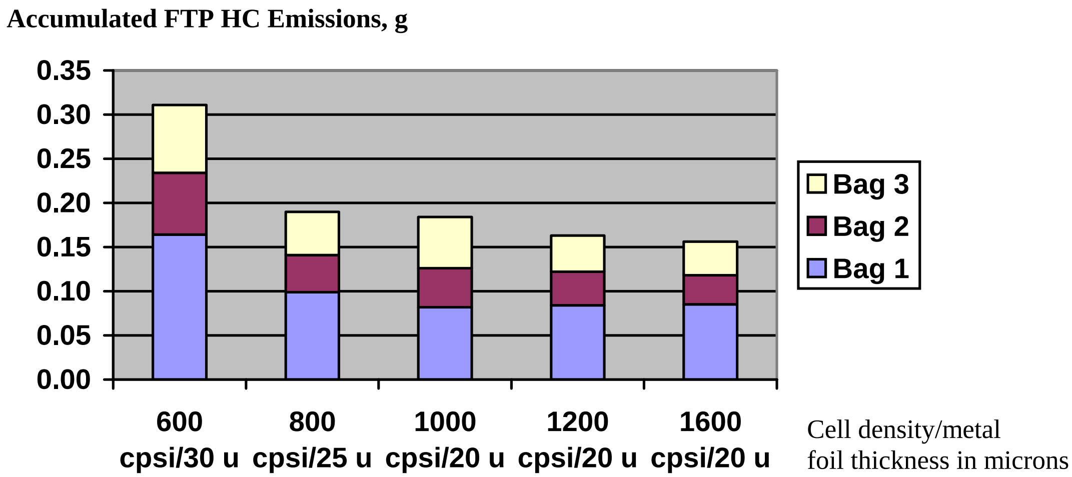


Figure 8. Accumulated FTP HC emissions for a three-way catalyst coated on high cell density metal substrates [see (27) for details]

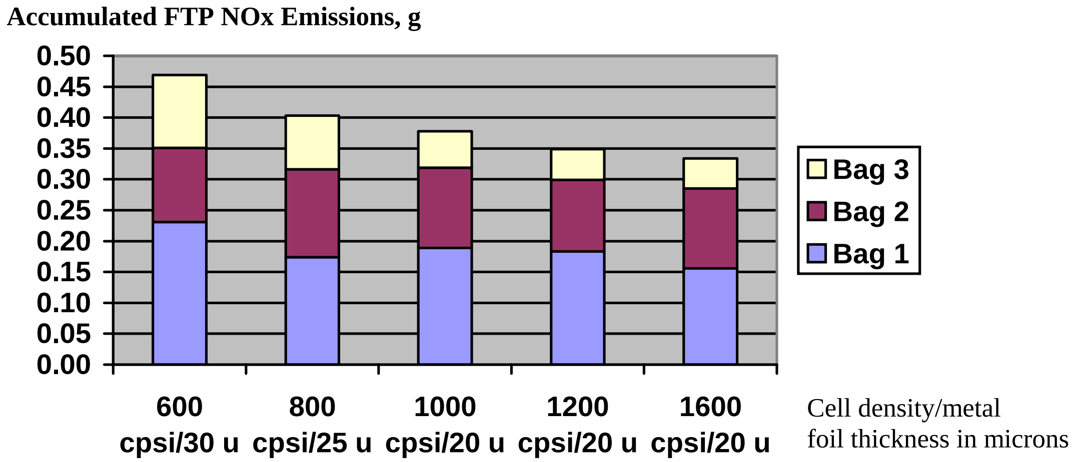


Figure 9. Accumulated FTP NOx emissions for a three-way catalyst coated on high cell density metal substrates [see (27) for details]

The production of high cell density ceramic and metallic substrates are subject to the many quality system requirements of the auto industry. These advanced substrates are manufactured with precise specifications on all key fabrication parameters, resulting in only small variations in the key performance-related physical properties such as bulk density, cell density, and wall thickness. For example, ceramic monolith wall thickness typically varies by +/- 0.5 mils or less for nominal wall thickness in the 2-4 mil range. Similarly metal foil thickness in metal substrates varies by +/- 0.2 to 0.3 microns for foils in the 20-50 micron range. Cell densities in ceramic substrates are controlled by the precision die used in the extrusion process and process controls associated with the extrusion and firing operations. Cell densities in metal substrates are controlled by tight specifications on the process used to produce corrugated foils, as well as process controls on other key production operations. As an example, cell densities in metal substrates vary by +/- 5% for high cell density substrates ranging from 600 cpsi to 1600 cpsi. Modifications to traditional canning operations and mounting materials have also been developed for high cell density, thin wall ceramic substrates to ensure a mechanically robust, durable converter package. Similarly high cell density, thin wall metal substrates have re-engineered brazing strategies and matrix/mantle connection methods to maintain required mechanical durability for all light-duty vehicle applications.

2.3 Advanced Three-Way Catalysts

Three-way catalysts have traditionally relied on highly dispersed precious metals (Pt, Pd, Rh) supported on high surface area aluminum oxide with the addition of a variety of base metal oxide promoters and oxygen storage materials to provide the simultaneous HC and CO oxidation and NOx reduction behavior required in automotive emission control applications. Oxygen storage and release behavior of TWCs is an important functionality required to maintain acceptable performance during air/fuel perturbations that occur as a result of the closed loop air/fuel feedback control algorithm associated with oxygen sensors. Cerium oxide-based materials contained in TWC formulations have been the primary source of this oxygen storage behavior. Catalyst performance criteria associated with meeting the low emission requirements of Tier 2 or LEV II applications include maintaining high conversion efficiencies for all three criteria pollutants during all phases of vehicle operation (e.g., start phases, accelerations, decelerations, cruise conditions) for extended operational lifetimes (i.e., 120,000 mile durability). These demands for high conversion efficiencies and extended durability have evolved TWC formulations and design strategies significantly in the last ten years.

The interest in cold-start performance discussed with close-coupled converters previously puts emphasis on TWC light-off characteristics, especially with respect to HCs (Light-off generally refers to the catalyst temperature required to achieve significant conversion activity with respect to the pollutants of interest.). Pd-based TWCs (e.g., Pd-only, Pd/Rh, or Pt/Pd/Rh trimetallic catalyst formulations) became the preferred choice for close-coupled applications due to the inherent good HC light-off performance of Pd relative to Pt or Rh (references include: 17, 20, 31, 33, 36, 38, 40, 51, 54, 57-59, 67, 69, 72-75, 86, 90, 91). Close-coupled applications, also place a premium on catalyst thermal stability/durability since these close-coupled converters expose catalyst materials to significantly higher operating temperatures than temperatures associated with converters located in cooler, underfloor locations. This thermal durability requirement also placed attention on Pd-based close-coupled TWCs due to Pd's superior thermal stability compared to other precious metals. The thermal stability of other catalytic materials used in TWC formulations was equally important in meeting the demands of close-coupled catalysts. This need resulted in the concerted development of new catalyst materials such as stabilized aluminas (a support material for precious metals) and stabilized cerias (a promoter and oxygen storage material), and the development of more stable precious metal impregnation strategies that helped to push maximum catalyst operating temperatures from 800^{o}C to over 1000^{o}C over the last ten years. The longer durability requirements of Tier 2 and LEV II emission regulations, as well as the inclusion of heavier light-duty trucks with their relatively higher exhaust temperatures compared to passenger cars, contributed to this focus on improving TWC thermal stability.

TWCs with high conversion efficiencies and extended durability with respect to NOx (hydrocarbons and CO, as well) are additional important criteria of Tier 2 and LEV II emission systems. The need for high performance and extended durability catalysts influenced all aspects of catalyst design and the selection of materials used as supports, promoters, and oxygen storage materials. Enhancements in oxygen storage materials, in particular, have been a key element in pushing catalyst performance in advanced TWC formulations. New families of ceria-zirconia materials have been developed that provide higher capacities of thermally stable oxygen storage and release functionalities to TWCs (references include: 8, 20, 28, 31, 33, 38, 47, 48, 51, 58, 61, 68, 71, 85, 87). Synergies between these new ceria-zirconia materials and the catalytically active precious metals have led to improvements in intrinsic catalyst light-off characteristics, broader three-way operating windows with respect to the simultaneous oxidation and reduction reactions as a function of inlet air/fuel ratio, and more highly dispersed and thermally stable precious metal activity. Figure 10 provides an example of TWC performance improvements with respect to NOx emissions stemming from the use of new materials like advanced ceria-zirconia-based oxygen storage materials (31).

New catalyst design strategies have also been developed to better tailor precious metal performance in advanced catalysts. A primary example of these tailored design strategies is the development of multi-layer catalyst coating architectures in which preferred precious metal functionalities and oxygen storage performance can be segregated to maximize performance and minimize unwanted negative interactions that may result by co-mingling certain catalyst materials (16, 17, 28, 31, 36, 38, 47, 58, 90). For example, undesirable alloying of precious metals due to high temperature sintering phenomenon can be minimized by segregating precious metals in unique chemical layers in a multi-layer coating format. An example of the performance improvements achieved by new multi-layer catalyst architectures is shown in Figure 11 (86). These advanced catalyst materials and catalyst design strategies have cascaded through all TWC formulations (precious metal types including: Pd-only, Pd/Rh, Pt/Rh, and trimetal) and applications (close-coupled and underfloor converters) to deliver cost-effective high performance and durable catalysts required to meet the needs of Tier 2 and LEV II light-duty applications.

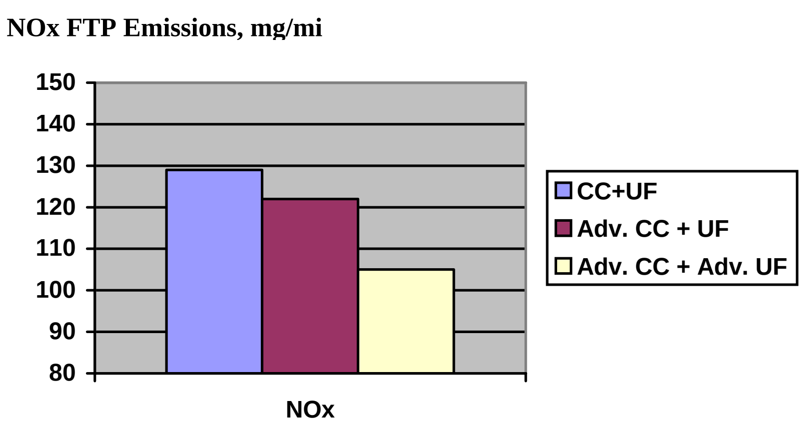


Figure 10. Impact of advanced catalyst formulations on NOx FTP emissions from a 5.3 liter, V8 test vehicle equipped with close-coupled (50 g/ft^3 Pd-only) + underfloor converters (30 g/ft^3 Pt/Rh=3/1) [see (31) for details]

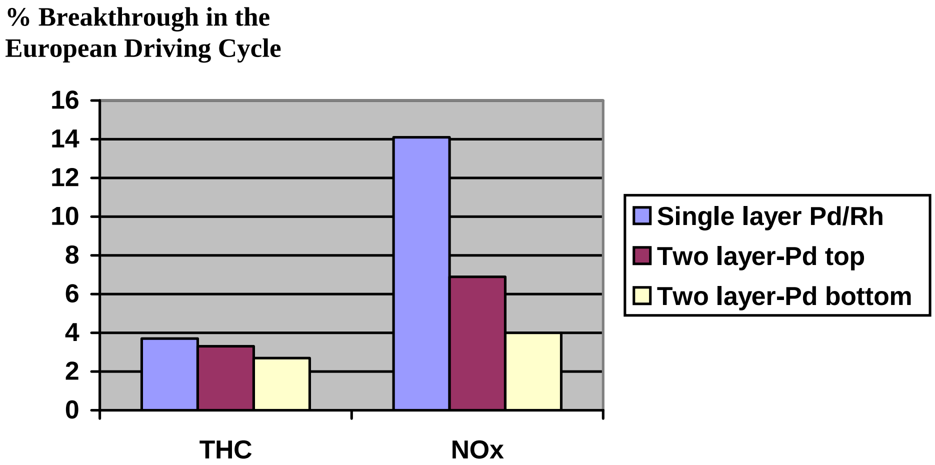


Figure 11. Impact of catalyst coating architecture (single layer vs. double layer) on total hydrocarbon (THC) and NOx performance of a Pd/Rh three-way catalyst (100 g/ft^3 total precious metal loading with Pd/Rh=5/1; 100 h aged catalyst on a 1.8 liter, 4 cylinder test vehicle; see (86) for details)

To achieve the full performance benefits of these advanced catalyst/advanced substrate combinations for Tier 2 and LEV II applications, it has also been necessary to develop improved engine operating algorithms that more closely match inlet catalyst conditions with the optimal operating window of the catalyst in order to maximize catalyst efficiency for all three criteria pollutants. The discussion on close-coupled converters included the development of cold-start engine operating strategies that accelerate converter heat-up during the crucial cold-start process. Similarly with respect to NOx emissions, tighter air/fuel control strategies during all modes of vehicle operation (especially high NOx emission modes associated with vehicle accelerations and decelerations) have been developed to achieve the low NOx emission requirements of the Tier 2 and LEV II programs. Precise air/fuel control strategies balance the relative concentration of oxidants and reductants in the exhaust stream within the catalyst's preferred operating window under highly dynamic vehicle operations. Similarly, vehicle calibrators can make use of exhaust gas recirculation (EGR) strategies to minimize engine-out NOx levels during some vehicle operating modes and maximize emission system performance. These EGR calibration strategies may involve either internal EGR calibrations through changes in exhaust valve lift or timing characteristics or external EGR calibrations through changes in the duty cycle of an external EGR valve during certain portions of a given driving cycle. The interplay and optimization of engine controls and emission control technology is a necessary part of the overall systems approach and integration required in meeting Tier 2/LEV II low NOx emission goals on light-duty vehicles.

New high performance TWCs have also required the development of new precision substrate coating processes and equipment capable of producing and placing complex coating formulations on the interior walls of ceramic and metallic substrates (both standard and advanced high cell density substrates) in high volume production. These advanced catalyst formulations have also been tailored to be compatible with advanced high cell density substrates (9, 16, 30, 31, 38, 39). For example, the volume-based catalyst loading on a high cell density substrate must be balanced to provide required performance and durability characteristics without adversely affecting the overall thermal mass (and the resulting dynamic heat-up) and pressure drop characteristics of the coated substrate. Like substrate manufacturing processes, catalyst manufacturing processes must also be operated within the rigorous automotive industry quality control requirements. Catalyst formulation and coating specifications on all materials (precious metals, support materials, oxygen storage materials, etc.) minimizes physical and chemical variations between production parts and production lots of a given catalyst type.

3.0 MECA Light-Duty Vehicle Demonstration Program

A program to demonstrate the performance of advanced emission control systems in light of the then proposed California LEV II light-duty vehicle standards and the EPA's consideration of Tier 2 emission standards was conducted at Southwest Research Institute during the 1997-1998 timeframe on behalf of the Manufacturers of Emission Controls Association (MECA). In particular this test program targeted the low NMOG and NOx emission levels associated with the Tier 2 and LEV II emission limits detailed previously in Tables 1 and 2, and the capability of advanced emission control systems to provide equivalent light-duty passenger car performance on light-duty trucks, another key component of both the Tier 2 and LEV II programs. For this program, two passenger cars (a six-cylinder and an eight-cylinder engine) and two light-duty pick-up trucks (a six-cylinder LDT1 [California light-duty truck 1 weight class] and an eight-cylinder LDT3 [California light-duty truck 3 weight class]) were selected for testing, modification, and emission system performance optimization. The LDT3 was 1999 Federal Tier I compliant while the other three vehicles were 1997 Federal Tier I compliant, and were purchased from local car dealerships in the San Antonio, Texas, area. The results of this program provide examples of the kinds of emission system design choices and overall systems performance optimization that are required to upgrade a light-duty vehicle's emission performance from Tier 1 and LEV I compliance to the more severe emission requirements of the Tier 2 and LEV II programs.

Each new vehicle was driven 4,000 miles on California Phase II reformulated gasoline over the EPA ASADP RDP-II mileage accumulation driving cycle (52). After this initial mileage break-in was completed, each vehicle was emissions tested in its stock, baseline configuration on the FTP-75 test cycle. In these and all other FTP tests run as part of this program, test vehicles were fueled with emissions grade California Phase II reformulated gasoline. Hydrocarbon speciation and modal emissions analyses were performed on each cycle of the FTP test. The stock baseline modal emissions were examined and various systems including advanced three-way catalysts, high cell density substrates, and modified vehicle controls were developed in order to lower tailpipe emissions of each test vehicle significantly below their baseline Tier 1 emission performance levels.

After installing the advanced systems, the vehicles were again driven for 4,000 miles on

California Phase II reformulated fuel using the EPA ASASP RDP-II mileage accumulation driving cycle. The base performance of the advanced catalyst system was then determined with the stock vehicle controls over the FTP-75 test cycle. As part of an effort to optimize the emission performance of these advanced emission systems, the base modal emission test results were analyzed and vehicle control modifications were formulated to reduce the remaining high emission modes of operation. Control modifications were performed using a computer controlled-signal intercept system [Emissions Reduction Intercept and Control system or ERIC] (53). This computer intercept methodology was used to recognize and modify only driving modes associated with high tailpipe emission modes, thereby minimizing the level of modification to the stock vehicle control system. The control tuning approach developed for each vehicle was unique to the platform. The computer intercept techniques used in this program were capable of modifying selected vehicle control parameters without setting codes in the vehicles' on-board diagnostic monitoring systems. Tuned control strategies had no measurable impact on the test vehicles' fuel economy over the FTP driving cycle. The modified control strategies also did not result in any detectable changes to vehicle drivability during FTP evaluations.

After the advanced technology systems and the modified engine controls were integrated and tuned, each vehicle was tested in the final tuned configuration over multiple modal FTP-75 tests cycles. Hydrocarbon speciation was performed on each cycle of two of the final FTP tests. These results characterized the tuned emission performance of each advanced emission system after 4,000 vehicle miles. Each advanced catalyst system was then engine aged using an accelerated thermal aging cycle. The aging cycle used was an engine dynamometer cycle based on the published General Motors RAT-A aging schedule. California Phase II reformulated gasoline was used for all of the engine aging done in this program. The aging cycle used in this program adjusted the inlet exhaust temperature to the first catalyst in the converter system to 820°C during the stoichiometric cruise mode of the aging cycle. For the two passenger car systems, 100 hours of aging time with this schedule was used to simulate a high mileage condition. For the light-duty trucks, system aging time was extended to 125 hours in recognition of the more severe duty cycles of some light-duty pick-up trucks relative to passenger cars. The actual mileage correlation to aging hours is application specific, but as referenced in the literature (see (52) for references on accelerated aging), 100 hours of engine aging with the RAT-A cycle can correspond to 100,000 miles of in-service use on some vehicle platforms. The systems were retested over the FTP-75 after engine aging on each test vehicle to characterize the emission performance durability of each system. No modifications to the optimized control strategies developed during the program's tuning phase were made after aging of the emission components.

Emission results for three of the four test vehicles used in this program are summarized in the following section. Additional details concerning this test program, as well as the results for the one vehicle not discussed in this paper (a 1997 Tier 1 Buick LeSabre equipped with a 3.8 liter V6 engine), are provided by Webb et al.(52).

3.1 Advanced Emission Control System Descriptions and Test Results

Each of the advanced emission control systems used in the MECA test program make use of the three key technologies reviewed in previous sections of the paper - close-coupled converters, high cell density substrates, and advanced three-way catalysts - to achieve the tailpipe emission goals associated with Tier 2 or LEV II requirements. These high performance emission systems were combined with modifications to each of the vehicle's factory-supplied, Tier 1 engine operating strategies to maximize their emission benefits during various vehicle driving modes.

3.1.1 1997 Tier 1 Ford Crown Victoria

The Ford Crown Victoria tested had an eight-cylinder (V-8), 4.6 liter engine with a four-speed automatic transmission. The stock exhaust emission control system included dual close-coupled and underbody catalytic converters (one set on each bank of the V-8) and dual EGO sensors (before and after the first catalyst) on each bank. All stock Tier 1 compliant converters utilized 400 cpsi ceramic substrates. The stock exhaust joined together after the converters into a single exhaust. During installation of the advanced emission control system, the following hardware modifications were made:

- Dual close-coupled and underfloor converters were installed in place of the stock system, one set on each bank, in locations similar to the stock system. The close-coupled converters utilized high cell density substrates and an advanced Pd-only catalyst. Additional details are discussed below.

- An electric air pump (vehicle powered) with a single point air injection probe on each bank, and a UEGO sensor for feedback to the control system were added to the vehicle.

- A water-cooled EGR transfer tube was developed using the stock transfer tube component.

The close-coupled converters employed two ceramic substrates configured in a cascade manner. The first position employed a 76 mm dia. x 76 mm long, 600 cpsi/4 mil wall thickness ceramic substrate coated with an advanced Pd-only catalyst (250 g/ft^3 Pd). The second position of the cascade utilized a 101.6 mm dia. x 85 mm long, 400 cpsi/4 mil wall thickness ceramic substrate coated with an advanced Pd/Rh catalyst (150 g/ft^3 Pd/Rh = 9/1). The underfloor position contained a 101.6 mm dia. x 111.3 mm long, 400 cpsi/4 mil wall thickness ceramic substrate coated with an advanced Pd/Rh catalyst (80 g/ft^3 Pd/Rh = 9/1).

The strategies employed during the emissions tuning phase of the program focused on balancing cold- and hot-start enrichment, providing cold-start NOx control, and modifying EGR control during hard accelerations. During the emissions tuning phase of the program, the following control parameters were modified and tuned:

- Closed-loop secondary air injection for exhaust A/F control during cold- and hot-start open-loop operation.

- Mode activated EGR control modification (intercept control triggered by conditions defining a moderate to hard vehicle acceleration).

- Cold-start EGR control (first 50 seconds of the FTP driving cycle).

Following the tuning phase, the advanced emission system for the Ford Crown Victoria was bench engine aged for 100 hours using the 820°C RAT-A schedule. Figure 12 shows the tuned FTP NMOG and NOx results for the Crown Victoria with the advanced catalyst system at 4,000 miles and after 100 hours of engine aging, compared to the stock (Tier 1 system) 4,000-mile results and the 120,000 mile Tier 2, Bin 5 standards (equivalent to LEV II LEV standards). CO FTP emissions, although not included in Figure 12, were far below Tier 2 or LEV II requirements for all system configurations evaluated in this program.

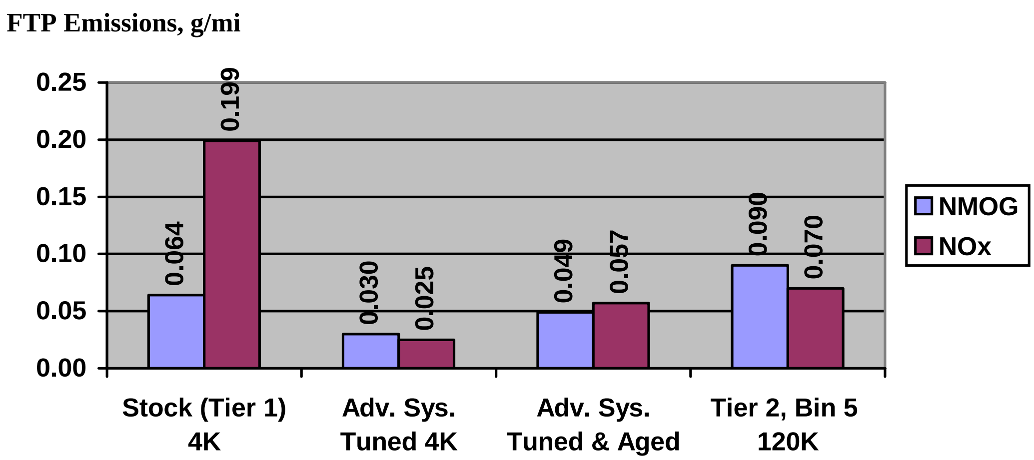


Figure 12. FTP emission performance of a 1997 Ford Crown Victoria equipped with an advanced emission control system

3.1.2 1997 Tier 1 Toyota T100

The Toyota T100 tested had a six-cylinder (V-6), 3.4 liter engine with a single exhaust and a four-speed automatic transmission. The Tier 1 compliant, stock exhaust emission control system included a single underbody catalytic converter and dual EGO sensors (before and after the catalyst). The underbody converter utilized a 400 cpsi ceramic substrate. This vehicle did not have an external EGR system.

During installation of the advanced emission system the following hardware modifications were made:

- Dual closed-coupled and a single underbody converter all utilizing high cell density, metallic substrates, with Pd-based advanced catalysts were installed in place of the stock underbody catalyst. Additional details are discussed below.

- The stock EGO sensors were moved to before and after the passenger side close-coupled catalyst.

- An additional stock EGO sensor was installed upstream of the driver side close-coupled catalyst.

- An electric air pump with port air injection probes on each bank of the V-6, and dual UEGO sensors for feedback to the control system were added to the vehicle.

The dual close-coupled converters on this vehicle were configured one on each cylinder bank of the stock V-6 engine. The exhaust outlet pipes of these dual close-coupled converters were then joined and into a single exhaust line that contained the single underbody converter. In each case, the close-coupled and underbody converters utilized 98.6 mm dia. x 130 mm long, 600 cpsi metallic substrates (30 micron thick metal foil walls) coated with an advanced trimetallic catalyst (250 g/ft^3 Pt/Pd/Rh = 1/22/2).

The strategies employed during the emissions tuning phase of the program focused on balancing cold-start engine enrichment, and correcting the effect of high speed fuel-control imbalances (caused by conversion of the exhaust from a single to a dual configuration, thereby removing A/F feedback from one bank). The following controls were modified or added and tuned:

- Closed-loop secondary air injection for exhaust A/F control during cold-start open-loop operation.

- Primary EGO sensor control switching at vehicle speeds greater than 40 mph to compensate for flow induce A/F imbalance caused by the new exhaust configuration.

Following the tuning phase, the advanced emission system for the Toyota T100 was bench engine aged for 125 hours using the 820°C RAT-A schedule. Figure 13 shows the 4,000 mile and the 125-hour aged, tuned FTP NMOG and NOx emissions results for the Toyota T100 pick-up with the advanced catalyst system compared to the stock (Tier 1) 4,000-mile results and the 120,000 mile Tier 2, Bin 5 standards (equivalent to LEV II LEV standards). CO FTP emissions, although not included in Figure 13, were far below Tier 2 or LEV II requirements for all system configurations evaluated in this program.

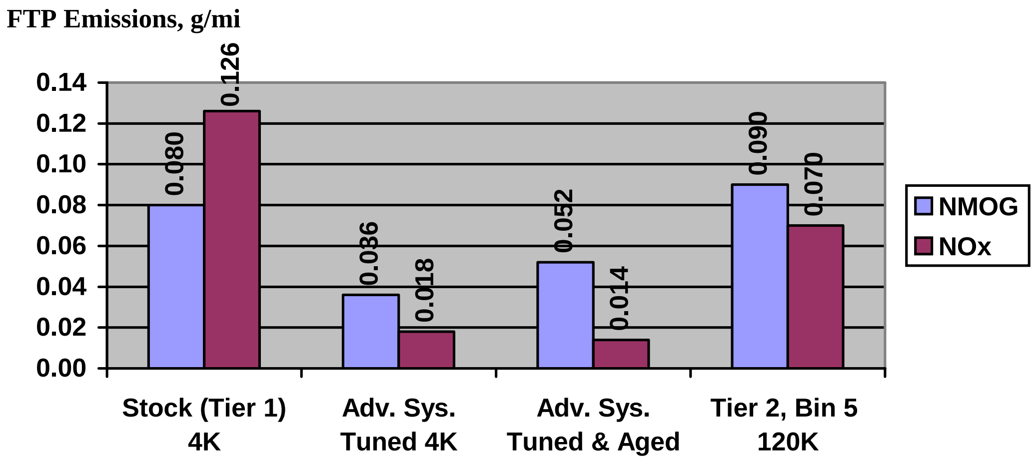


Figure 13. FTP emission performance of a 1997 Toyota T-100 light-duty truck equipped with an advanced emission control system

3.1.3 1999 Tier 1 Chevrolet Silverado

The Silverado tested was classified as a LDT3 weight class light-duty truck and was certified as an EPA Tier 1 vehicle. The vehicle had a new generation 5.3 liter Vortec V-8 engine with dual exhaust, and a four-speed automatic transmission. The stock exhaust emission control system included two closed-coupled cylindrical catalysts (one per bank), and four EGO sensors (before and after each catalyst). The stock Tier 1 converters on this light-duty truck employed standard cell density, ceramic substrates. During installation of the advanced emissions control system, the following hardware modifications were made:

- The stock catalysts were replaced with dual closed-coupled high cell-density ceramic substrates with advanced Pd-based catalysts. Additional details are discussed below.

- The stock front EGO sensors were moved about one foot closer to the engine to accommodate the new installation.

- An electric air pump, (operated using vehicle power) with single point air injection probes on each bank, and dual UEGO sensors for feedback to the control system were added to the vehicle.

Each bank of the dual advanced converter system contained a close-coupled converter that utilized a 54.6 mm dia. x 55.5 mm long, 600 cpsi/4 mil wall thickness ceramic substrate. The close-coupled converters contained an advanced Pd/Rh catalyst (217 g/ft^3 Pd/Rh = 11.5/1). The close-coupled converter was followed by a larger converter that contained three 118.4 mm dia. x 80.3 mm long, 600 cpsi/4 mil wall thickness ceramic substrates. The first substrate location in this larger converter was coated with an advanced Pd-only catalyst (200 g/ft^3 Pd), with the second and third substrate locations coated with an advanced Pd/Rh catalyst (112 g/ft^3

Pd/Rh = 8.3/1).

The strategies employed during the emissions tuning phase of the program focused on balancing cold-start engine enrichment, providing NO_x control during cold-start, shifting the overall exhaust A/F bias slightly, and eliminating hot-start engine enleanment strategies. The following controls were modified or added and tuned:

- Closed-loop secondary air injection for exhaust A/F control during cold-start open-loop operation.
- Closed-loop EGR control during cold-start (the stock EGR system was inactive during cold-start phase).
- EGO switch point shifting to allow for exhaust bias adjustment.
- Fuel injector interception during hot-start to eliminate engine enleanment.

Following the tuning phase, the advanced emissions system was bench-aged for 125 hours using the 820°C RAT-A schedule. Figure 14 shows the 4,000 mile and the 125-hour aged, tuned FTP NMOG and NOx emissions results for the Chevrolet Silverado with the advanced system. Also shown in the figure are the FTP NMOG and NOx emission results for the stock (Tier 1) system at 4,000 miles and the 120,000 mile Tier 2, Bin 5 standards (equivalent to LEV II LEV standards). CO FTP emissions, although not included in Figure 14, were far below Tier 2 or LEV II requirements for all system configurations evaluated in this program.

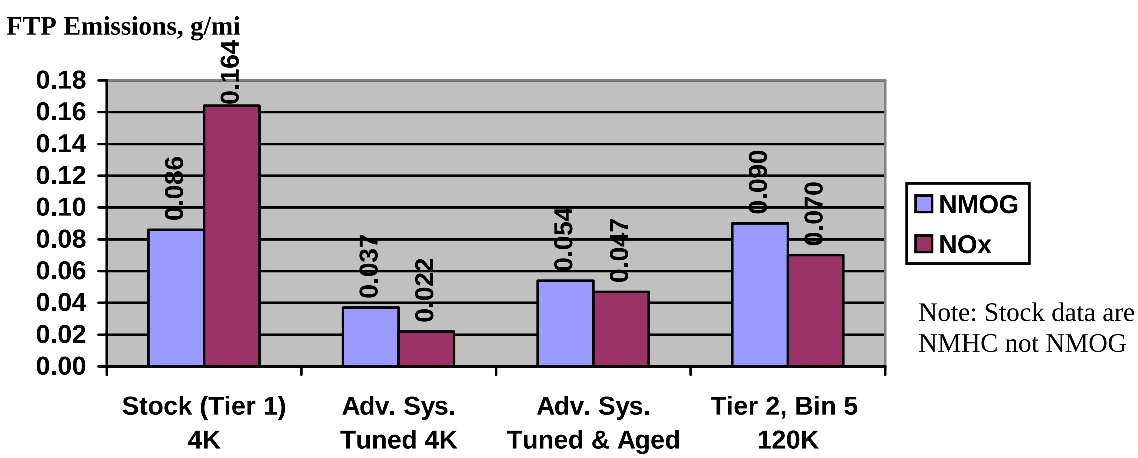


Figure 14. FTP emission performance of a 1999 Chevrolet Silverado light-duty truck equipped with an advanced emission control system

3.2 MECA Light-Duty Vehicle Demonstration Program Summary

The composite FTP emissions for the 100-hour aged Ford Crown Victoria, and the 125-hour aged Toyota T100 and Chevrolet Silverado light-duty trucks with tuned advanced emission technology systems, were below the 120,000 mile tailpipe emission standards for both the EPA Tier 2, Bin 5 and California LEV II LEV certification categories. A fourth test vehicle, a 1997 Buick LeSabre, was also evaluated with an advanced emission control system featuring high cell density substrates, advanced three-way catalysts, and air gap insulated exhaust components. The 100-hour aged FTP performance of this advanced emission system on the Buick LeSabre was also below the EPA Tier 2, Bin 5 and California LEV II LEV certification emission levels (52).

The results from this test program provide clear evidence that a variety of advanced emission control technologies are available to significantly lower tailpipe emission levels from Federal Tier 1 levels to LEV emission levels associated with the California LEV II program and Tier 2, Bin 5 emission levels associated with the EPA Tier 2 regulations. This program was especially successful in demonstrating very low NOx tailpipe emission levels (below 0.07 g/mi for each of the three aged systems evaluated), a key feature of both the light-duty Tier 2 and LEV II programs. Also, this program provides evidence that a light-duty truck, when equipped with an advanced emission control system, was capable of reaching similar ultra-low emission levels as the passenger cars evaluated in this program, another key feature of both the Tier 2 and LEV II programs.

Although not detailed in this paper, speciated hydrocarbon emission results obtained as a part of this test program allowed for comparisons between toxic hydrocarbon emissions (e.g., benzene, formaldehyde, acetaldehyde, 1,3 butadiene) on test vehicles in their stock Tier 1 configurations with the Tier 2 compliant, tuned, advanced emission technology systems. The total toxic emissions for each vehicle with the tuned, 4,000 mile advanced technology systems were considerably lower than the 4,000 mile stock vehicle systems. The large reductions observed in toxic emissions with the advanced catalyst systems on each of the three vehicles tested highlights the synergy between improved hydrocarbon performance and improved performance in reducing toxic emissions. Technologies aimed at improved cold-start hydrocarbon emission performance, in general, also provide significant reductions in toxic emissions. Figure 15 compares averaged toxic hydrocarbon FTP emissions for the vehicles tested in the MECA program with data published by the U. S. Auto/Oil program for several different vehicle fleets (all test data obtained with California Phase II reformulated gasoline). This comparison shows dramatic reductions in toxic hydrocarbon emissions as vehicle and emission technology moved from the mid-1980s, to Tier 1 compliant vehicles, to the Tier 2/LEV II compliant vehicles evaluated in the MECA test program. Data shown for the Auto/Oil "Advanced Technology Fleet" in Figure 15 are representative of LEV I compliant vehicles.

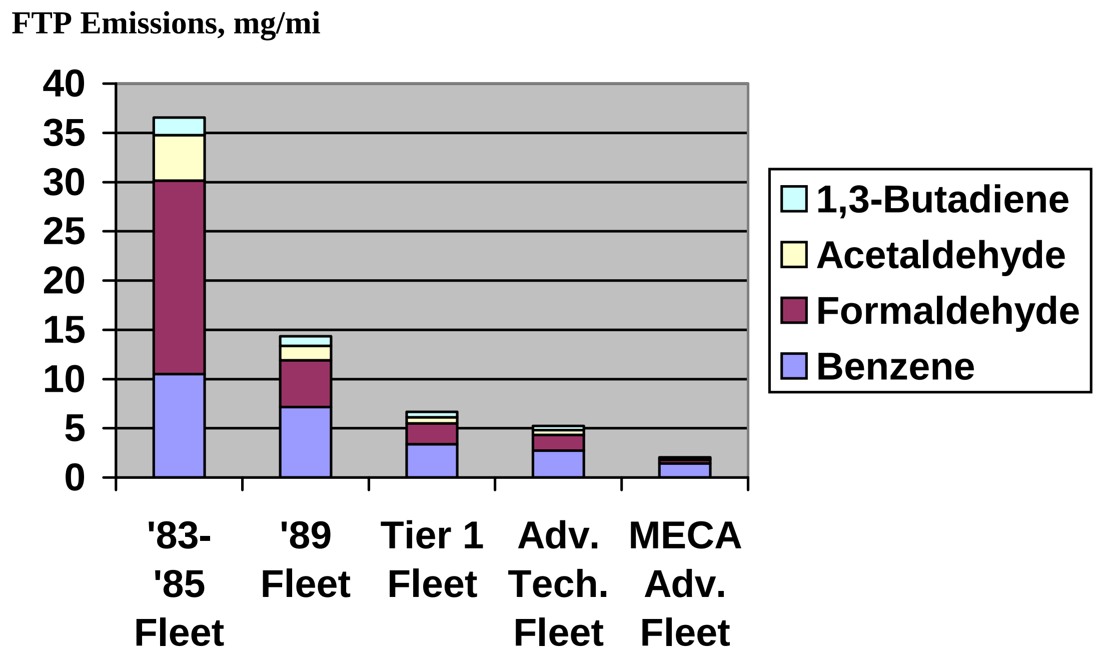


Figure 15. Toxic hydrocarbon FTP emissions from various light-duty vehicle fleets fueled with California Phase II reformulated gasoline [data for non-MECA fleets taken from U.S. Auto/Oil test programs]

The MECA test program results exhibit the importance of the systems design approach on vehicle emission performance. In order to reach the Tier 2 and LEV II levels demonstrated by each of the test vehicles, it was important and necessary to install advanced emission control systems and to modify selected engine control parameters. In each case, the test vehicles made use of advanced converter technologies that were passive in design. They incorporated advanced catalyst formulations, high cell density ceramic and metallic substrates, and close-coupled converter technologies. Due to constraints of the scope of this test program, no effort was made to determine optimal emission system characteristics (e.g., converter system volumes in either the close-coupled or underfloor locations, total precious metal content) or completely optimized engine calibration strategies required to reach the Tier 2, Bin 5 or LEV II emission goals on any of the test vehicles. However, the design approaches used on these test vehicles demonstrate that advanced emission control components and their associated performance characteristics, along with engine operating strategies are all elements of an integrated suite of emission control options that must be utilized and optimized with respect to each other in order to achieve the low emission requirements of the Tier 2 and LEV II regulatory programs. Systems integration and optimization are critical to maximizing the emission performance and durability needed to maintain the low hydrocarbon, CO, and NOx emissions over the entire useful life (e.g., 120,000 miles of driving) of the vehicle.

4.0 MECA Large Light-Duty Truck Test Program

MECA conducted a test program in the 2005-2006 timeframe to test the potential for achieving ultra-low HC and NOx emissions from large light-duty gasoline vehicles (for a more complete discussion of the MECA light-duty truck test program see SAE paper no. 2007-01-1261). The goal of the program was to select two, heavy light-duty trucks or SUVs (LDT3/LDT4), apply advanced emission control technologies, and integrate the emission control technologies with the engines to demonstrate the potential for achieving ultra-low hydrocarbon and NOx emission levels on large, heavier light-duty vehicles.

Two large, heavy light-duty gasoline vehicles (2004 model year Ford F-150 with a 5.4 liter V8 and GMC Yukon Denali with a 6.0 liter V8) were baselined for emission performance over the FTP driving cycle in their stock configurations. Advanced emission systems were designed for both vehicles employing advanced three-way catalysts, high cell density ceramic substrates, and advanced exhaust system components. The engine-aged, advanced emission systems of both vehicles produced ultra-low hydrocarbon and NOx emissions at exhaust levels significantly below California's 120,000 mile LEV II ULEV emission standards.

4.1 F-150 and Denali Baseline Stock Emissions

The stock emission system on the GMC Denali included only one catalytic converter per cylinder bank of the V8 engine. These converters were located approximately at the toe-board position in the exhaust system (i.e., not a close-coupled location relative to the outlet of the engine's exhaust manifolds). The stock emission system on the Ford F-150 included close-coupled converters located near the exit of each the engines exhaust manifolds, followed by a second, underfloor converter on each bank of the V8.

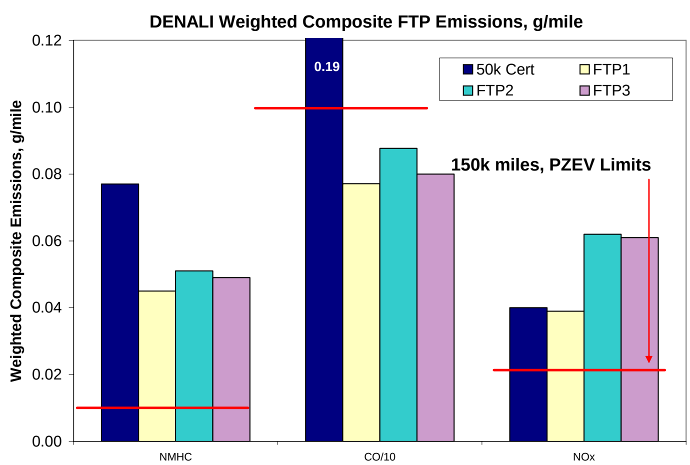


Figure 16. Weighted FTP Stock, Baseline Emissions – Denali

Table 6. FTP Certification, Stock and 150K PZEV Limits – Denali

	50K miles EPA Cert. Data	120K miles EPA Cert. Data	Measured, 4K miles	PZEV, 150K miles standard
NMHC or NMOG, g/mile	0.077	0.087	0.048	0.01
CO, g/mile	1.9	2.2	0.8	1.0
NOx, g/mile	0.04	0.08	0.054	0.02

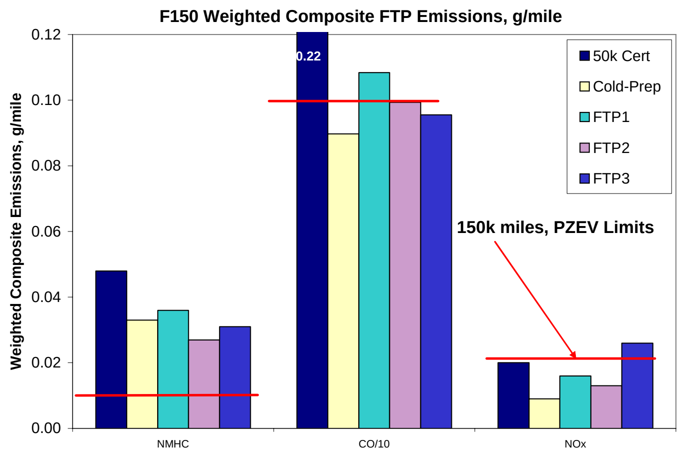


Figure 17. Weighted FTP Stock, Baseline Emissions – F-150

Table 7. FTP Certification, Stock and 150K PZEV Limits – F-150

	50K miles EPA Cert. Data	120K miles EPA Cert. Data	Measured, 4K miles	PZEV, 150K miles standard
NMHC or NMOG, g/mile	0.048	0.054	0.032	0.01
CO, g/mile	2.2	2.6	0.982	1.0
NOx, g/mile	0.02	0.03	0.016	0.02

4.2 F-150 Advanced Catalyst System Emission Results

FTP emission results obtained with the F-150 equipped with the de-greened advanced emission system, operated using the vehicle's stock engine calibration are summarized in Table

8. The advanced system with its advanced catalyst formulations and high cell density ceramic substrates significantly reduced NMHC and NOx emissions relative to the stock emission system. The largest impacts of the advanced emission system were in reducing cold-start and hot-start hydrocarbon emissions and cold-start NOx emissions. FTP NOx emissions with the low mileage, advanced emission system were well below the California SULEV full useful life NOx standard of 20 mg/mi.

Table 8. F-150 Weighted FTP Emissions for Advanced System with the Baseline Engine Control Calibration

Test	Weighted FTP Emissions, g/mile			Fuel Economy, mpg
	NMHC	CO	NOx	
Test 1	0.021	0.749	0.002	13.6
Test 2	0.020	0.692	0.001	13.5
Test 3	0.023	0.806	0.001	13.5
Test 4	0.024	0.812	0.002	13.6
Average, Adv. Sys	0.022	0.765	0.002	13.6
Average, Stock	0.032	0.982	0.016	13.3

The advanced emission system designed for the F-150 was then aged for 220 hours on an engine dynamometer. The aged F-150 advanced emission system was then re-installed on the vehicle and a duplicate set of FTP tests was conducted on consecutive days using the stock engine calibration strategy. Table 9 shows result of each test, the average of the two tests, and the average values for the tests conducted with the advanced emission system before accelerated engine aging.

Table 9. F-150 Weighted FTP Emissions Results with De-Greened and Aged Advanced Emission System Using the Stock Engine Calibration

Test ID	NMHC g/mile	CO g/mile	NOx g/mile	MPG
Test 1	0.032	6.2	0.042	13.4
Test 2	0.036	10.8	0.025	13.4
Avg. Aged	**0.034**	**8.5**	**0.034**	**13.4**
Avg. De-greened	**0.022**	**0.77**	**0.002**	**13.6**

The aged, advanced emission system on the F-150 showed a large increase in NOx emissions, a moderate increase in NMHC emissions, and more than a ten-fold increase in CO emissions. In an absolute emission sense, the aged advanced system is still capable of very low NMHC and NOx emissions on this vehicle with the F-150's stock engine calibration. Average, aged results for the advanced system with respect to NMHC and NOx are at levels that are below ARB's 120K mile LEV II ULEV limits for these two regulated pollutants (120K LEV II ULEV limits: 55 mg/mi NMOG and 70 mg/mi NOx). The high value for CO emissions observed with the aged, advanced system may stem, in part, from the stock air-fuel control strategy. The stock calibration appeared to have a rich bias with frequent net rich and net lean air-fuel excursions under various transient conditions. The rich bias of this air-fuel strategy is also likely responsible for the extremely low NOx emissions observed on this vehicle with the de-greened advanced system.

4.3 Denali Advanced Catalyst System Emission Results

After installation on the Denali and break-in, the FTP emissions were established for the advanced emission system with the stock vehicle calibration. Table 10 lists the values for each FTP test run with the advanced catalyst system and the average of the two tests compared to the average baseline stock vehicle results. Figures 18 and 19 compare the accumulated modal total hydrocarbon and NOx emissions, respectively, for the Denali equipped with the advanced emission system and the stock system, tested with the vehicle's stock engine calibration strategy. The advanced system with its close-coupled + underfloor converter configuration utilizing advanced catalyst formulations and substrates significantly lowered hydrocarbon and NOx emissions in each phase of the FTP, including large reductions in cold-start and hot-start emissions.

Table 10. Weighted FTP Emissions for Advanced System with Stock Denali Engine Calibration

Test	Weighted FTP Emissions, g/mile			Fuel Economy, mpg
	NMHC	CO	NOx	
Test 1	0.016	0.338	0.016	13.0
Test 2	0.017	0.356	0.019	12.9
Average, Adv. System	0.017	0.347	0.018	13.0
Average, Stock	0.048	0.816	0.054	12.7

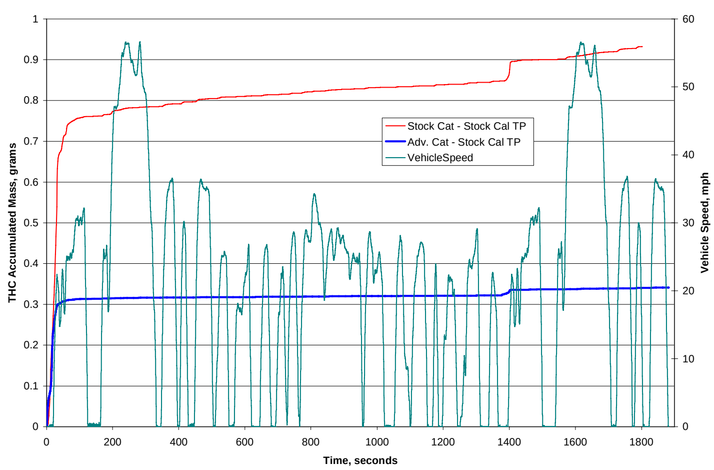


Figure 18. Accumulated THC Mass Emissions for the Denali Stock and Advanced System, both with the Stock Vehicle Calibration

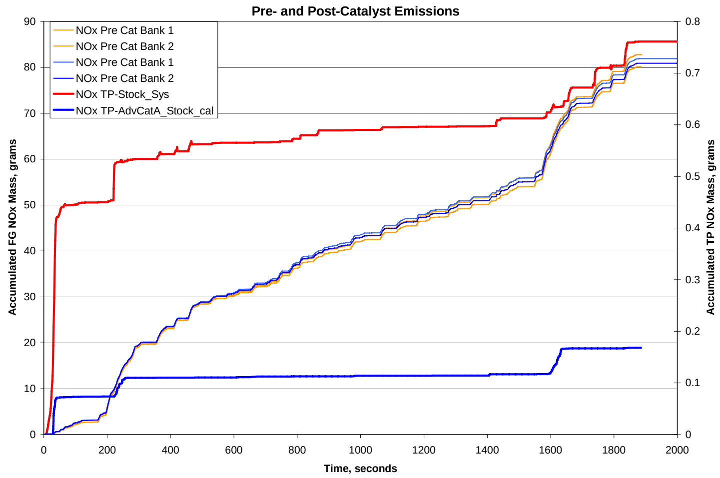


Figure 19. Modal NOx Emissions for the Denali Stock and Advanced System, both with the Stock Vehicle Calibration

Following these emission tests using the Denali's stock engine calibration strategy, work was completed to modify the Denali's stock calibration strategy to further optimize the emission performance of this vehicle. The calibration work focused on two main areas: a revised cold-start strategy that would accelerate close-coupled catalyst heat-up and selective air/fuel control biasing under driving conditions that showed NOx breakthrough emissions with the stock calibration strategy.

For the modified cold-start strategy, the cold spark-timing was retarded by 12 degrees more than the stock calibration timing while the vehicle's transmission was in the park position. Following a cold-start, the idle speed was increased from 900 rpm to 1100 rpm. Spark timing was also retarded approximately 5 degrees when the vehicle was shifted into drive and during the first acceleration of the first "hill" of the FTP. Less significant changes at cold-start included reducing the cranking volumetric efficiency table by 30 percent, increasing the target air-fuel ratio by 15 percent, and enabling closed-loop control immediately after crank. These cold-start strategies have been shown by others to be effective in increasing catalyst heat-up rates and reducing cold-start emissions, and work done as a part of this program also showed this modified cold-start strategy was successful in accelerating the heat-up of the advanced emission system's close-coupled converters at the start of the FTP. With the use of this modified cold-start strategy, the catalyst bed temperature of the close-coupled converters installed on the Denali, reached 350°C in approximately 10 seconds compared to 16 seconds with the stock calibration strategy. Catalyst bed temperatures were measured on the substrate centerline at a depth of 1-inch from the front face.

With respect to improvements in NOx emission performance, at high-speed, high-load conditions, as in the second "hill" of the FTP test, the spark timing was retarded three degrees relative to the stock calibration to reduce NOx breakthrough. Finally, on the hot-start, the air-fuel ratio was biased slightly rich to eliminate a NOx spike at the start of the first "hill" following the hot-start.

FTP emission tests were then completed on the Denali with the advanced emission system and the modified calibration strategy. The results of these triplicate tests are given in Table 11. The advanced emission system combined with the modified engine calibration strategies provided significant additional reductions for all three regulated pollutants and produced exhaust emission levels with these low mileage catalysts that were below the California SULEV full useful life exhaust emission limits of 10 mg/mi NMOG, 1.0 g/mi CO, and 20 mg/mi NOx.

The advanced emission system designed for the Denali was then aged for 220 hours on an engine dynamometer. The aged Denali advanced emission system was then re-installed on the vehicle and a set of three FTP tests was conducted on consecutive days using the modified engine calibration strategy discussed above. Table 12 shows result of each test, the average of the three tests, and the average values for the triplicate tests conducted with the catalyst system before accelerated engine aging.

Table 11. Denali Low-Mileage FTP Emissions Results with the Advanced Emission System and Modified Engine Calibration

Test	Weighted FTP Emissions, g/mile			Fuel Economy, mpg
	NMHC	CO	NOx	
Test 1	0.010	0.226	0.014	12.3
Test 2	0.009	0.193	0.008	12.6
Test 3	0.009	0.212	0.012	12.6
Avg. Adv. System with Mod. Cal.	0.009	0.210	0.011	12.5
Avg. Adv. System with Stock Cal.	0.017	0.347	0.018	13.0
Avg. Stock System	0.048	0.816	0.054	12.7

Table 12. Denali Advanced System Weighted FTP Emissions Summary Before and After Engine Aging

Test ID	NMHC, g/mi	CO, g/mi	NOx, g/mi	MPG
Test 1	0.018	0.332	0.027	12.7
Test 2	0.027	0.467	0.028	12.9
Test 3	0.033	0.804	0.041	12.7
Average Aged	0.026	0.534	0.032	12.8
Average De-greened	0.009	0.210	0.011	12.5

The FTP results for the aged advanced system show more than a two-fold increase in regulated emissions compared to the de-greened system. On an absolute emissions basis, however, this aged system is still achieving very low hydrocarbon, CO, and NOx emissions on this large test vehicle. The average, aged FTP emission results for this advanced emission system and modified engine calibrations are well below ARB's 120K mile LEV II ULEV limits (55 mg/mi NMOG, 70 mg/mi NOx, and 2.1 g/mi CO) and marginally below the 50K mile LEV II ULEV limits (40 mg/mi NMOG, 50 mg/mi NOx, and 1.7 g/mi CO). These aged results are also well below the 120K mile EPA Tier 2, Bin 3 limit for NMOG (55 mg/mi) and just above the 120K mile Tier 2, Bin 3 NOx limit (30 mg/mi). Some small changes in engine-out hydrocarbon and NOx emissions were observed over the course of this testing on the Denali. The increases observed in tailpipe THC and NOx emissions for the advanced emission system after engine aging are largely associated with higher cold-start and hot-start emissions during the first and last 505 seconds of the FTP.

4.4 MECA Large Light-Duty Truck Test Program Summary

Both test vehicles were able to demonstrate ultra-low hydrocarbon and NOx exhaust emissions using similar, but not identical, aged, advanced emission systems designed for each vehicle. These advanced emission system designs incorporated three-way catalyst formulations, ceramic substrate designs, and exhaust components that are commercially available and are consistent with advanced emission system designs used to achieve ultra-low exhaust emissions on smaller, light-duty vehicles including four, five and six-cylinder passenger cars certified to California's SULEV emission standards.

Although some degradation in emission performance was observed for both advanced systems following the 220 hours of engine aging, it is important to note that in most cases these aged, advanced systems are still performing at high conversion efficiency for hydrocarbons and NOx. Figures 20, 21, and 22 compare the catalyst system efficiency for hydrocarbons, CO, and NOx during each FTP test phase before and after catalyst aging for the advanced system design used on the Denali. Aged catalyst efficiencies for this system were 99+ percent for NOx for all FTP phases, while hydrocarbon and CO aged catalyst efficiencies remained above 92 percent in the cold-start phase of the FTP (Bag 1), and greater than 96 percent efficiency in the stabilized

(Bag 2) and hot-start (Bag 3) phases of the driving cycle.

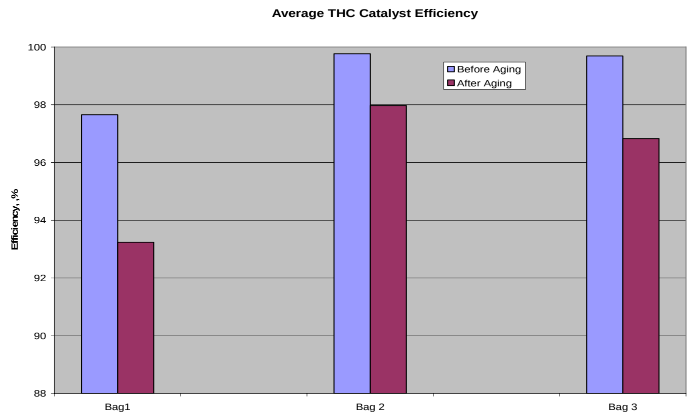


Figure 20. Denali THC Catalyst Efficiency Comparison Before and After Advanced System Aging

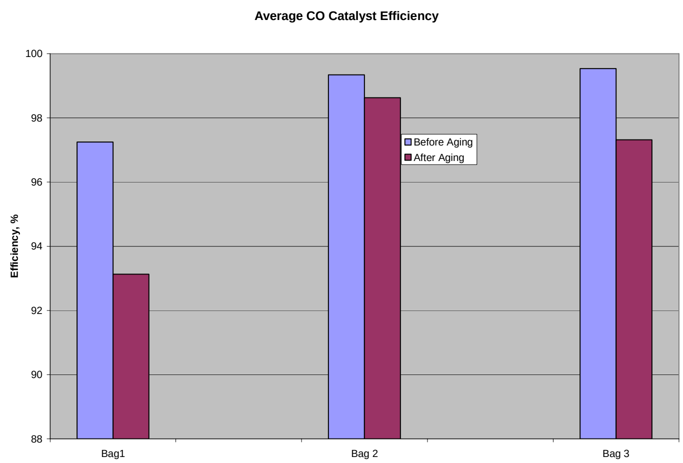


Figure 21. Denali CO Catalyst Efficiency Comparison Before and After Advanced System Aging

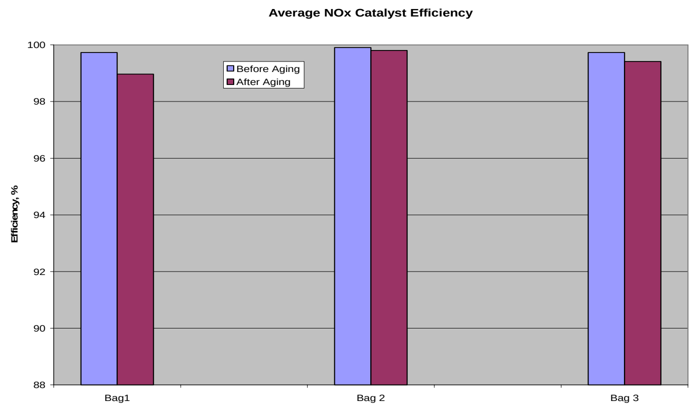


Figure 22. Denali NO_X Catalyst Efficiency Comparison Before and After Advanced System Aging

Achieving ultra-low emissions on heavy, light-duty vehicles like the two used in this program, is achievable using a systems approach that includes advanced engine controls and advanced emission system designs. This program achieved these low exhaust emissions primarily through advanced emission system designs and relatively, straight-forward engine calibration strategies. Other system parameters not evaluated as a part of this program, can also be further optimized on large, light-duty vehicles and provide additional opportunities for further emission reductions from such vehicles. These additional system options include more effective exhaust thermal management strategies such as lighter-weight exhaust manifolds, more sophisticated air-fuel control strategies, and more advanced fuel injection systems that help facilitate lean cold-start strategies. In some cases some engine-based system strategies may focus more on reducing engine-out emissions as part of an overall systems approach to achieving ultra-low exhaust emissions. Given the large engine-out emission profiles associated with large displacement engines, combinations of optimized engine-based and emission system strategies are required to achieve and maintain ultra-low emissions on large light-duty vehicles.

5.0 Market Penetration of Advanced Emission Control Technologies

The high performance attributes of advanced catalysts and high cell density substrates, coupled with the need to meet more stringent emission standards such as Tier 2 and LEV II standards in the U.S. have resulted in strong acceptance and market demand for these technologies. Substrate suppliers, for example, estimate that in 2003 approximately 50% of the substrates used in North American light-duty vehicle applications were “standard” 400 cpsi designs with the remaining 50% of production targeting thin wall and ultra thin wall ceramic and metallic substrate designs, including cell densities of 600 cpsi or higher. Market projections indicate that the application of these advanced thin wall and ultra thin wall high cell density substrates will expand to approximately 75% of the North American light-duty applications by 2007.

Similar strong current use and growth for these advanced substrates is forecast for light-duty vehicle applications in Japan, Europe, and Korea. Like the U.S., demand for advanced high performance emission technologies in these markets is driven by tighter light-duty emission standards that are being implemented during this decade (e.g., Japan and Korea's Low Emission Vehicle programs, Japan's voluntary introduction of vehicles surpassing their LEV requirements, and Euro 3 and Euro 4 emission regulations). More than 80% of the substrates produced in 2003 for Japan light-duty applications are expected to be advanced, thin wall and ultra thin wall designs. By 2007 this advanced substrate demand will grow to more than 90% of the light-duty applications in Japan. European light-duty substrate usage closely mirrors the North American projections with 2003 usage levels of advanced substrates of about 50% growing to approximately 75% by 2007. Korean light-duty applications are currently heavy users of "standard" 400 cpsi substrates, but penetration of advanced substrates is expected to grow in this market significantly by 2007 (from approximately 20% usage in 2003 to 45% usage in 2007). Market demand for advanced substrates is also forecast to grow in developing regions of the world as they begin to implement tighter vehicle emission standards. For example, light-duty vehicles in China and other developing markets in Asia are forecast to shift from the current exclusive use of "standard" 400 cpsi substrates to in excess of 30% thin and ultra thin wall designs including high cell density (e.g., 600 cpsi), advanced substrates by 2007. India, Brazil, and Mexico are other countries like China that will be implementing more stringent emission regulations for hydrocarbons and/or NOx on light-duty vehicles during this decade. As these emission regulations are implemented, emissions systems will be redesigned for higher performance putting more emphasis on advanced catalysts and advanced, high cell density substrates.

Catalyst manufacturers, as well, are already producing significant fractions of their total light-duty catalyst production using advanced materials and advanced design strategies highlighted previously in this paper. These advanced TWC formulations are being produced on both "standard" 400 cpsi substrates, as well as new thin wall and ultra thin wall, advanced high cell density ceramic and metallic substrates. Continuous improvement of advanced catalyst formulations through the introduction of new materials and new processing methods is an integral feature of the catalyst development cycles used by the industry.

Substrate manufacturers, catalyst manufacturers, converter packaging material suppliers, and exhaust component manufacturers have all made multi-million dollar investments in both the development of new advanced emission control technologies and the high production manufacturing equipment required to produce automotive quality products in a cost-effective manner. The current large volume demand for high performance emission technologies, and the future forecasts for growth of these advanced technologies around the globe in light-duty vehicle applications are clear indications that the emission performance benefits associated with advanced emission control technologies are an integral part of the systems approach required to bring light-duty vehicles in compliance with extremely low emission standards like the EPA Tier 2 and California LEV II programs.

6.0 Conclusion

The EPA Tier 2 and California LEV II light-duty programs established demanding emission compliance goals for the full range of light-duty cars and trucks sold across the United States starting with the 2004 model year. Included in these goals are significantly lower hydrocarbon and NOx emission levels and extended durability requirements compared to preceding emission standards for the various weight classes of vehicles included within the light-duty segment. Advanced emission control technologies have been developed and are being used to achieve the high emission conversion efficiencies necessary for Tier 2/LEV II compliance. Tier 2/LEV II vehicles will rely heavily on close-coupled converters, high cell density substrates, advanced three-way catalysts, and other advanced exhaust system components to achieve the fast converter light-off and high conversion efficiencies under all dynamic vehicle operating modes necessary for achieving extremely low emission levels. The performance of these advanced emission technologies depends strongly on integrating and optimizing their operation with other key technologies including advanced engines, advanced engine operating strategies, clean fuels, and clean lubricants. This systems approach is the hallmark of bringing light-duty vehicles into the age of ultra-low emissions. The fact that motor vehicle and emission control manufacturers worldwide are pursuing the system strategies highlighted in this paper is compelling evidence that they represent the most cost effective, technically sound approach to meeting the very stringent emission standards of the future.

References

The references included here provide a comprehensive list of SAE technical papers published between 1998 and early 2003 that discuss the characteristics and performance of the key Tier 2/LEV II advanced emission control technologies highlighted in this paper (close-coupled converters, high cell density substrates, advanced three-way catalysts). A few pre-1998 SAE technical papers have also been included in this reference list. The reference list is organized by year of publication with 2003 papers listed first followed by successively later publication years. Details of the MECA light-duty truck test program discussed in section 4.0 of this report can be found in SAE paper 2007-01-1261.

1. SAE 2003-01-0819: "FTP and US06 Performance of Advanced High Cell Density Metallic Substrates as a Function of Varying Air/Fuel Modulation" K. Mueller-Haas, R. Brueck, both of Emitec; J. Rieck of Johnson Matthey; C. Webb, K. Shaw, both of Southwest Research Institute; SAE 2003 International Congress, Detroit
2. SAE 2003-01-0817: "Development of PZEV Exhaust Emission Control System" T. Kidokoro, K. Hoshi, K. Hiraku, K. Satoya, T. Watanabe, T. Fujiwara, all of Toyota; H. Suzuki, Denso; SAE 2003 International Congress, Detroit
3. SAE 2003-01-0816: "Development of Third Generation Gasoline PZEV Technology" H. Oguma, M. Koga, S. Momoshima, K. Nishizawa, S. Yamamoto, all of Nissan; SAE 2003 International Congress, Detroit
4. SAE 2003-01-0815: "A Catalyzed Hydrocarbon Trap Using Metal-impregnated Zeolite for SULEV Systems" K. Higashiyama, T. Nagayama, M. Nagano, S. Nakagawa, all of Hitachi; S. Tominaga, K. Murakami, I. Hamada, all of Babcock-Hitachi; SAE 2003 International Congress, Detroit
5. SAE 2003-01-0814: "Development of a Low Precious-metal Automotive Perovskite Catalytic System for LEV-II" Y. Matsuzono, M. Sakanushi, H. Kitagawa, all of Honda; SAE 2003 International Congress, Detroit
6. SAE 2003-01-0813: "Design of a Practical Intelligent Catalyst" N. Sato, K. Narita, M. Kimura, all of Cataler; H. Tanaka, I. Tan, M. Uenishi, N. Kajita, M. Taniguchi, all of Daihatsu; SAE 2003 International Congress, Detroit
7. SAE 2003-01-0812: "Research on the Co-free Intelligent Catalyst" I. Tan, H. Tanaka, M. Uenishi, N. Kajita, M. Taniguchi, all of Daihatsu; Y. Nishihata, J. Mizuki, both of the Japan Atomic Energy Research Institute; SAE 2003 International Congress, Detroit
8. SAE 2003-01-0811: "Development of Three-way Catalyst Using Composite Alumina-Ceria-Zirconia" T. Kanazawa, J. Suzuki, T. Takada, T. Suzuki, A. Morikawa, A. Suda, H. Sobukawa, M. Sugiura, all of Toyota; SAE 2003 International Congress, Detroit
9. SAE 2003-01-0658: "Impact of Ultra Thinwall Catalyst Substrates for TIER2 Emission Standards" K. Hughes, K. Schmitz, both of Corning; D. Radke of GM; K. Zerafa, B. Light, both of OMG; SAE 2003 International Congress, Detroit
10. SAE 2002-01-0730: "Vehicle Comparison of Advanced Three-way Catalysts and Hydrocarbon Trap Catalysts" T. Ballinger and P. Andersen, both of Johnson Matthey; SAE 2002 International Congress, Detroit
11. SAE 2002-01-0358: "Development of Thinnest Wall Catalyst Substrate" K. Oouchi, K. Shibata, K. Nishizawa, all of Nissan; H. Tanabe, Calsonic; SAE 2002 International Congress, Detroit
12. SAE 2002-02-0356: "Ultra Thin Wall Substrates – Trends for Performance in FTP and US06 Tests" K. Hughes, Corning, and W. Witte, Ford; SAE 2002 International Congress, Detroit

13. SAE 2002-01-0354: "Effect of Cell Geometry on Emissions Performance of Ceramic Catalytic Converters" T. Leonhard and P. Floerchinger, both of Corning; A. Degen, W. Held, S. Hinze, E. Pott, all of VW; SAE 2002 International Congress, Detroit
14. SAE 2002-01-0352: "Ultra Thinwall Light-off Performance – Varying Substrates, Catalysts, and Flow Rates' Models and Engine Testing" K. Hughes and P. Floerchinger, both of Corning; SAE 2002 International Congress, Detroit
15. SAE 2002-01-0350: "Product Design and Development of Ultra Thin Wall Ceramic Catalytic Substrate" Y. Aoki, Y. Miyairi, Y. Ichikawa, F. Abe, all of NGK; SAE 2002 International Congress, Detroit
16. SAE 2002-01-0349: "Utilization of Advanced Three-way Catalyst Formulations on Ceramic Ultra Thin Wall Substrates for Future Legislation" J. Schmidt, J. Franz, N. Merdes, M. Brady, all of DaimlerChrysler; W. Mueller, D. Lindner, T. Bog, D. Clark, all of OMG; T. Buckel W. Stoepler, R. Henninger, H. Ermer, all of Faurecia; F. Abe, M. Makino, A. Kunz, C. Vogt, all of NGK; SAE 2002 International Congress, Detroit
17. SAE 2002-01-0348: "Catalyst Design for Meeting Stringent LEV-2 NOx Regulation" H. Ohmoto, T. Kobayashi, K. Ishikawa, T. Yamada, all of N.E. Chemcat; SAE 2002 International Congress, Detroit
18. SAE 2002-01-0347: "Advanced Performance of Metallic Converter Systems Demonstrated on a Production V8 Engine" R. Brueck, K. Mueller-Haas, Juergen Breuer, all of Emitec; C. Webb of Southwest Research Institute: SAE 2002 International Congress, Detroit
19. SAE 2002-01-0345: "A Systematic Approach towards Low Precious Metal Three-way Catalyst Application" M. Votsmeier, T. Bog, D. Lindner, J. Gieshoff, E. Lox, T. Kreuzer, all of OMG; SAE 2002 International Congress, Detroit
20. SAE 2002-01-0344: "Advanced Low Platinum Group Metal Three-way Catalyst for LEV-II and ULEV-II Compliance" T. Truex, S. Golden, A. Polli, R. Hawthorne, R. Hatfield, M. Cotton, all of Catalytic Solutions; SAE 2002 International Congress, Detroit
21. SAE 2001-01-3664: "Integration of Engine Controls, Exhaust Components, and Advanced Catalytic Converters for ULEV and SULEV Applications" M. Karwa, Ricardo; F. Hill, J. Biel, both of Benteler Automotive; M. Crocker, DMC^2; SAE 2002 Spring Fuels and Lubricants Meeting, Reno
22. SAE 2001-01-1350: "First ULEV Turbo Gasoline Engine – the Audi 1.8 l, 125 kW 5-Valve Turbo" B. Pfalzgraf, M. Fitzen, J. Siebler, H. Erdmann, all of Audi; SAE 2001 International Congress, Detroit
23. SAE 2001-01-1314: "Development of a SULEV Capable Technology for a Full Size Gasoline PFI V8 Passenger Car" M. Karwa, Ricardo; J. Biel, F. Hill, both of Benteler Automotive; M. Crocker, DMC^2; SAE 2001 International Congress, Detroit
24. SAE 2001-01-1310: "Development of Second Generation of Gasoline PZEV Technology" K. Nishizawa, S. Mitsuishi, K. Mori, S. Yamamoto, all of Nissan, SAE 2001 International Congress, Detroit
25. SAE 2001-01-1301: "An Intelligent Catalyst" H. Tanaka, M. Uenishi, I. Tan, all of Daihatsu; M. Kimura, Toyota; J. Mizuki, Y. Nishihata, both of Japan Energy Research Institute; SAE 2001 International Congress, Detroit
26. SAE 2001-01-0930: "Prediction of Catalytic Performance During Light-off Phase with Different Wall Thickness, Cell Density, and Cell Shape" R. Becker, R. Wilson, both of Environex; M. Brayer, C.Vogt, M. Makino, all of NGK; SAE 2001 International Congress, Detroit
27. SAE 2001-01-0929: "Application Guideline to Define a Catalyst Layout for Maximum Catalytic Efficiency" P. Marsh, F. Acke, both of Volvo; R. Konieczny, R. Brueck, P. Hirth, all of Emitec; SAE 2001 International Congress, Detroit
28. SAE 2001-01-0927: "Utilization of Advanced Pt/Rh TWC Technologies for Advanced Gasoline Applications with Different Cold Start Strategies" J. Schmidt, M. Busch, A. Waltner, C. Enderle, B.

Heil, all of DaimlerChrysler; D. Lindner, W. Mueller, L. Mussmann, E. Lox, T. Kreuzer, all of DMC[2]; SAE 2001 International Congress, Detroit
29. SAE 2001-01-0925: "Study of Modern Application Strategies for Catalytic Aftertreatment Demonstrated on a Production V6 Engine" R. Brueck, F. Kaiser, R. Konieczny, all of Emitec; C. Webb, A. Anderson, both of Southwest Research Institute; SAE 2001 International Congress, Detroit
30. SAE 2001-01-0924: "Application of Advanced Three-way Catalyst Technologies on High Cell Density Ultra-thin Wall Ceramic Substrates for Future Emission Legislations" R. Domesle, D. Lindner, W. Mueller, L. Mussmann, M. Votsmeier, E. Lox, T. Kreuzer, all of DMC[2]; M. Makino, C. Vogt, both of NGK; SAE 2001 International Congress, Detroit
31. SAE 2001-01-0923: "Palladium and Platinum/Rhodium Dual-Catalyst NLEV and Tier IIa Close-Coupled Emission Solutions" B. Williamson, R. Richmond, J. Nunan, A. Bortun, H. Robota, all of ASEC; SAE 2001 International Congress, Detroit
32. SAE 2001-01-0660: "Development of the Automotive Exhaust Hydrocarbon Adsorbent" T. Kanazawa, K. Sakurai, both of Toyota; SAE 2001 International Congress, Detroit
33. SAE 2001-01-0659: "Advanced Low Platinum Group Metal Three-way Catalysts for Tier 2 and LEV II Compliance" S. Golden, A. Polli, R. Hatfield, M. Cotton, T. Truex, all of Catalytic Solutions; SAE 2001 International Congress, Detroit
34. SAE 2000-01-2930: "Improvement of a Highly Efficient Hybrid Vehicle and Integrating Super Low Emissions" T. Inoue, M. Kusada, H. Kanai, S. Hino, Y. Hyodo, all of Toyota; SAE 2000 Fall Fuels & Lubricants Meeting, Baltimore
35. SAE 2000-01-2881: "Durability of Ultra Thin Wall Catalyst Solutions at Similar Restriction and Precious Metal Loading" C. Kirby, R. Richmond, D. Ball, G. Tripp, all of Delphi; B. Williamson of ASEC; SAE 2000 Fall Fuels & Lubricants Meeting, Baltimore
36. SAE 2000-01-1954: "The Effect of Aging Temperature on Catalyst Performance of Pt/Rh and Pd/Rh TWCs" K. Nagashima, G. Zhang, T.Hirota, H. Muraki, all of Johnson Matthey; SAE 2000 Spring Fuels & Lubricants Meeting; Paris
37. SAE 2000-01-0892: "In-line Hydrocarbon Adsorber System for Reducing Cold-Start Emissions" S. Yamamoto, K. Matsushita, S. Etoh, M. Takaya, all of Nissan, SAE 2000 International Congress, Detroit
38. SAE 2000-01-0860: "Palladium and Platinum/Rhodium Dual-Catalyst Emission Solutions for Close-Coupled or Underfloor Applications" W. Williamson, D. Ball, D. Linden, M. Zammit, H. Robota, all of ASEC; SAE 2000 International Congress, Detroit
39. SAE 2000-01-0502: "Use of High Cell Density Substrates and High Technology Catalysts to Significantly Reduce Vehicle Emissions" D. Lafyatis, N. Will, A. Martin, J. Rieck, J. Cox, J. Evans, all of Johnson Matthey; SAE 2000 International Congress, Detroit
40. SAE 2000-01-0501: "Comparison of Pd-only, Pd/Rh, and Pt/Rh Catalysts in TLEV, LEV Vehicle Applications – Real Vehicle Data vs. Computer Modeling Results" D. Lindner, L. Mussmann, J. van den Tillaart, E. Lox, A. Roshan, G. Garr, all of DMC[2]; R. Beason, Ford; SAE 2000 International Congress, Detroit
41. SAE 2000-01-0500: "Improved Catalyst Systems for SULEV Legislation: First Practical Experience" G. Holy, AVL; R. Brueck, P. Hirth, both of Emitec; SAE 2000 International Congress, Detroit
42. SAE 2000-01-0494: "Prediction of Catalytic Performance for Ultra Thin Wall And High Cell Density Substrates" K. Umehara, M. Makino, M. Brayer, all of NGK; R. Becker, R. Watson, both of Environex; SAE 2000 International Congress, Detroit
43. SAE 2000-01-0493: "Design Considerations for Advanced Ceramic Catalyst Supports" S. Gulati, Corning; SAE 2000 International Congress, Detroit
44. SAE 1999-01-3631: "Performance Parameters for Advanced Ceramic Catalyst Supports" S. Gulati,

Corning; SAE 1999 Fall Fuels & Lubricants Meeting, Toronto
45. SAE 1999-01-3630: “Evaluation of High Cell Density Substrates for Advanced Catalytic Converter Emissions Control” W. Moore, R. Richmond, G. Vaneman, all of Delphi; D. Dou, ASEC; SAE 1999 Fall Fuels & Lubricants Meeting, Toronto
46. SAE 1999-01-3629: “Emission Reduction Technologies for Turbocharged Engines” S. Mitsuishi, K. Mori, K. Nishizawa, S. Yamamoto, all of Nissan; SAE 1999 Fall Fuels & Lubricants Meeting, Toronto
47. SAE 1999-01-3627: “Development of Advanced Platinum-Rhodium Catalyst for Future Emissions Requirements” R. Brisley, N. Collins, C. French, D. Morris, M. Twigg, all of Johnson Matthey; SAE 1999 Fall Fuels & Lubricants Meeting, Toronto
48. SAE 1999-01-3625: “Low Emission Three-way Catalyst and OSC Material Development for OBD Diagnostics” T. Maunula, A. Vakkilainen, A. Lievonen, K. Torkkell, K. Nishkanen, M. Harkonen, all of Kemira Metalkat; SAE 1999 Fall Fuels & Lubricants Meeting, Toronto
49. SAE 1999-01-3472: “Computer Simulation of the FTP Performance of TWCs” J. Evans, G. Ansell, C. Brown, J. Cox, D. Lafyatis, P. Millington; all of Johnson Matthey; SAE 1999 Fall Fuels & Lubricants Meeting, Toronto
50. SAE 1999-01-1230: “In-line Hydrocarbon Adsorber” N. Noda, H. Mizuno, J. Suzuki, T. Hiramatsu, P. Busch, all of NGK; SAE 1999 International Congress, Detroit
51. SAE 1999-01-0776: “Dual-Catalyst Underfloor LEV/ULEV Strategies for Effective Precious Metal Management” W. Williamson, D. Dou, H. Robota, all of ASEC; SAE 1999 International Congress, Detroit
52. SAE 1999-01-0774: “Using Advanced Emission Control Systems to Demonstrate LEV II ULEV on Light-duty Gasoline Vehicles” C. Webb, B. Bykowski, P. Weber, all of Southwest Research Institute; D. McKinnon of MECA; SAE 1999 International Congress, Detroit
53. SAE 1999-01-0773: “ERIC – A System to Modify Vehicle Emissions through Computer Controlled Signal Interception” C. Webb, Southwest Research Institute; SAE 1999 International Congress, Detroit
54. SAE 1999-01-0772: “Technology for Reducing Exhaust Gas Emissions in Zero Level Emission Vehicles (ZLEV)” N. Kishi, S. Kikushi, N. Suzuki, T. Hayashi, all of Honda; SAE 1999 International Congress, Detroit
55. SAE 1999-01-0770: “The Necessity of Optimizing the Interactions of Advanced Post-Treatment Components in order to Obtain Compliance with SULEV Legislation” R. Brueck, P. Hirth, W. Maus, all of Emitec; SAE 1999 International Congress, Detroit
56. SAE 1999-01-0767: “The Development of a BMW Catalyst Concept for LEV/EU3 Legislation for a 8 Cylinder Engine by using Thin Wall Ceramic Substrates” P. Ehmann, BMW; N. Rippert, Boysen; K. Umehara, C. Vogt, both of NGK; SAE 1999 International Congress, Detroit
57. SAE 1999-01-0309: “Comparison of Pd-only vs. Pd-Rh Catalysts: Effects of Sulfur, Temperature and Space Velocity” D. Lafyatis, C. Bennett, M. Hales, D. Morris, J. Cox, R. Rajaram, all of Johnson Matthey; SAE 1999 International Congress, Detroit
58. SAE 1999-01-0308: “Improvements in Pd:Rh and Pt:Rh TWCs” P. Andersen, T. Ballinger; both of Johnson Matthey; SAE 1999 International Congress, Detroit
59. SAE 1999-01-0307: “Development of Low Light-off Three Way Catalyst” S. Ichikawa, T. Takemoto, H. Sumida, Y. Koda, K. Yamamoto, M. Shigetsu, K. Komatsu, all of Mazda; SAE 1999 International Congress, Detroit
60. SAE 1999-01-0273: “Thermal Shock Resistance of Standard and Thin Wall Ceramic Catalysts” S. Gulati, M. Zak, L. Jones, all of Corning; J. Rieck, M. Russ, both of Johnson Matthey; M. Brady of DaimlerChrysler; SAE 1999 International Congress, Detroit
61. SAE 1999-01-0272: “The Impact of High Cell Density Ceramic Substrates and Washcoat Properties

on the Catalytic Activity of TWCs" J. Schmidt, A. Waltner, G. Loose, A. Hirschmann, A. Wirth, all of DaimlerChrysler; W. Mueller, J. van den Tillaart, L. Mussmann, D. Lindner, J. Gieshoff, all of DMC[2]; K. Umehara, M. Makino, K. Biehn, A. Kunz, all of NGK; SAE 1999 International Congress, Detroit

62. SAE 1999-01-0271: "A Comparison of Emissions and Flow Restriction of Thinwall Ceramic Substrates for Low Emission Vehicles" D. Ball, G. Tripp, Delphi; L. Socha, A. Heibel, M. Kulkarni, Corning; P. Weber, Southwest Research Institute; D. Linden, ASEC; SAE 1999 International Congress, Detroit
63. SAE 1999-01-0269: "Thin Wall Ceramic Catalyst Supports" S. Gulati, Corning; SAE 1999 International Congress, Detroit
64. SAE 1999-01-0268: "High Cell Density and Thin Wall Substrate for Higher Conversion Ratio Catalyst" S. Kikushi, S. Hatcho, T. Okayama, S. Inose, all of Honda; K. Ikeshima, NGK; SAE 1999 International Congress, Detroit
65. SAE 982635: "Physical Durability of Thin Wall Ceramic Substrates" S. Gulati, Corning; SAE 1998 International Fall Fuels and Lubricants Meeting, San Francisco
66. SAE 982634: "Performance of Different Cell Structure Converters, A Total Systems Perspective" L. Socha, Jr., A. Heibel, both of Corning, B. Kessler, J. Rieck, both of Johnson Matthey; G. Mitchell, Chrylser; P. Weber, J. Buckingham, both of Southwest Research Institute; SAE 1998 Fall Fuels and Lubricants Meeting, San Francisco
67. SAE 982553: "A 45% Engine Size Catalyst System for MDV2 ULEV Applications" S. Sung, R. Ober, R. Casper, G. Miles, all of Engelhard; SAE 1998 Fall Fuels and Lubricants Meeting, San Francisco
68. SAE 980675: "Characterization of OBD-II Features of Advanced Pd-Rh Catalysts and Relation to Catalyst Composition and Design" J. Nunan, G. Denison, W. Williamson, M. Henk, all of ASEC; SAE 1998 International Congress, Detroit
69. SAE 980674: "Engine-Out and Tailpipe Emission Reduction Technologies of V-6 LEVs" H. Takahashi, Y. Ishizuka, M. Tomita, K. Nishizawa, all of Nissan; 1998 SAE International Congress, Detroit
70. SAE 980670: "Fatigue and Performance Data for Advanced Thin Wall Ceramic Catalysts" S. Gulati, Corning; B. Williamson, J. Nunan, K. Andersen, all of ASEC; J. Best, Delphi; 1998 SAE International Congress, Detroit
71. SAE 980668: "High Temperature Stability of Ceria-Zirconia Supported Pd Model Catalysts" J.-P. Cuif, S. Deutsch, M. Marczi, all of Rhodia; H.-W. Jen, G. Graham, W. Chun, R. McCabe, all of Ford; 1998 SAE International Congress, Detroit
72. SAE 980667: "New Low Cost and High Performance Catalyst – Single Layer Pd/Rh Catalyst Development" S. Taniguchi, T. Yoshikawa, M. Horiuchi, M. Jenkin, all of ICT; D. Lindner, L. Mussmann, both of Degussa; 1998 SAE International Congress, Detroit
73. SAE 980666: "Development of Single Coated Pd/Rh Three Way Catalyst for CCC Application" Y. Song, J. Jang, G. Yeo, all of Hyundai; J. Lee, Heesung Engelhard; 1998 SAE International Congress, Detroit
74. SAE 980664: "Influence of Support Materials on Durability of Palladium in Three-Way Catalyst" M. Yamamoto, H. Tanaka, both of Daihatsu; 1998 SAE International Congress, Detroit
75. SAE 980663: "Development of Close-Coupled Catalyst Systems for European Driving Conditions" A. Waltner, G. Loose, A. Hirschmann, all of Daimler-Benz; L. Mussmann, D. Lindner, W. Mueller, all of Degussa; SAE 1998 International Congress, Detroit
76. SAE 980423: "In-line Hydrocarbon Adsorber for Cold Start Emissions – Part II" N. Noda, A. Takahashi, Y. Shibagaki, H. Mizuno, all of NGK; 1998 SAE International Congress, Detroit
77. SAE 980422: "Application of In-Line Hydrocarbon Adsorber Systems" J. Abthoff, R. Kemmler, H.

Klein, M. Matt, all of Daimler-Benz; H. Robota, W. Wolsing, J. Wiehl, all of ASEC; S. Dunne, UOP; SAE 1998 International Congress, Detroit

78. SAE 980420: "New Ultra Thin Wall Metal Catalysts for Close-Coupled Applications" R. Brueck, R. Diewald, W. Maus, L. Wieres, F.-W. Kaiser, all of Emitec; SAE 1998 International Congress, Detroit
79. SAE 980419: "Airless In-line Adsorber System for Reducing Cold Start HC Emissions" M. Patil, Y. Peng, K. Morse, all of Corning; 1998 SAE International Congress, Detroit
80. SAE 980418: "The Development of BMW Catalyst Concepts for LEV/ULEV and EU III/IV Legislations, 6 Cylinder Engine with Close Coupled Main Catalyst" E. Otto, F. Albrecht, J. Liebl, all of BMW; 1998 SAE International Congress, Detroit
81. SAE 980417: "Design and Optimization of a Close-Coupled Catalyst Concept for Audi 4-Cylinder Engines" G. Faltermeier, B. Pfalzgraf, both of Audi; R. Brueck, Emitec; A. Donnerstag, VW; SAE 1998 International Congress, Detroit
82. SAE 980416: "An Improved Underfloor Catalyst for 5-cylinder Turbo-Charged Engines" M. Laurell, I. Gottberg, T. Idoffsson, all of Volvo; 1998 SAE International Congress, Detroit
83. SAE 980415: "Development of the High Performance L4 Engine ULEV System" N. Kishi, S. Kikuchi, Y. Seiki, A. Kato, K. Fujimori, all of Honda; 1998 SAE International Congress, Detroit
84. SAE 980045: "Design of a Dual Wall Air Gap Exhaust Manifold" C. Santanam, D. Priebe, both of GM; T. Scofield, K. Grable, both of Benteler Automotive; SAE 1998 International Congress, Detroit
85. SAE 970463: "(Ce, Zr)O_2 Solid Solutions for Three-Way Catalysts" J.-P. Cuif, G. Blanchard, O. Touret, A. Seigneurin, M. Marczi, E. Quemere, all of Rhone-Poulenc; SAE 1997 International Congress, Detroit
86. SAE 960802: "Reduction of Exhaust Gas Emissions by Using Pd-based Three-way Catalysts" D. Lindner, E. Lox, R. van Yperen, K. Ostgathe, T. Kreuzer, all of Degussa; SAE 1996 International Congress, Detroit
87. SAE 960798: "Advanced TWC Technologies Using CeO_2/ZrO_2 Solid Solutions" J. Nunan, W. Williamson, H. Robota, all of ASEC; SAE 1996 International Congress, Detroit
88. SAE 960261: "Close-coupled Catalytic Converters for Compliance with LEV/ULEV and EG III Legislation – Influence of Support Material, Cell Density and Mass on Emission Results" B. Pfalzgraf, M. Rieger, G. Ottowitz, all of Audi; SAE 1996 International Congress, Detroit
89. SAE 950789: "Design Criteria for Metallic Substrates for Catalytic Converters" R. Brueck, R. Diewald, P. Hirth, F.-W. Kaiser, all of Emitec; SAE 1995 International Congress, Detroit
90. SAE 950255: "Trimetallic Three-Way Catalysts" A. Punke, U. Dahle, S. Tauster, H. Rabinowitz, all of Engelhard; T. Yamada, N.E. Chemcat; SAE 1995 International Congress, Detroit
91. SAE 950254: "High Temperature Ultra Stable Close-Coupled Catalysts" Z. Hu, R. Heck, both of Engelhard; SAE 1995 International Congress