Emission Control of Two- and Three-Wheel Vehicles

September 2014

Manufacturers of Emission Controls Association
www.meca.org

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EXECUTIVE SUMMARY

Two-wheel and three-wheel vehicle production has been expanding rapidly over the past decade, especially in the urbanized areas of Asia. Motorcycles play important roles in fulfilling both personal and commercial transportation needs in most Asian and many southern European cities. The smaller physical size of motorcycles allows for easier navigation in heavily congested areas. Purchase and maintenance are substantially lower than the corresponding costs for even small automobiles, making the types of low-cost motorcycles sold throughout most of Asia and southern Europe a more economically efficient transportation option.

The global motorcycle market reached a total industry value of approximately $63.5 billion in 2010. Market growth is expected to accelerate to a yearly rate of 6% between 2010 and 2015, to reach almost $85 billion. Global sales of motorcycles will be fuelled by rising standards of living in developing nations. Demand gains for motorcycles will also be supported by higher petroleum costs due to the superior fuel efficiency motorcycles provide compared to light vehicles. A rebound from the 2007-2009 recession in developed countries like the U.S. will lead to higher sales, particularly of medium and heavy motorcycles.

Motorcycles are one of the most affordable forms of motorized transport and, for most of the world's population, they are the most common type of motor vehicle. About 200 million motorcycles, including mopeds, motor scooters, motorized bicycles, and other powered two- and three-wheelers, are in use worldwide, or about 33 motorcycles per 1,000 people.

Most motorcycles (58%) are in the developing countries of Asia (Southern and Eastern Asia, and the Asia Pacific countries, excluding Japan) with most of the bikes in the 50-350 cubic centimeter (cc) engine displacement category, while 33% of cars, 195 million, are concentrated in the U.S. and Japan. There are approximately 1.5 million active motorcyclists in the United Kingdom, representing around 3% of the UK adult population. Total demand for motorcycles in Europe during 2012 declined approximately 10% from the previous year to approximately 779,000 units. Total demand for motorcycles and all-terrain vehicles in the U.S. during 2012 increased approximately 2% from the previous year to approximately 678,000 units, although demand has yet to fully recover. The majority of these motorcycles have engines greater than 750 cc all the way up to the 2,000 cc touring bikes.

Motorcycles emit substantial quantities of hydrocarbons (HCs), carbon monoxide (CO), and particulate matter (PM). These pollutants have significant adverse health effects and deteriorate environmental quality. The contribution to urban air pollution where these vehicles are in use has become an increasingly common phenomenon. This is especially noticed in densely populated areas of the world that rely on motorcycles as an essential means of transportation.

To address the serious pollution problems posed by two-wheel vehicles, a growing number of countries worldwide have implemented, or are in the process of implementing, motor vehicle pollution control programs aimed at substantially reducing harmful emissions from spark-ignited two-wheel vehicles. Taiwan has the tightest motorcycle emission standards in the world having further tightened its motorcycle emission standards in 2007 and re-classified motorcycles by engine displacement with the cut point at 150 cc (see Table 1). Furthermore, the new regulations have added a cold-start component to the test cycle. In early 2008, the Taiwan EPA announced that it will begin a buy-back program to phase out two-stroke engines.

In the U.S., the California and Federal motorcycle emission standards were harmonized in 2006. In 2008, California further tightened the emission limits for the largest Class III bikes (>280 cc) and these limits harmonized in the Federal program in 2010 (see Table 1). Unlike California, which does not impose limits on the smallest motorcycles (<50cc), the Federal program requires that these scooters meet the same emission limits as the larger Class I and II motorcycles. Catalytic exhaust controls have been developed as a result of these regulations and are generally recognized to be the most cost-effective way to meet stringent emission standards. Thus, fully developed and proven emission control systems are readily available. Other countries are now adopting similar regulations and standards.

Similar exhaust control catalyst technology that is used on automobiles and light-duty trucks can be used for two- and four-stroke motorcycles. These catalysts include simpler design oxidation catalysts on the smaller motorcycles to control CO and HC, all the way up to three-way catalysts with closed loop air/fuel ratio control on the largest four-stroke engines. Motorcycle catalysts are most often deposited on metallic substrates to simplify incorporation into the exhaust system. While the transfer of this technology poses challenges due to the size of the motorcycles and the backpressure sensitivity of their engines, many experiences that are learned from the auto and light-duty truck application have been applied to the development of effective catalyst technology for motorcycles.

1.0 INTRODUCTION

Worldwide, motorcycle usage is increasing at a rapid pace, especially in the urbanized areas of Asia. Approximately 200 million motorcycles are estimated to be in use and this number is growing at a rapid rate, especially in Asia, where the average annual rate of growth for the region is 15%, with annual growth rates at or above 5% in most Asian countries. The majority of these vehicles are powered by two-stroke engines. Two-stroke engines have very high exhaust emissions. This paper examines the growth of motorcycles and the need to control their emissions, with an emphasis on the emission control technologies as well as standards that regulate them.

The large population of two-wheel vehicles accounts for a significant portion of global mobile source hydrocarbon (HC) and carbon monoxide (CO). NOx emissions from two-stroke engine vehicles are relatively small compared to other mobile sources. Confronted with the need to address deteriorating air quality, a growing number of countries worldwide have implemented, or are in the process of implementing, programs to substantially reduce gaseous emissions from spark-ignition (SI) two-wheel vehicles. In making pollution control decisions, countries in the North America, Asia and Europe, are considering a number of issues such as the levels of the emission standards to implement as well as the types of control strategies that should be required.

Motorcycle populations are sensitive to geography and economic prosperity and, therefore, their populations are very significant in many areas of the world. Motorcycles outnumber four-wheel vehicles in a number of Asian countries and growth in motorcycle population is dramatic. Asia accounts for almost 85% of new motorcycle sales and, because of comparatively lower Asian per capita automobile and truck ownership, air quality in Asia is substantially more sensitive to motorcycle emissions impacts than non-Asian cities. Motorcycle emissions are estimated to contribute as much as 40% of PM and CO_2, 50% of CO, and 70% or more of volatile organic compounds (VOCs) in some Asian cities.

The majority of the global motorcycle population uses small displacement engines, generally 50 to 150 cc, which complicates emission control issues due to the low cost, space limitations, and simple design characteristics of small engine technology. Like other motor vehicles, the majority of existing motorcycles use internal combustion engine (ICE) designs that utilize the energy released by burning fuel to turn a crankshaft. Almost all large motorcycles (>100cc) are of a four-stroke design, while smaller motorcycles have historically been two-stroke engine designs because of their generally high power-to-weight ratio, lower production and maintenance issues, and lower purchase and maintenance costs. Existing emission standards have had a major impact on engine design and four-stroke technology now dominates new motorcycle production for displacements as low as 100 cc.

Relative to four-stroke engines, two-stroke engine designs offer several advantages for size-restricted applications. Two-stroke engines depend on relatively simple cylinder sidewall ports while four-stroke engines require comparatively complex mechanical valve systems to control intake and exhaust port functions. Additionally, as two-stroke engines generate one power stroke per crankshaft revolution compared to one power stroke per two crankshaft revolutions in a four-stroke engine, two-stroke engines are smaller and more compact than the equivalent-output four-stroke engines.

2.0 WORLDWIDE EMISSION STANDARDS FOR TWO-WHEEL VEHICLES

2.1 Standards

Two-wheel emission control regulations were first introduced in the U.S. in 1978. Two-wheel vehicles are now regulated in many countries and the allowable emissions limits vary widely. The stringency of the standards depends on several factors, including the extent of the existing pollution problem, as well as various political and economic factors. As would be expected, the more demanding control requirements tend to be found in areas with the highest concentration of two-wheel vehicles.

Certification emission standards for motorcycles have been implemented in many countries. Most of the emissions standards through the mid- to late-1990s were based on warm-start emissions testing with no or limited durability requirements. These requirements have become progressively more stringent on different schedules in different countries. The evolution in emission standards has resulted in emission reductions from motorcycles. In addition to consumer benefits such as reduced noise and better fuel efficiency, emission standards have been a significant contributor to the shift in the global motorcycle market towards more four-stroke engines. The majority of all two-stroke motorcycles currently sold in countries such as India, Taiwan, and Thailand come equipped with catalytic converters, while new standards may spur an additional shift toward fuel-injected four-stroke engines.

Current motorcycle emission standards continue to focus primarily on CO and HC. NOx standards are also common, but motorcycles are currently low NOx emitters. However, with the exception of a PM standard for compression-ignition motorcycles in India and Europe, there are no motorcycle PM standards, despite the fact that two-stroke PM emissions can be very high.

The most important factor in the relationship between certification and in-use emissions is the lack of full life durability requirements and in-use compliance requirements. Motorcycle emissions durability testing is typically limited to between 6,000 and 15,000 km during certification, although 30,000 km requirements are being applied in some cases to the largest (>280 cc) motorcycles. These durability requirements do not compare to the real-world travel data that show annual average accumulations for in-use two-wheel motorcycles of 8,000 to 10,000 km. Implementation of a realistic useful life durability requirement is essential to ensuring that adopted emissions control systems are effective with a reasonable deterioration rate when operated and maintained properly.

Another important component that is needed for effective motorcycle emission standards that is generally lacking is in-use emission testing requirements. These in-use requirements are distinguished from periodic emissions inspection requirements that might be established by local regulation in that they consist of the performance of a full certification-type emissions test on a selected sample of well-maintained vehicles to ensure that certification emissions standards can be met in-use. This is a common practice in the U.S., through which a substantial number of emissions-related defects are identified, that were not evident during the actual certification process.

Since not all motorcycles are used and maintained as recommended by manufacturers, emissions inspection and maintenance (I/M) requirements are also an important component of in-use emissions control (see Section 6.0). Both India and Taiwan currently have periodic motorcycle I/M programs that require compliance with CO and HC emission standards during an idle test. India is also considering the adoption of centralized loaded mode testing. Other countries administer random smoke tests and many also administer in-use manufacturer-based idle test standards for CO and HC. California has proposed a motorcycle I/M program beginning in 2010 to deter exhaust system tampering on low mileage motorcycles, however the legislation was not adopted.

There is also a general movement toward cold-start emissions testing. With the exception of the U.S., older motorcycle emissions standards were generally based on hot-start emissions measurement. Cold-start emissions impacts were likely to be minor with non-catalyst-equipped motorcycles. However, catalyst applications have become widespread in the motorcycle industry so that cold-start emission characteristics will increasingly dominate overall motorcycle emissions profiles and cold-start emissions testing should be considered as an integral part of any effective certification testing program.

Taiwan, Thailand, and the U.S., were the first countries to include evaporative emission limits with their motorcycle standards. In the U.S., the California ARB implemented an evaporative HC standard of 2 grams per test that applies to the sum of diurnal and hot soak emissions measured during a certification SHED test. In 2010, ARB proposed more stringent evaporative emission standards for motorcycles (including the addition of on-board refueling vapor recovery, ORVR) but has yet to finalize these tighter evaporative emission requirements. Similar diurnal emission requirements are in effect in Taiwan and Thailand. The U.S. EPA adopted fuel system permeation limits that took effect with the 2008 model year. The adopted standards restrict fuel tank permeation to 1.5 g/m^2/day and fueling system hose permeation to 15 g/m^2/day. This limit reduces fuel tank and hose permeation by 85 to 95%. The European Union has now included evaporative emission limits for motorcycles starting with their 2016-2017 Euro 4 standards, with additional tightening of evaporative emission limits included with their 2020 Euro 5 standards. India has recently adopted its first evaporative emission standards for two-wheelers. The India Bharat IV standards that were adopted in July 2014 give manufacturers some flexibility by allowing certification under two different sets of evaporative emission standards. The alternative evaporative emission standards allowed are 2 or 6 grams of HC emitted during the SHED test. Manufacturers can elect to deploy vehicle designs able to meet the lower evaporative emission standard and rely less on tailpipe HC emission controls, or opt for the higher evaporative emission standard and employ engine and exhaust emission control systems to achieve lower tailpipe HC emissions, depending on which is the most cost-effective solution for them. (Evaporative emission control technologies are described in Section 4.2.)

Currently, the use of catalyst technology to reduce the emission of harmful exhaust gases from two-wheel vehicles is widely used in Taiwan, Thailand, India, Japan, the United States, and Europe. Many countries have recently begun to incorporate durability requirements for motorcycle emissions into their regulations. The U.S. and Europe have the most stringent durability requirements: up to 5 years or 30,000 km. Some other countries have durability requirements from 6,000 to 15,000 km (see Table 1).

Table 1. Summary of Major Motorcycle Emission Regulations

Country	Vehicle	Emissions (g/km)				Test Cycle	Durability Test	Effective Year
		HC	CO	NOx	HC+NOx			
USA 49 States and Canada	< 50 cc	1	12			FTP	5 yrs or 6K km useful life	2006
	50-279 cc	1	12			FTP or optional WMTC	5 yrs or 12K km (50-169 cc) & 18K km (170-279 cc) useful life	2006
	≥280 cc		12		1.4	FTP or optional WMTC	5 yrs or 30K km useful life	2006
	≥280 cc		12		0.8	FTP or optional WMTC	5 yrs or 30K useful life	2010
USA: CA	50-279 cc	1	12			FTP	5 yrs or 12K km (50-169 cc) & 18K km (170-279 cc)	1982

							useful life	
	280-699 cc	1	12			FTP	5 yrs or 30K km useful life	1988
	≥ 700 cc	1.4	12			FTP	5 yrs or 30K km useful life	1988
	≥ 280 cc		12		1.4	FTP	5 yrs or 30K km useful life	2004
	≥ 280 cc		12		0.8	FTP	5 yrs or 30K km useful life	2008
Taiwan	< 150 cc	0.8	0.2	0.15	0.95	CNS cold start	15K km	2007
	>150 cc	0.3	0.2	0.15	0.45	CNS cold start	15K km	2007
India	All MCs		2		2	India Drive Cycle	1.2 DF	2000
	All MCs		1.5		1.5	India Drive Cycle	1.2 DF or 30K km	2005
	All MCs		1		1	India Drive Cycle	1.2 DF	2008/ 2010
	All 2-Wheelers		1		1.0[1]; 1.0[2]	India Drive Cycle	30K km	2010
	Class 1 and Subclass 2-1[3]		1.403	0.39	0.79[1]; 0.59[2]	WMTC GTR-2	30K km	2016/ 2017
	Subclass 2-2[4]		1.970	0.34	0.67[1]; 0.47[2]	WMTC GTR-2	30K km	2016/ 2017
	Subclass 3-1 and 3-2[5]		1.970	0.20	0.40[1]; 0.20[2]	WMTC GTR-2	30K km	2016/ 2017
China	< 150 cc	0.8	2	0.15		ECE R40	5 yrs or 30K km	2007
	> 150 cc	0.3	0.2	0.15		ECE R40	5 yrs or 30K km	2007
	Moped (< 50 cc)		1		1.2	ECE R47	10K km	2006
EU	Moped		1		1.2	Cold start 8-cycle R47	15K km	2002
	2,4-S < 150 cc	0.8	2	0.15		Cold start 6-cycle ECE R40, WMTC 2009	30K km for all or 12K km 51-169 cc, 18K km 170-269 cc, 30 km ≥ 270 cc	2006
	2,4-S ≥ 150 cc	0.3	2	0.15		Cold start 6-cycle ECE R40+EUDC, WMTC 2009		2006
	2,4-S Vmax < 130 kph	0.75	2.62	0.17		WMTC		2007
	2,4-S Vmax ≥ 130 kph	0.33	2.62	0.22		WMTC		2007
	Moped	0.63	1.0	0.17		ECE R47	11K km or DF=1.3 CO; 1.2 HC and NOx	2017
	< 130 kph	0.38	1.14	0.07		WMTC Phase 2	20K km	2016
	≥ 130 kph	0.17	1.14	0.09		WMTC Phase 2	35K km or assigned DF=1 PM; 1.3 HC, CO	2016

							and NOx	
	All MC	0.1 0	1.0	0.06		WMTC	20K km for <130 kph; 35K km for ≥130 kph, or assigned DF=1.0 for PM; 1.3 for HC, CO and NOx	2020

[1] Indian Bharat III and IV standards for evaporative test ≤ 2.0 g/test
[2] Indian Bharat III and IV standards for evaporative test ≤ 6.0 g/test
[3] Indian Bharat IV standards Class 1: 50 cc<V_d<150 cc and V_{max} ≤ 50 km/h or V_d< 150 cc and 50 km/h<V_{max}<100 km/h; Sub-class 2-1: V_d<150 cc and 100 km/h<V_{max}<115 km/h or V_d≥150 cc and V_{max}<115 km/h
[4] Indian Bharat IV standards Subclass 2-2: 115 km/h ≤ V_{max} < 130 km/h
[5] Indian Bharat IV standards Subclass 3-1: 130 km/h < V_{max}< 140 km/h; Subclass 3-2: V_{max} ≥ 140 km/h

2.2 Test Methods

As stated above, two types of testing are used for emissions measurements on motorcycles – mass emissions under load and idle emissions. Mass emission testing requires the use of a test method that is designed to be representative of driving conditions encountered during actual vehicle operation. As driving conditions can vary widely from country to country, several different test methods are being used. However, all mass emission testing can be characterized as multi-mode driving patterns that contain idles, accelerations, decelerations, and steady-state cruises repeated over a fixed time interval. A chassis dynamometer and an exhaust gas sampling system are used for these multi-mode test methods.

Significant effort has been undertaken to develop a global motorcycle test cycle over the last decade by the United Nations Economic Commissions for Europe. The World Motorcycle Test Cycle (WMTC) has been finalized and includes three test components characteristic of urban, rural, and highway driving, with different weighting factors for each component based on motorcycle size and design. In 2011, WMTC was amended to include amendments to the performance requirements and reference fuel.

The U.S. EPA and California ARB recognize the FTP whereas the European Union and many Asian countries prefer the ECE R40 or ECE R47 cycles. The European Union shifts to using the WMTC cycle with their latest round of emission standards (Euro 4, Euro 5). The ECE R47 test method is used primarily for vehicles having engine displacements less than 50 cc and maximum speeds less than 50 km/hour. India has adopted a test method that is unique to their own driving conditions, known as the India Driving Cycle or the IDC. India's future Bharat IV standards will utilize a version of the WMTC cycle.

3.0 ENGINE DESIGNS FOR TWO- AND THREE-WHEEL VEHICLES

3.1 Two-Stroke versus Four-Stroke Engine Comparison

Two-stroke and four-stroke engines each have their own specific advantages and disadvantages. The simplicity of design, size to power ratio (space envelope), light weight, low number of moving parts, ease of maintenance, and excellent power and torque characteristics make two-stroke engines attractive power plants where the cost of transportation and high specific power output are important. For example, with the same displacement, a two-stroke engine can produce up to 1.4 times as much power as a four-stroke engine. The two-stroke engine has two primary disadvantages: 1) poor fuel utilization during the cylinder scavenging process because of the valve-less design, and 2) high HC and PM emission rates. A common considered strategy to reduce the emissions from two-wheel vehicles is to change from two-stroke to four-stroke engines.

Four-stroke engines have significantly lower HC emissions, but there are tradeoffs to this approach in terms of increased vehicle complexity, cost, and weight. The four-stroke engine requires up to 50% more physical space within the vehicle frame for an equivalent power output, and maintenance costs are higher. Consequently, while it is possible to substantially reduce base engine HC emissions from two-wheel vehicle fleets by converting to four-stroke power plants, this may not be the most cost-effective solution for all markets. The differences between the combustion processes in these two engine designs will be detailed below.

3.2 Two-Stroke Engines

The primary emissions from two-wheel vehicles powered by a two-stroke engine are HCs, CO, and particulate matter (PM) emissions in the form of white smoke. NOx emissions are typically very low for two-stroke engines because of the effect of high residual combustion gas retained in the combustion chamber which acts as an internal EGR. NOx emissions are not regarded as a significant issue for two-stroke engine vehicles.

A two-stroke engine relies on the pressurized flow of the compressed intake charge to force combustion products out of the cylinder. Because intake and exhaust gases are entering and leaving the cylinder simultaneously, this results in a portion of the intake charge escaping through the exhaust port without being combusted. The simplest two-stroke designs rely on a carbureted air/fuel intake charge and therefore 15 to 40% of the escaping charge is unburned fuel. These so-called scavenging emissions result in high emissions of HC and increased consumption of fuel compared to four-stroke engines.

Due to the lubrication technology used on the basic two-stroke engines, scavenging also results in high PM emissions. Two-stroke engines compress the intake charge during the power stroke of the piston. Piston rings cannot be as efficient lubricating system seals in a two-stroke engine since the intake, transfer, and exhaust ports all penetrate the cylinder wall. Therefore, two-stroke engines generally rely on “total loss” lubricating systems, where oil is mixed with the fuel or introduced into the fuel-air mixture and consumed during the combustion process. A portion of the lubricating oil is exhausted without being combusted during the scavenging process and represents the bulk of PM emissions from two-stroke engines. It is estimated that unburned lubricating oil comprises 80 to 95% of total two-stroke PM emissions. Depending on the specific fuel-to-oil mixing ratio that was used, unburned oil is often exhibited by the white smoke emissions that are common from two-stroke engines. Furthermore, the use of inferior quality oil worsens two-stroke PM emissions and therefore oils specifically formulated to control smoke and PM emissions from two-stroke motorcycles have been developed.

Although scavenging losses result in increased PM and HC emissions, they facilitate a NOx emissions benefit. Due to the overlap of the intake and exhaust portions of the two-stroke combustion cycle there is some mixing of the intake and exhaust charge resulting in “internal” exhaust gas recirculation (EGR). This mechanism effectively constrains peak cylinder combustion temperatures and limits NOx formation.

Further development to improve the efficiency and reduce emissions from two-stroke motorcycles has focused on incorporating air assisted fuel injection on these engines (discussed in greater detail in Section 4.1). This effectively controls the air-to-fuel ratio of the intake charge and reduces scavenging loses.

3.3 Four-Stroke Engines

In contrast to two-stroke engines, four-stroke engines require two piston cycles for every combustion cycle. Therefore, for engines running at the same speed, a four-stroke engine will produce half the work as a two-stroke engine. However, four-stroke engines provide greater combustion control as each of the four combustion strokes occur during a distinct movement of the piston through the cylinder. The four strokes consist of intake, compression, combustion, and exhaust. This effectively separates the exhaust and intake strokes of the combustion cycle and controls the scavenging losses. As a result, both HC emissions and fuel consumption are reduced relative to two-stroke engines. The baseline emissions comparison of four-stroke versus conventional two-stroke designs offers an immediate benefit of approximately 95% HC, 30% CO, and 80% PM, with an increase in NOx of 200% relative to the low level of the two-stroke. An increase of about 35% in fuel efficiency can also be expected.

Because four-stroke engines do not offer the internal EGR effects of the two-stroke engines, NOx emissions tend to be higher. To control combustion temperatures and NOx emissions, the intake charge of small four-stroke engine is usually set rich. This in turn results in higher CO emissions.

While four-stroke engine technology has been the dominant technology for large motorcycles for decades, it has recently begun to extend to motorcycles with displacements as low as 100 cc. Research has begun to develop economical 50 cc four-stroke designs, and some four-stroke designs of this size are entering the market.

Relative to two-stroke designs, four-stroke motorcycles result in reduced emissions of PM and HC, increased emissions of NOx and higher fuel economy which translates to lower greenhouse gas (GHG) emissions. The CO emissions are comparable for both designs. Four-strokes do offer some advantages in being able to implement exhaust emission controls due to the ability to more finely control the intake and exhaust characteristics through the use of high pressure fuel injection. Catalytic exhaust controls are being offered for both designs.

3.4 Air/Fuel Calibration

Air/fuel calibration of both two-stroke and four-stroke engines directly affects the release of undesirable pollutants to the environment. The net oxygen available for combustion is governed by the air/fuel calibration for a given engine or engine family. The scavenging losses in a two-stroke engine cause inhomogeneous mixtures of oxygen and gasoline to enter the exhaust. This occurs to a lesser extent in four-stroke engines due to better air/fuel control. In order to achieve good drivability, the engines are typically calibrated to run fuel rich. As the air/fuel mixture becomes more fuel rich, less oxygen is available in the cylinder for complete combustion of the fuel mixture and, consequently, more HC and CO are released to the atmosphere. The formation of NOx is also dependent on engine air/fuel ratios. Fuel rich mixtures have lower combustion temperatures and, therefore, form less NOx. This is the case for both two-stroke and four-stroke engines. However, four-stroke engines tend to be calibrated more fuel lean and, as a result, cylinder combustion temperatures are higher resulting in more NOx than that from a two-stroke engine.

Sometimes manufacturers will incorporate supplemental air delivery systems in the exhaust stream to increase the oxygen content in the exhaust. This may be in the form of a simple reed valve and is the simplest, most cost-effective exhaust control device. Reed valves can be used with or without the incorporation of catalytic exhaust controls. (Further discussion of secondary air injection strategies will be covered in Section 4.3.)

3.5 Motorcycle Markets

Motorcycles in different markets have very different design drivers. The U.S motorcycle market is dominated by recreational market and the motorcycles are mostly larger than 500 cc, made up mostly by cruisers and sport bikes. The performance of the motorcycle is more important than economy.

The European motorcycle market is recreational and commuter use and has a wide range of motorcycle sizes, from 50 cc mopeds to large sport bikes and cruisers, including quadricycles and minicars. The performance of the motorcycles and the economy are both important in the European market.

The Indian motorcycle market is dominated by small motorcycles, nearly all under 500 cc for mostly daily commuter use. Fuel economy of the motorcycle is more important than high speed performance and low cost is also imperative.

The Chinese motorcycle market is dominated by small motorcycles, nearly 90% of which are under 125 cc, for daily commuter use. However, owners want good performance and low cost is imperative so most motorcycles still do not use electronic fuel injection.

4.0 EMISSION CONTROL TECHNOLOGIES FOR MOTORCYCLES

4.1 Engine Combustion Controls

Over the last decade or so, various emission control technologies have been introduced into the motorcycle marketing response to adopted emission standards. The first approach to reducing emissions from any engine focuses on optimizing the combustion process. Costs are an important factor in the application of two-stroke engines and therefore, the cost of improvements must be weighed against the cost of a four-stroke engine.

The obvious focus for reducing emissions from two-stroke engines must consider reductions in scavenging loses. The approaches that have been considered, attempt to separate the air and fuel intake strategies by using air to accomplish scavenging. One such approach incorporates direct injection to introduce fuel directly into the combustion chamber once the exhaust port is closed. PM reductions can be achieved by not mixing lubricating oil with the fuel. Low pressure fuel injectors, in combination with compressed air, reduces the cost of the injection system and keeps the costs competitive. The use of compressed air enables air/fuel ratios as high as 30:1 allowing lean combustion over most of the engine cycle and improved fuel economy.

This stratified combustion process effectively reduces 80% of the HC and CO emissions along with a 50% reduction in PM relative to conventional two-stroke engine-out emissions. The corresponding NOx emissions do increase; however, this is small relative to the low NOx emissions baseline of the conventional two-stroke. The improved fuel economy offered by direct injection technology applied to two-stroke engines results in about a 40% reduction in total carbon or CO_2 emissions. The direct injection technology for two-stroke engines is available on at least seven European motorcycle models and is being introduced in India on three-wheeled motorcycles. This latest gasoline direct injection technology can be applied to both two-stroke and four-stroke engines. At low loads, the engine runs very lean whereas at high loads it can operate in a homogeneously charged mode and high mixing of the combustion charge.

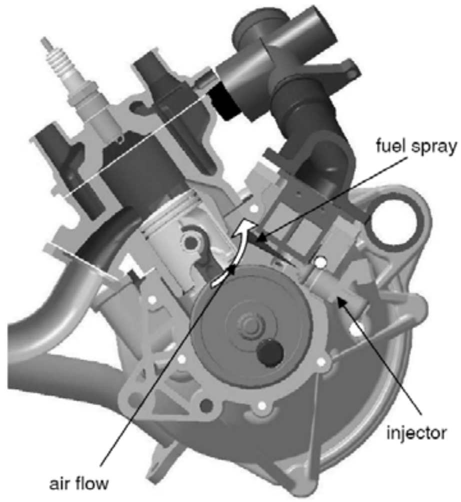

Figure 1. Schematic of a two-stroke engine fitted with low pressure fuel injection (SAE 2006-32-0065).

There has also been substantial research into reducing the cost and improving engine performance of four-stroke engines. The technologies employed mirror those that are commonly used on larger four stroke engines such as direct fuel injection systems to control air/fuel ratios near stoichiometric and EGR or retarding valve timing to reduce NOx emissions.

Incorporation of fuel injection (FI) to four-stroke engines does offer significant air to fuel ratio control advantages over the older carbureted designs. Rather than injecting directly into the combustion chamber, as in the case of direct injection (DI), FI technology typically injects fuel into the cylinder intake port to allow additional time for vaporization. This also allows the use of lower pressure injectors thus reducing costs. Fuel injection technology has demonstrated 40% reduction in HC, 80% reduction in CO and a 50% increase in NOx over carbureted four-stroke engines. The better fuel control results in approximately 20% improved fuel efficiency and corresponding reductions in CO_2.

4.2 Evaporative Controls

The purpose of evaporative emissions systems is to reduce or eliminate the release of vaporized HC into the atmosphere. These systems have been used on automobiles since the 1960s in the form of PCV or positive crankcase ventilation valves. Evaporative emission control systems on cars have increased in complexity over the years but only fairly recently been applied to motorcycles. The countries with evaporative emission limits on motorcycles is expanding from the U.S., Taiwan, and Thailand, to include the European Union and India in the coming years. The HC vapors and VOC react in the atmosphere and contribute to the formation of photochemical smog. Although there is little information available on global evaporative emission rates, it is estimated that the rate ranges from 0.02 to 1.5 g/mi based on emission factor models such as COPERT III and MOBILE6.2. The major source of these emissions is from the fuel system and therefore it is not surprising that fuel injection technology provides significant evaporative emissions benefits. Fuel injection systems effectively eliminate the vaporization of fuel from open carburetors. Other significant sources of evaporative emissions from the fuel system include permeation of the fuel tank and fuel delivery hoses.

Types of evaporative emissions are classified into five categories:

- Diurnal: This represents gasoline that evaporates due to the rise in ambient temperature.
- Running losses: Represent gasoline that vaporizes due to the heat of the engine and exhaust system during normal operation.
- Resting losses: Natural permeation that occurs from the fuel delivery system while not operating under ambient conditions.
- Hot Soak: Vaporization of fuel due to the retained heat of the engine after the engine is turned off.
- Refueling: Represents the fuel vapors that escape from the tank by the displacement of liquid fuel.

Evaporative emissions are measured using a sealed housing for evaporative determination (SHED) apparatus over the course of a multi-day Federal Test Procedure (FTP) to quantify all of the various forms of evaporative emissions. This testing is generally most effective in determining diurnal and hot soak emissions.

Evaporative emissions control on motorcycles consists of carbon canisters connected to the fuel system to capture and recycle HC vapors back to the intake of the engine to be combusted (Figure 2). The carbon is a high surface area pelletized material that adsorbs fuel vapors via loose chemical bonds and releases them in a controlled fashion via a purge solenoid. The purge solenoid is activated by the on-board control module when the exhaust is running lean. Most fuel tanks on motorcycles are metal and exhibit no permeation. A vented fuel cap serves to allow air to enter as fuel is depleted while venting expanded vapors in the fuel tank into the carbon canister.

Figure 2. Carbon canister used to capture evaporative emissions on motorcycles.

Resting loss emissions are estimated to make up about 65% of the total motorcycle evaporative emissions. Some manufacturers have begun using plastic molded gas tanks. In this case, gas tanks are made of layered polymers and blends that reduce tank permeation by 95%. Similar types of thermo-polymers are molded as thin (0.1 mm) layers in the inside of fuel lines to achieve similar permeation reductions.

Starting with the 2008 model year, the U.S. EPA adopted fuel system permeation limits that harmonize with California. The regulations are expected to reduce fuel tank and hose permeation by 85 to 95%. The combination of carbon canisters, the use of low permeable polymers, and fuel injection systems has been demonstrated as a very effective evaporative emissions control strategy.

4.3 General Overview of Catalyst Technology

Catalysts used to treat exhaust gases from two-wheel vehicles are based on two-way or three-way catalyst technology originally developed for gasoline cars and trucks. Two-way technology serves to oxidize HC and CO whereas three-way catalysts add the third functionality of reducing NOx. Catalysts are generally composed of a thin coating of platinum group metals dispersed on a composite of inorganic materials, mainly oxides, applied to the surface of a catalytically inactive metallic or ceramic honeycomb-like support, referred to as the substrate. The substrate design provides the surface on which the thin catalytic layer is applied. The exhaust gases flow through the open channels of the honeycomb substrate and thus come in contact with the catalyst. Currently, most catalyst designs for two-wheeled vehicles employ metallic substrates which can take on many shapes and sizes (Figure 3).

Figure 3. Motorcycle catalysts and substrates can take on many shapes and sizes. These may include coated expansion cones, perforated heat tubes, and coated metallic substrates.

Metal substrates are used because they provide strength against high exhaust pulsations, thermal shock and vibration; low back pressure provided by thin metal foil cell walls in a wide variety of cell densities; can be welded directly into headers, exhaust pipes and mufflers; cost of matt mounting and canning like ceramics is avoided; exposed mantles can be chrome plated for styling; can be made in small sizes up to large sizes; and big ceramic suppliers have shown no interest in making small substrates.

The space restrictions common to two-wheel applications limits the size and location where catalysts substrates can be incorporated into the exhaust stream. A catalyst can be completely incorporated into the existing exhaust system and not detract from the attractive chrome exhaust (Fig. 4). The simplest configuration may involve coating a catalyzed washcoat directly onto the inside of the exhaust pipe. The advantage of the latter approach is that there is minimal impact on the exhaust design, noise characteristics or back-pressure. Due to the limited geometric surface area, the emissions reductions may also be nominal. If the former approach is used, design modifications may be necessary to the exhaust system to minimize power losses and maximize thermal management to heat up the catalyst.

Figure 4. Catalyst engineered and integrated to fit inside the chrome muffler.

The precious group metal (PGM) catalysts that are deposited within the thin catalytic layer on the substrate consist of platinum, palladium, and rhodium, either individually or in combination. In order to achieve a maximum exposure of the catalytically active metals to the exhaust gases, the metals are finely dispersed over a very high surface area made up of metal oxides. The thin structure is commonly referred to as the active catalytic layer or "washcoat." Alumina is usually the primary washcoat component. Three-way catalysts used on four-stroke motorcycles typically contain platinum, and/or palladium, as well as rhodium for the simultaneous control of CO, HC, and NOx.

The efficiency of catalyst technology is a function of many parameters, including substrate form, substrate cell size, catalyst formulation, the location of the catalytic device, its operating temperature environment, and exhaust gas compositions. Regardless of the type of catalytic unit or the mounting location, specific consideration must be given to insulation and heat shielding of the external surfaces of the exhaust system to prevent potential burns to the riders.

4.4 Catalytic Converters for Motorcycle Engines

Catalytic technology uses a catalyst to assist in chemical reactions to convert the harmful components of the vehicle's exhaust stream to harmless gases. The catalyst performs this function without being changed or consumed by the reactions that take place. In particular, the catalyst, when installed in the exhaust stream, promotes the reaction of HC and CO with oxygen to form carbon dioxide and water. The chemical reduction of NOx to nitrogen is caused by reaction with CO over a suitable catalyst, typically rhodium. The role of the catalyst in promoting these beneficial reactions is depicted in Figure 5.

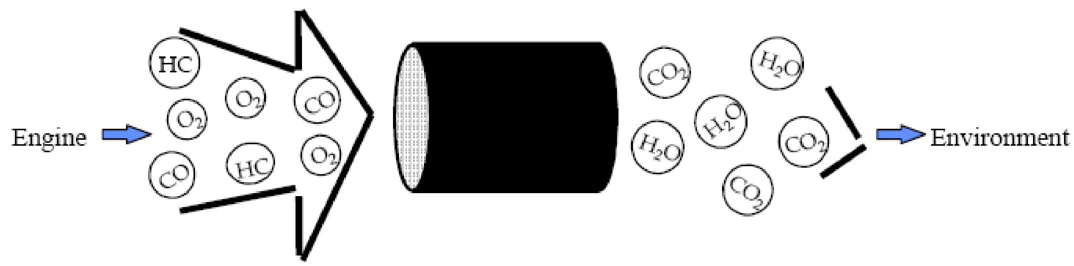

Figure 5. Diagram of two-way oxidation catalyst showing reactants and products in the exhaust.

4.4.1 Catalytic Controls for Two-Stroke Engines

Two-stroke engines pose significant challenges with incorporating a catalyst. The simultaneous conversion of HC, CO, and NOx requires very precise, near stoichiometric, intake charge control that is not possible for typical two-stroke motorcycle engines. The simple designs of these engines along with the need for a rich intake charge for combustion stability makes precise air/fuel ratio control around the stoichiometric combustion point difficult. Furthermore, the small engine sizes (<100 cc) for small motorcycles presents significant space limitations and makes the incorporation of a catalyst difficult. Small motorcycle engines tend to be more sensitive to exhaust backpressure and resultant power loss than larger four-stroke engines and therefore require applications engineering to design a suitable substrate to present the catalyst to the exhaust. Finally, the fact that most small motorcycles continue to use low-cost carbureted fueling systems makes it more difficult to control intake air/fuel ratios.

Despite these drawbacks, catalytic converters are possible on two-stroke motorcycle engines to meet the emission standards in some Asian countries. As two-stroke engines inherently emit low NOx emissions, the catalyst designs tend to focus primarily on effective oxidation of HC and CO and the reduction of white smoke or PM. Normally, this type of catalyst, commonly referred to as a two-way or oxidation catalyst, would have only limited effectiveness due to the fuel rich intake charge composition typical of two-stroke engines. The typical two-stroke scavenging losses provide one source of oxygen, but this is usually not enough to achieve 100% conversion of HC and CO. In advanced two-stroke engine designs, oxygen availability is improved by adjusting the air-to-fuel ratio to provide a relatively lean intake charge. Additionally, a simple passive secondary air injection system (SAI), such as a reed valve, can be installed upstream of the catalyst to provide excess air to the catalyst. To meet the more stringent Euro 2 standards on the same moped as shown in Figure 6 required the use of two catalysts in combination with SAI as shown in Figure 7. Further reductions may be achieved by applying a catalyst coating to the inside of the expansion cone.

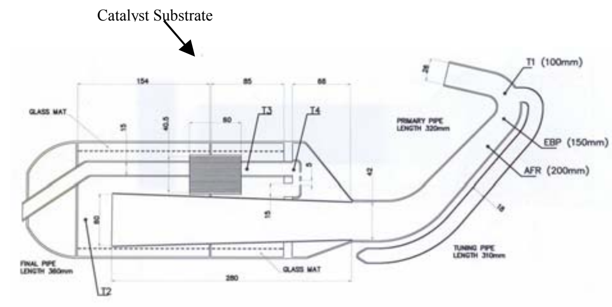

Figure 6. Example of a single catalyst fitted within moped muffler without secondary air injection.

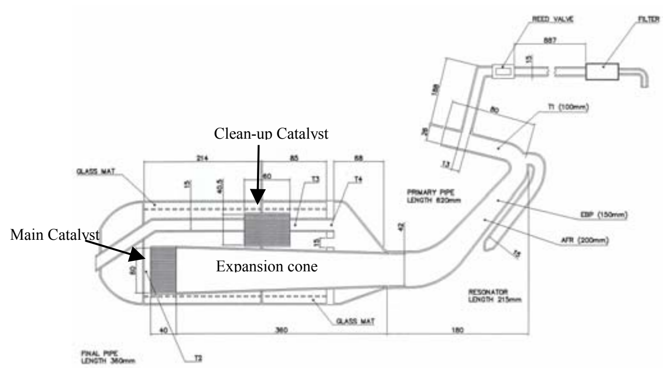

Figure 7. Two-stroke 50 cc moped muffler equipped with SAI via reed valve and dual catalysts, in separate locations to control exhaust temperature.

Another beneficial use of catalyst technology on two-stroke engines is the reduction of white smoke (particulate matter). It is estimated that conversion efficiencies of an oxidation catalyst on a two-stroke engine are on the order of 50% for HC, 50% for CO, and 45% for PM without the use of secondary air. The addition of secondary air injection is estimated to increase average conversion efficiencies to approximately 80% for HC, 75% for CO, and 70% for PM.

While two-way oxidation catalysts are effective in reducing the soluble component of PM or SOF, some manufacturers are developing catalyzed particulate filters for two-stroke 50cc scooter exhaust. In addition to performing the oxidative function to reduce CO and HC these high porosity wall flow filters were shown to reduce 99.5% of the PM with little to no backpressure increase above the stock configuration after 16,000 km durability testing.[3]

4.4.2 Catalytic Controls for Four-Stroke Engines

Oxidation catalyst on four-stroke engines can provide substantially higher emission reductions of HC than on two-stroke engines. The lower engine-out HC of four stroke engines and higher exhaust temperatures results in lower exotherms and faster light-off of the catalyst, thus extending catalyst life. The rich air/fuel calibration of four-stroke engines may limit the availability of oxygen for post-combustion oxidation of HC and CO and therefore four-stroke engines must use a secondary air injection system upstream of the catalyst (such as the reed valves discussed previously in Section 4.3.1). Sometimes unique solutions must be applied to meet tighter emission standards. In one particular Euro 3 compliant 150 cc scooter design, a perforated heat tube was used upstream of the main catalyst to facilitate early catalyst light-off to reduce cold start emissions (Figure 8). Oxidation catalysts in combination with secondary air are capable of achieving estimated reduction of 80% for HC and 90% for CO with a corresponding increase of 35% in CO_2 emissions due to the conversion of HC and CO emissions to CO_2.

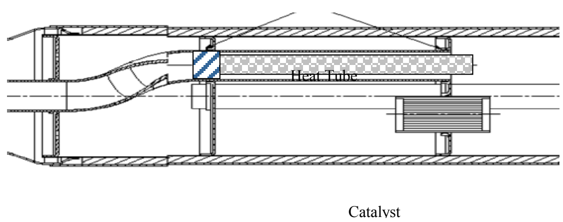

Figure 8. Catalyzed heat tube attached to muffler intake facilitates exhaust light-off.

A three-way catalyst system allows for the simultaneous conversion of HC, CO, and NOx. Although some benefit in emissions reduction can be derived from TWCs on carbureted motorcycles, an optimized system would have precise, closed loop, air/fuel control around the stoichiometric air/fuel ratio together with a fuel injection system. In this way, the NOx conversion is highest when the air/fuel ratio is on the rich side of stoichiometry while HC and CO conversion is optimized in the presence of a stoichiometric-to-lean air/fuel mixture. Modern three-way catalyst systems utilize an oxygen storage component, such as ceria, in the washcoat. Because ceria readily changes its valence from 3+ to 4+ depending on the surrounding oxygen content, it effectively stores oxygen during lean operating periods and releases stored oxygen during rich operating periods. Ceria acts to buffer the oxygen content, at the catalyst surface, near the stoichiometric point.

Closed-loop three-way catalyst systems include oxygen sensors installed on either side of the catalyst which provide exhaust oxygen content information to the air/fuel management system to adjust the intake mixture in response to oxygen sensor output. Such closed-loop controlled systems can be expected to deliver reductions of 75% HC, 50% CO, and 50% NOx along with a corresponding 20% increase in CO_2 relative to an uncontrolled four-stroke engine. Incorporation of catalysts may require further engine calibration, such as ignition timing retard, to facilitate catalyst warm-up and air/fuel ratio control.[2]

There are many emission design challenges that need to be overcome to move from Euro 3 to Euro 4 requirements. Motorcycle emission levels must be reduce by more than 50% to comply with Euro 4 standards relative to the Euro 3 standards. There is also a durability requirement added with three options: EPA AMA Motorcycle Driving Cycles; SRC-LeCV Driving Cycles; and assigned deterioration factors (1.3 for CO, 1.2 for HC and NOx). In order to meet the tighter Euro 4 requirements, catalyst design must be modified. These catalyst design options include: increase PM loading to improve conversion efficiencies and light-off; increase catalyst volume to lower space velocity to increase gas residence time and conversion efficiencies; increase substrate cell density to increase geometric surface area (GSA) to allow greater dispersion of catalyst washcoat and PM which lessens the effects of sintering and poison accumulation and shortens diffusion distances; and the development of new catalyst washcoat formulations.

Technical solutions are also under development to comply with the more stringent Euro 5 emission requirements that will take effect in 2020. Cold-start emissions will be an important consideration for complying with future Euro 5 standards and motorcycle manufacturers are already drawing from cold-start emission solutions developed for passenger cars by moving catalyst closer to the engine. Close-coupled converters with advanced catalysts designed for durability in harsh thermal environments have been utilized in passenger car applications since the 1990s and offer motorcycles a pathway for reducing cold-start emissions. Close-coupled converter light-off can also be facilitated by cold-start engine calibration strategies that accelerate catalyst heat-up. Figure 9 depicts a motorcycle exhaust system that incorporates close-coupled catalysts.

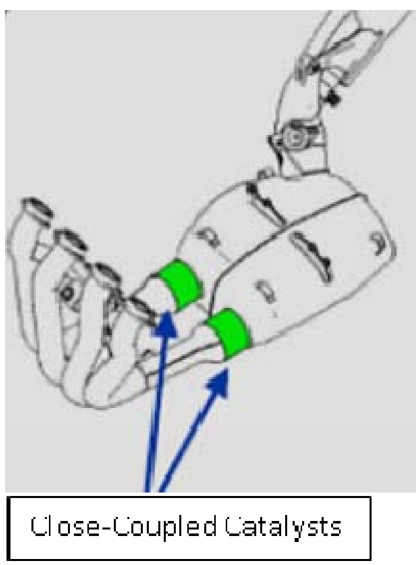

Figure 9. Advanced motorcycle exhaust system including close-coupled catalysts[4].

5.0 OTHER CONSIDERATIONS FOR FURTHER EMISSION REDUCTIONS

5.1 Fuel Quality Controls

The most common means of catalyst deactivation due to poisoning results from impurities in the fuel or lubricating oils. Catalyst poisons are classified as “physical” or “chemical”. Chemical poisons, such as lead, cause loss of catalyst performance by combining with the precious metal catalytic components and rendering them inactive. Physical masking agents deactivate catalytic performance by forming a barrier between the catalytically active metals and the exhaust gas. The sources of poisons can include the motor oil, fuel, or wear of engine components.

Fuel quality is equally as important as the quality of lubricant used in motorcycles. The use of gasoline with no lead, phosphorus, or manganese, and very low sulfur levels is critical to maximizing the durability of catalytic converters. Additionally, proper gasoline qualities are critical to minimizing engine-out emissions. Catalyst-equipped vehicles should be fueled only with an unleaded, low phosphorus gasoline, with as low a sulfur content as practical since all of these compounds inhibit catalyst functionality. As little as one or two tank fulls of leaded gasoline is all that is needed to destroy the catalysts pollution control capabilities. Even residual lead in unleaded gasoline at levels as low as a few milligrams/ liter (or gallon) will very slowly accumulate on the catalyst and cause performance degradation. More than 185 countries have stopped adding lead to gasoline, with only six (Afghanistan, Algeria, Iraq, North Korea, Myanmar and Yemen) still using small amounts. These last remaining countries with leaded gasoline are expected to remove lead from their gasoline pools by 2015 or 2016. In those areas where leaded and unleaded fuels are available, care must be taken to avoid mis-fueling. Phosphorus should be limited to 0.001 grams per liter, with sulfur not to exceed 500 ppm, although sulfur limits will ideally be 50 ppm or lower (the European Union has a 10 ppm gasoline sulfur cap in place and California/the rest of the U.S. moves toward a 10 ppm gasoline sulfur average starting in 2017).

Lubricating oil is a potential source of physical poisons as well. For four-stroke motorcycles, in-use lubricating oil quality is less of an issue due to the typically low oil consumption of these engines. Four-stroke engine oils contain higher amounts of lube oil ash – including compounds of phosphorous, zinc and calcium. As these engines age, depending on the operating conditions and maintenance, oil consumption tends to increase resulting in possible harm to the catalyst. Two-stroke engines, on the other hand, employ a “total loss” lubricating oil strategy, lube oil impurities may significantly impact catalysts. Operators in some developing countries may use mineral oil blended with fuel due to its availability and low cost. This can result in increased PM emissions from two-stroke motorcycles by several orders of magnitude. Two-stroke motorcycle oils have been formulated with low-ash content to reduce smoke emissions. During normal use a certain amount of lube oil ash will accumulate on catalyst surfaces. However, too much accumulation will cause a decline in catalyst performance. Two-stroke engine catalyst technology designs have been developed with open porous surfaces that maintain performance even with some ash accumulation.

Proper maintenance of four-stroke engines is necessary for long life. Lube oil changes at recommended intervals is very important. Poor maintenance resulting in high oil consumption will result in higher accumulation of oil ash masking poisons on the surface of the catalyst and result in lower catalyst performance.

The combination of advanced catalyst designs and the development of modern two-stroke and four-stroke lubricating oil formulations along with SAE specifications for lubricating oils have reduced the concern for gross negative impacts of oil on catalyst performance. However, the improper use of four-stroke oils in two-stroke engines or use of low grade two-stroke oils can expose the catalyst to high levels of catalyst poisons and negatively impact catalyst performance.

5.2 Alternative Fuels

Alternative fueling options for motorcycles are becoming more common as awareness of GHG emissions grows. Some examples of alternative fuel that have been demonstrated on motorcycles include electrification and hybridization, alternative fossil fuel such as CNG and LPG, or biofuels such as ethanol.

The use of certain fuels such as CNG, electrification, and hybridization presents specific challenges on two-wheeled motorcycles with respect to packaging and space constraints. Installation on three-wheel motorcycles offers some flexibility. Additional system requirements may be needed to facilitate the use of alternate fuels on motorcycles. For example, the application of CNG or LPG on two-stroke applications requires the installation of a lubricating oil pump since it is not possible to manually mix oil and fuel. A CNG system typically consists of a high pressure fuel tank, a pressure regulator, and a gaseous carburetor.

Certain Indian cities have a high percentage of three-wheeled, CNG powered motorcycles due to air quality-driven clean-fuel requirements. Two-stroke CNG motorcycles can reduce NMHC and NOx emissions by about 80%, and CO emissions by about 60%. Four-stroke engines exhibit reductions in NMHC emissions by about 75% and CO emissions by about 60%, while NOx emissions tend to increased by about 30% due to higher air/fuel ratios. On the down side, greenhouse gas emissions (methane) in the form of evaporated fuel and unburned HCs present significant challenges from CNG vehicles. Methane has a global warming potential of 23 times that of CO_2 resulting in CO_2-equivalent emission rates of 46 g/km for four-strokes and 115-161 g/km for two-strokes fueled with CNG.[1]

The use of LPG in motorcycles is conceptually similar to that of CNG although it can be stored as a liquid and thus eliminates some of the space constraints of CNG. LPG tanks tend to be cylindrical for safety reasons and this tends to limit their application on two-wheeled motorcycles since most of the available space is irregular in shape.

The issues around the use of ethanol or other biofuels on motorcycles is similar to those in automotive or truck applications. From an engine design standpoint, they tend to require minor fueling system upgrades to ensure that potential negative impacts on elastomers are avoided and permeation properties are addressed within the fuel delivery system.

Electric or hybrid electric motorcycles have the potential to provide significant air quality benefits while exhibiting even greater challenges than automobiles in terms of weight and space constraints. A few studies have demonstrated about 10% reductions in CO and HC+NOx, with a 15% reduction in fuel consumption on a hybrid motorcycle (see SAE 2006-32-0102).

To date, only one country has begun to adopt zero-emission regulations for motorcycles. Taiwan currently requires that two percent of motorcycles under 50 cc must emit zero emissions. The government provides incentives to offset the difference in cost relative to a gasoline motorcycle. Despite these subsidies, only about 25,000 electric motorcycles were purchased by 2001. This is well below the mandated levels due to consumer dissatisfaction with operating range, recharge time, motorcycle weight, and cost.

6.0 INSPECTION AND MAINTENANCE

Vehicle inspections are a tool employed to ensure that vehicles meet applicable exhaust emission standards under normal operating conditions. These inspections most commonly use gas concentration analysis test methods where gas samples are taken and analyzed with a direct reading instrument at vehicle idling conditions. Two different types of inspections are commonly performed: 1) periodic inspections in which the vehicle is inspected at an approved testing station at regular fixed time intervals (i.e., annual), and 2) spot inspections performed on a random basis by pulling vehicles off the road for on-site inspection (generally referred to as "roadside inspections"). However, it is not clear that those idle test standards are capable of detecting any but the most serious emissions failures. In the absence of specific in-use emissions research aimed at designing an effective I/M test, the use of certification idle emissions requirements would represent a reasonable compromise between design and implementation requirements. But as motorcycle engine controls become more sophisticated, it will not be possible to evaluate on-road emissions performance through idle testing alone.

Periodic inspection and maintenance tests are a critical component of a comprehensive motorcycle emissions reduction strategy. I/M programs consist of measuring motorcycle emissions and requiring consumer repairs when those emissions exceed specified levels. These programs can require significant investments in labor and equipment, as well as trained personnel to conduct the emissions test, but the investments can be recouped through inspection fees. Before implementing the I/M program, it is important that effective research be conducted to establish reliable emissions testing procedures and pass/fail criteria that are fair to both consumers and manufacturers. It is not typically possible to administer a certification-type emissions test in the field, so I/M tests generally tend to be less precise and often rely on emissions test measurements that comprise only a fraction of certification test measurements.

7.0 CONCLUSION

- The rapidly expanding fleet of two-wheel vehicles worldwide accounts for a significant fraction of global hydrocarbon and carbon monoxide air pollution, particularly in urbanized areas where the two-wheel vehicle is the primary mode of private transportation.

- A typical approach taken by countries was to phase-in the regulations and emission standards. Now that two-wheel emissions control programs have proven successful the technology needed is readily available. Countries can now go directly to strict emission control regulations and standards. Such regulations and standards require the use of advanced catalyst technology and advanced engine improvements.

- Catalyst technology has clearly demonstrated the ability to achieve significant emissions reductions from both two-stroke and four-stroke two-wheel vehicles. Countries that have adopted emission standards that have resulted in the use of catalytic technology include Austria, Switzerland, Taiwan, Thailand, and the United States.

- There are additional opportunities to reduce VOC emissions from motorcycles by implementing evaporative emission standards that are more closely aligned with U.S. evaporative emission standards that are in place for light-duty gasoline vehicles.

- Two-wheel vehicles equipped with two-stroke power plants can comply with stringent hydrocarbon and carbon monoxide emissions standards by using catalyst technology – which in addition removes a high percentage of particulate emissions. Therefore, in markets where the cost of basic transportation and higher specific power output are important, these preferred power plants will continue to find widespread use.

- Unleaded fuel must be available in markets where catalyst technology is employed. In those areas where leaded and unleaded fuels are available, care must be taken to avoid mis-fueling

- To ensure compliance with applicable exhaust emission standards, a vehicle inspection and maintenance (I/M) program should be implemented. A program requiring annual inspections of all two-wheel vehicles subject to emissions regulations is recommended.

8.0 REFERENCES

1. "Air Emissions Issues Related to Two and Three-Wheeled Motor Vehicles", Prepared for ICCT by Meszler Engineering Services, July 2007.

2. "Research into New Emission Control Techniques for Motorcycles to Achieve the Euro-3 Regulation", S. Akamatsu, T. Kono, H. Miyata and M. Uraki, SAE 2004-32-0032.

3. "Reduction of Nano-Particle Emissions from Gasoline 2-stroke Engines Using CLM^{TM} Ceramic Exhaust Filters", N. Loren et. al. Submitted to the SAE Small Engine Technology Conference, Milwaukee, WI, September 9-11, 2008. SAE 2008-32-0011.

4. "Development of gas exchange and performance of motorbikes below the influence of actual and future emission regulations", J. Post, C. Landerl and J. Quell, Der Arbeitsprozess Des Verbrennungsmotors, Graz, Austria, September 25, 2009.