Air Emissions Issues Related to Two- and Three-Wheeled Motor Vehicles

An Initial Assessment of Current Conditions and Options for Control

July 2007

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Prepared for the International Council on Clean Transportation

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Primary research for this report was conducted during the first half of 2005. While it is believed that the presented information continues to accurately reflect current conditions, it is possible that advances have occurred that are not fully reflected in the presented material.

Acknowledgement: The author would like to sincerely thank Narayan V. Iyer for his thoughtful and detailed comments on a draft version of this report. His consideration has contributed significantly to the accuracy of this final report. Mr. Iyer had no influence on whether or how his comments were incorporated and therefore should not be held accountable for either the data or opinions expressed herein. Any and all errors are the sole responsibility of the author.

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Acronyms and Abbreviations

API .... American Petroleum Institute
A/F .... air/fuel ratio
cc .... cubic centimeter
Cat .... catalyst
CH_4 .... Methane
CI .... Compression Ignition
CNG .... Compressed Natural Gas
config .... configuration
CO_2 .... Carbon Dioxide
CO .... Carbon Monoxide
CPSI .... cells per square inch (catalyst substrate density)
DI .... Direct Injection (typically into an ICE combustion chamber)
ECE .... Economic Commission for Europe
ECE R40 .... ECE driving cycle for motorcycles of 50cc and greater
ECE R47 .... ECE driving cycle for motorcycles under 50cc
EGR .... Exhaust Gas Recirculation
EU .... European Union
EUDC .... ECE Extra-Urban Driving Cycle
evap .... evaporative
exh .... exhaust
FI .... Fuel Injection (typically into an ICE intake port)
FTP-75 .... U.S. Federal emissions Test Procedure (of 1975), a U.S. driving cycle
g .... gram(s)
GHG .... Greenhouse Gas
g/km .... grams per kilometer
g/mi .... grams per mile
$g/m^2/day$ .... grams per square meter of surface area per day
HC .... Hydrocarbons (used synonymously with VOC in this report)
hr .... hour(s)
ICCT .... International Council on Clean Transportation
ICE .... Internal Combustion Engine
IDC .... Indian Driving Cycle
I/M .... motor vehicle Inspection and Maintenance program
IPCC .... Intergovernmental Panel on Climate Change
IRF .... International Road Federation

Acronyms and Abbreviations

- continued -

ISO .... International Organization for Standardization
ISO 6460 .... ISO driving cycle for motorcycles
JASO .... Japanese Automotive Standards Organization
km .... kilometer(s)
km/hr .... kilometers per hour
LPG .... Liquefied Petroleum Gas
max .... maximum
mi .... mile(s)
mi/hr .... miles per hour
mod .... modified
mod FTP75 .... modified FTP-75, a version of the FTP-75 cycle modified for motorcycles
MSRP .... Manufacturers Suggested Retail Price
NMHC .... Non-Methane Hydrocarbons (= HC minus methane)
NO_x .... Oxides of Nitrogen
N_2O .... Nitrous Oxide
OEM .... Original Equipment Manufacturer
Oxy .... oxidation
Oxy Cat .... oxidation catalyst
PGM-FI .... Programmed Fuel Injection (a Honda fuel injection technology)
PM .... Particulate Matter
ppm .... parts per million
rpm .... crankshaft revolutions per minute (a measure of engine speed)
SAI .... secondary air injection
SI .... Spark Ignition
Tg .... Teragrams (= 10^{12} grams = trillion grams = million metric tons)
TWC .... three-way catalyst
U.S. .... United States
VOC .... Volatile Organic Compounds (used synonymously with HC in this report)
WMTC .... World Motorcycle Test Cycle
yrs .... years

1. Executive Summary

This report is intended to present a summary of the current regulatory environment, provide appropriate background information, and introduce potential control measures for consideration in future policy development. It is expected that ICCT staff will prepare a subsequent and more focused report on policy development options that builds off of the material presented herein. Except where specifically noted, the term "motorcycle" is used generically throughout this report to describe both two-wheeled and three-wheeled motor vehicles. Three-wheeled vehicles are typically developed from two-wheel technology. Both utilize the same engine designs and have similar emissions issues. Thus the term "motorcycle" includes all equipment commonly referred to as mopeds, scooters, and motorcycles, as well as three-wheeled vehicles that are known locally by such names as autorickshaws (India and Sri Lanka), baby taxis (Bangladesh), mishuks (Bangladesh), tempos (Bangladesh, India, and Sri Lanka), and tuk-tuks (Thailand).

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 residents to navigate heavily congested areas in a reasonably efficient manner. Purchase and maintenance costs are also 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, especially for lower income residents.

Asia accounts for almost 85 percent of new motorcycle sales, with Europe a distant second at about 8 percent. In recent years, there has been tremendous growth in motorcycle sales in Asia, with annual growth rates at or above 5 percent in most countries. Table ES-1 shows the annual growth in motorcycle ownership between 1989 and 2002 for 17 Asian countries or regions. Seven countries or regions had growth rates over 10 percent, with ownership in mainland China growing at an astounding 25 percent per year. If mainland China's growth continues, its current motorcycle fleet will double in just three years.

Asian markets reflect a pronounced bias toward small displacement engines of 125cc and less. This is in dramatic contrast to the distribution of motorcycles in the United States and northern Europe, where 500cc and larger engines dominate sales, and sales of small motorcycles are modest. Given the dominant role of Asia in the global motorcycle market, the bias found in Asian markets translates directly into a global bias for small motorcycles.

In light of the importance of smaller motorcycles in the global market, the emissions-related discussions presented in this report focus primarily on small displacement motorcycles (i.e., those with displacements of up to about 250cc). From both a design and cost standpoint, small displacement motorcycles present a more difficult emissions control target, so that the small motorcycle focus reflects a more challenging emissions control analysis.

Table ES-1. Growth in Asian Motorcycle Populations (1989-2002)

Country (or Region)	Annual Growth Rate	Estimated 2002 Population	Years for Population to Double
Mainland China	25%	62,105,412	3
Nepal	16%	204,121	5
Vietnam	15%	9,436,024	5
Philippines	14%	1,735,814	5
Cambodia	13%	333,663	6
Laos	11%	201,948	7
India	10%	41,760,670	7
Indonesia	9%	16,775,380	8
Thailand	9%	16,886,204	8
Bangladesh	7%	285,895	10
Sri Lanka	7%	710,356	10
Pakistan	7%	2,729,155	11
Hong Kong, China	5%	39,099	14
Taiwan, China	5%	12,459,333	14
Malaysia	5%	5,378,127	15
Japan	3%	1,404,074	26
Singapore	1%	134,799	70
Aggregate	**15%**	**172,580,075**	**5**

Emissions Inventories

Table ES-2 presents a sampling of motorcycle emissions fractions for selected cities where detailed emissions inventories for one or more pollutants have been developed. It is suspected that motorcycle emissions are significant contributors to overall emissions in most Asian cities, but the detailed emissions inventories necessary to make an affirmative determination are not yet available. On a global and total Asian basis, motorcycle emissions of NO_x and CO_2 are generally modest relative to total emission inventories, but emissions of VOC and, to a lesser extent, CO are significant.[1] A recent analysis concluded that the contribution of motorcycles to total transport sector VOC and CO emissions in 9 EU countries will increase from about 5 percent in 1995 to 15-20 percent by 2020 given existing emission control regulations. This is despite the fact that the analysis assumes that motorcycles will be responsible for only 2-3 percent of travel in 2020.

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[1] No estimate of total global or total Asian PM emissions is available to determine the significance of estimated motorcycle PM emissions on a global or total Asian basis.

Table ES-2. Motorcycle Share of Total Transportation Emissions in Selected Asian Cities

City	VOC	CO	PM	NOx	CO_2
Ho Chi Minh City, Vietnam	90%	70%	no estimate	12%	40%
Delhi, India	70%	50%	no estimate	no estimate	no estimate
Bangkok, Thailand	70%	32%	4%	<1%	no estimate
Dhaka, Bangladesh	60%	26%	42%	4%	no estimate

Emission Control Options and Technologies

Historically, the emissions characteristics of motorcycles have received less regulatory attention than has been directed at emissions associated with automobiles and trucks (although substantially more attention has been devoted in a limited number of countries or regions -- such as India, Taiwan province of China, and Thailand). Initial controls have been adopted in many countries in response to existing emission standards and more advanced control are entering the market as standards become more stringent. While existing standards have resulted in motorcycle emission reductions (as well as consumer benefits such as reduced noise and improved fuel efficiency), significant additional reductions are possible. Additional regulatory challenges include maintaining emissions levels during the full useful life of the motorcycle under real-world driving conditions and expanding the scope of regulatory programs to include evaporative emissions, durability, in-use compliance testing, and inspection and maintenance.

Several technologies are available to reduce emissions from motorcycles. These include catalytic converters for both two- and four-stroke motorcycles, direct injection technology for two-stroke motorcycles, the replacement of two-stroke motorcycle designs with four-stroke technology, and fuel-injection technology for four-stroke motorcycles. Table ES-3 provides a summary of the emission reduction cost-effectiveness of various emission control options evaluated in this report. As indicated, there are a number of technology options that provide consumer savings and could therefore be used to set stringent global emission standards for the near term.

Advances in aftertreatment catalyst technology are responsible in large part for the remarkable and continuing emission reductions observed in the automobile and light truck markets over the last three decades. Similar technology can be used for both two- and four-stroke motorcycles. While the transfer of this technology poses significant challenges due to the size of motorcycles and the backpressure sensitivity of their engines, many of the lessons learned in the auto and light truck sectors can be applied to the development of effective catalyst technology for the motorcycle sector.

It is critical that the fuel quality requirements for effective catalytic converter operation be recognized and implemented. Generally, this means that catalyst-equipped vehicles should be fueled only with an unleaded, low phosphorus gasoline -- with as low a sulfur content as

Table ES-3. Summary of Control Option Cost-Effectiveness ($/metric ton)

Technology	Calculation Base	Calculation Basis (1)	Technology Cost Only			Technology Cost with Fuel Savings (2)			
			HC Only	HC+NO_x	HC+CO+ NO_x+PM	HC Only	HC+NO_x	HC+CO+ NO_x+PM	Payback Period
2-Stroke Oxy Cat	Uncontrolled 2-Stroke	Individual	$136	$136	$65	$136	$136	$65	Never
2-Stroke Oxy Cat + SAI		Combined	$124	$124	$59	$124	$124	$59	Never
2-Stroke DI		Individual	$39	$39	$18	-$1,074	-$1,077	-$493	0.5 yrs
2-Stroke DI + Oxy Cat		Combined	$63	$63	$29	-$916	-$917	-$422	0.8 yrs
2-Stroke DI + Oxy Cat		Marginal Cat	$678	$678	$320	$678	$678	$320	Never
2-Stroke to 4-Stroke		Individual	$29	$29	$21	-$792	-$797	-$571	0.5 yrs
4-Stroke SAI	Uncontrolled 4-Stroke	Individual	$1,522	$1,522	$59	$1,522	$1,522	$59	Never
4-Stroke SAI + Oxy Cat		Combined	$891	$891	$59	$891	$891	$59	Never
4-Stroke TWC		Individual	$832	$779	$67	$832	$779	$67	Never
4-Stroke FI		Individual	$3,266	$4,019	$127	-$8,180	-$10,067	-$317	4.1 yrs
4-Stroke FI + TWC		Combined	$2,289	$2,192	$160	-$3,097	-$2,967	-$217	6.5 yrs
4-Stroke FI + TWC		Marginal Cat	$1,420	$1,136	$353	$1,420	$1,136	$353	Never
Permeation Controls	Uncontrolled	Individual	$81	$81	$81	-$1,342	-$1,342	-$1,342	<1 yr
Lubricating Oil Controls	Requires locality-specific analysis								
Alternative Fuels									
I/M Testing									
Usage Restrictions									

(1) Individual indicates that only a single technology is included in the cost-effectiveness calculation. Combined indicates that the combined cost of multiple technologies are included in a single cost-effectiveness calculation. Marginal indicates that the marginal cost of the indicated single technology is evaluated relative to the cost of the other technologies included in the package.

(2) Negative cost-effectiveness estimates signify control options that result in fuel savings that exceed the cost of the control technology (i.e., the overall cost is negative and emissions benefits effectively accrue for free).

practical. Gasoline should also be free of metals such as manganese. In countries where leaded gasoline is still available, regulatory efforts to prevent misfueling will have to be implemented.

Direct injection technology for two-stroke engines offers an effective means of allowing two-stroke scavenging to be accomplished using only intake air -- thereby substantially reducing motorcycle HC emissions and fuel consumption. Direct injection technology has already moved beyond the laboratory to mass-market applications. It is currently marketed on seven European motorcycle models and is slated for introduction into the Indian three-wheel motorcycle market. Equally important, direct injection technology is durable and should be able to demonstrate very low emissions deterioration over the full useful life of the motorcycle.

Like direct injection technology, four-stroke fuel consumption is substantially lower than that of a conventional two-stroke motorcycle. As a result, both technologies offer in-use fuel savings that offset the initial incremental technology cost. In fact, either technology pays for itself in less than one year, depending on mileage and fuel costs.[2]

Four-stroke engine emissions can be further reduced with additional aftertreatment. Fuel injection technology can also be applied to four-stroke engines and associated fuel savings will result in consumer payback in about four years. Adding a catalyst to a fuel injected four-stroke motorcycle can further reduce emissions, but the fuel savings payback period for fuel injection is extended to about 6.5 years since the catalyst results in no additional fuel savings.

The replacement of two-stroke engines with equivalent four-stroke designs is now viable across the entire range of motorcycle models. As a result of regulatory and market forces, most motorcycle manufacturers are shifting production from 2-stroke to 4-stroke engines. The result is much lower emissions and better fuel economy for this sector.

Evaporative Emissions

Recent emission standards in the United States, the State of California, and Thailand have started to include evaporative emission rates. Motorcycles sold in California are equipped with a small carbon canister to capture and recycle (back to the engine) evaporative HC. The U.S. Environmental Protection Agency recently adopted fuel system permeation limits that take affect beginning in model year 2008. The limits primarily target resting loss evaporative emissions and are expected to reduce fuel tank and hose permeation by 85-95 percent at a cost of approximately $2 per motorcycle. Evaporative controls also result in lifetime fuel savings of over $30 (discounted) per motorcycle since less fuel evaporates and the consumer investment is returned in less than one year.

Misuse of Engine Oil

The use (and overuse) of incorrect lubricating oil is a common problem that leads to higher than necessary PM emissions from two-stroke motorcycles in some countries.[3] The practice is so widespread in some areas that fueling station attendants automatically pre-blend the *incorrect* lubricating oil when two-stroke motorcycles refuel. In fact, a United Nations research program found it difficult to purchase gasoline for even four-stroke motorcycles without pre-mixed lubricating oil, even though such engines do not require oil of any type to be mixed with fuel. Bans on the use of the incorrect lubricating oil are in place in some areas. Another option might

[2] Of course, the actual payback period depends largely on usage rate of the motorcycle and the cost of fuel. Payback periods for limited use motorcycles or motorcycles in areas with low fuel costs will be longer, while payback for high use motorcycles or motorcycles in areas with high fuel costs will be shorter. The payback periods cited in this report are based on an assumed fuel price of $1.06 per liter ($4.00 per gallon) and assumed average annual travel of 4,260 km (2,650 mi). Fuel costs were based on the average retail fuel prices from various nations. Travel was based on odometer readings from in-use vehicles testing for in-use emissions.

[3] "Incorrect" lubricating oil indicates using either a lubricant formulation different than that recommended by the motorcycle manufacturer, or using the incorrect quantity of lubricating oil. This is principally an issue for two-stroke motorcycles with total loss lubrication systems (where lubricating oil is added to the combustion charge, either by being mixed into the fuel or through pump injection, and consumed with the intake air and fuel). For example, the use of straight mineral oil rather than two-stroke engine oil, or the use of an 8 percent oil-to-fuel ratio rather than the recommended 2 or 3 percent oil-to-fuel ratio.

be to require all pre-mix two-stroke motorcycles to install (retrofit) independent oil metering systems. While such systems would not eliminate the use of the wrong lubricating oil, they would reduce the frequency of over lubricating.

In-Use Testing

In-use testing on a selected sample of well-maintained vehicles helps to ensure that certification emission standards can be met in-use. Conversely, the lack of in-use emission testing requirements reduces the effectiveness of current motorcycle emission standards. In-use emissions testing would ensure that emissions control systems are effective when motorcycles are used as recommended. Of course, since not all motorcycles are used and maintained as recommended by manufacturers, emissions inspection and maintenance (I/M) requirements are also an important part of in-use emissions control.

Inspection and Maintenance

Periodic emissions inspection and maintenance (I/M) requirements are a critical element of a comprehensive motorcycle emissions reduction strategy. Taiwan province of China has administered an effective motorcycle I/M program since 1996. The program tests over 4 million motorcycles annually, failing between 10 and 40 percent (depending on motorcycle age). A review of annual failure rates shows a decrease in the age-specific failure rates over time, so the program appears to have been successful in removing higher emitting vehicles from the road or inducing durable repairs. India also administers a decentralized periodic inspection program for motorcycles. Successful I/M programs have been widely implemented in the automotive sector in many parts of the world and that experience can be translated into the design of effective motorcycle programs.

Alternative Fuels

As with any motorized vehicle, alternative fueling options for motorcycles can be pursued on both an original equipment and aftermarket (i.e., retrofit) basis. Options include electrification and hybridization (generally on an original equipment basis only), alternative fossil fuels such as CNG and LPG, or biofuels such as ethanol. Given the localized nature of issues that can affect the viability, cost, and emissions performance of fuel-switching, this report does not attempt to assign global “average” emission reduction or cost-effectiveness estimates to non-gasoline motorcycle policies. However, such policies should certainly be considered when locally evaluating the potential effectiveness of available control options

Behavioral Measures

In addition to technology-based measures, control measures targeting behavioral changes can also effect significant emission reductions. Such measures include any control strategy that attempts to reduce motorcycle usage rates either through direct restrictions or indirect mechanisms such as usage charges. The level of reductions achieved through such measures depends on both the design and scope of the implemented control, as well as the alternative transportation option(s) utilized in place of displaced motorcycles. Both the absolute effectiveness and cost efficiency of such measures are quite sensitive to local conditions, precluding the development of generalized estimates.

Future Research

The control of motorcycle emissions is an important element of an effective air quality control plan. Motorcycles can be significant contributors to air quality problems and there are several currently available control options. Nevertheless, there are also a number of issues where further research could result in significant additional enhancements to future motorcycle emissions control options. Among the more important of these research issues are:

- Continuing efforts to recruit and test existing in-use motorcycles.
- Further confirmation that existing particulate matter emissions measurement techniques are adequate for two-stroke motorcycle particulate that is dominated by lubricating oil emissions.
- Further work on globally harmonized emission standards and associated certification testing protocols, including country-specific issues related to the development of the World Motorcycle Test Cycle (WMTC).
- Expansion of emissions testing protocols to include evaporative emissions.
- Expansion of emissions testing protocols to include standards for HC, CO, NO_x, and PM.
- Expansion of emissions testing protocols to include real-world durability requirements.
- Where necessary, expansion of efforts to ensure that fuel quality is adequate to allow emissions control catalysts to function effectively in-use.
- Development of effective in-use enforcement protocols.
- Development of effective I/M test protocols and standards.
- Development of comprehensive educational and instructional programs for both citizens and repair personnel.

2. Introduction

This report is intended to summarize the current state of air emissions issues related to motorcycles, which satisfy a significant portion of the personal and commercial transportation requirements in many metropolitan areas.[4] While this may be surprising to readers in the Western Hemisphere and northern Europe, where motorcycles are viewed primarily as recreational vehicles, the great popularity and wide ranging utility of motorcycles is obvious to readers in southern Europe and especially Asia. In the metropolitan areas of such regions, motorcycles are omnipresent and, in many respects, an essential feature of the transportation system. The smaller physical size of motorcycles allows residents to navigate heavily congested areas in a reasonably efficient manner, impossible with larger automobiles and trucks. Additionally, since purchase and maintenance costs are substantially lower than corresponding costs for even small automobiles, motorcycles are an economically efficient transportation option.

While motorcycles, in the form of mopeds, scooters, and what are traditionally known as motorcycles,[5] fulfill not only the personal transportation needs of their riders, three-wheeled variants are also used extensively for commercial purposes in Asia. Small three-wheelers are used as taxis, typically capable of seating up to three passengers. These vehicles are locally known by such names as autorickshaws in India and Sri Lanka, baby taxis or mishuks in Bangladesh, and tuk-tuks in Thailand. Larger three-wheelers, known locally as tempos in Bangladesh, India, and Sri Lanka, are also used for taxi service and are capable of seating up to a dozen passengers.[6] Both small and large three-wheelers are derivatives of two-wheeler technology, relying on the same base engine technology as the two-wheeler. As a result, they present similar emissions challenges, although those challenges can be exacerbated by the more

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[4] For convenience, the term "motorcycle" is used generically throughout this report to describe both two-wheeled and three-wheeled motor vehicles (except where distinctions are explicitly noted). Three-wheeled vehicles are typically developed from two-wheel technology, utilizing the same engine designs, and thus reflecting similar fundamental emissions issues (albeit exacerbated to some extent by increased vehicle weight and load demands). Due to their more commercially-oriented operating cycles, three-wheeled vehicles can present unique challenges such as more rapid mileage accumulation, thus necessitating more frequent maintenance activity and potentially requiring more durable emissions control equipment. Where appropriate, the specific challenges associated with three-wheeler emissions control are discussed explicitly.

[5] Distinctions between mopeds, scooters, and motorcycles are more casual than formal. Mopeds generally utilize engines with displacements less than 50 cubic centimeters (cc) and have top speeds of less than 50 kilometers per hour (km/hr) -- 30 miles per hour (mi/hr) -- to comply with special vehicle registration and licensing allowances. Scooters often use smaller displacement engines than motorcycles, but larger displacement scooters are available, while small displacement motorcycles are common in many Asian cities. Thus, engine size in not a generally reliable distinguishing design characteristic for vehicles larger than mopeds. Scooters are more appropriately distinguished from what are typically known as motorcycles by differing design features such as step-through rear-engined frames, automatic transmissions (although there are manual transmission scooters available), and reduced weight. While engine size might offer an added distinction in North America and northern Europe where motorcycles with engines below 500cc are uncommon, the majority of motorcycles in Asia are much smaller, with displacements of 100-125cc being quite popular. From a regulatory perspective, scooters with engines that exceed the moped allowance limits are almost always treated as motorcycles, and in many countries there are no regulatory distinctions between mopeds, scooters, and motorcycles.

[6] For both small and larger three-wheelers, the indicated load capacity is expressed in terms of "design seating." In practice, however, these vehicles -- especially the larger three-wheelers -- are often overloaded.

demanding duty cycles of the three-wheelers. It is important to note, however, that while nearly all two-wheel motorcycles and most of their three-wheel counterparts are powered by spark-ignition engines, the penetration of compression-ignition engines in the larger three-wheeler market has been increasing. For example, compression-ignition engines may account for as much as 30 percent of current three-wheeler sales in India. Nevertheless, spark-ignition engines continue to dominate the global motorcycle market and, as such, constitute the focus of this report. With the exception of a very small number of novelty motorcycle conversions and off-road recreational vehicles, three-wheelers are virtually unknown in the Western Hemisphere -- and those that do exist perform no commercial function.[7]

Historically, the emissions characteristics of these vehicles have received less regulatory attention than has been directed at emissions associated with automobile and truck use, but relatively recent regulatory activity has resulted in significant initial emission reductions and plans for further control over the near term. This is not intended to diminish the regulatory activities of countries or regions such as India, Taiwan province of China, and Thailand, that have made significant advances in the motorcycle emissions control arena. Nonetheless, automobile and light truck regulatory activity has been advancing for over 40 years and the technology to reduce new vehicle emissions by 90-100 percent relative to pre-control vehicles has not only been demonstrated, but has been put in place across much of the globe. Additionally, automobile and light truck emissions regulations include stringent in-use emissions requirements to ensure that low emissions are not only demonstrated for new vehicles, but that low emissions are maintained throughout a vehicles lifetime. As a result, virtually all automobiles and light trucks are built with advanced electronic fueling controls and highly effective exhaust aftertreatment devices. In contrast, although emissions requirements for motorcycles are becoming increasingly stringent, they generally do not include robust in-use requirements and continue to be met with carbureted fueling technology and evolving aftertreatment devices. Since it is expected that motorcycle emissions control requirements will continue to advance, this initial report is intended to provide important background information on the affected vehicles, technology, and control options that might then serve as a foundation for potential future policy development.

It is important to note that no single report can adequately do justice to a global market as diverse as the motorcycle market. Accordingly, this report addresses issues from a broad brush perspective. Although it is targeted to both policy makers and the interested layman, it must be recognized that local conditions in any given country might vary significantly from the generalized conditions assumed in this report. Sources of such variability extend from potential differences in the local motorcycle market and existing regulatory requirements, to emissions impacts associated with local issues such as fuel quality and climatology, to technology cost effectiveness influences associated with issues such as local fuel price and annual motorcycle usage rates. Thus, all readers should recognize that detailed local analysis should precede any local regulatory efforts. While it is hoped that this report might provide important background material in the performance of such local analysis, it should be viewed as a reference, not a surrogate.

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[7] While generally true today, this has not always been the case. For example, three-wheelers were once popular in some European countries.

3. Background

To properly characterize issues surrounding the control of motorcycle emissions, it is first important to understand the attributes and significance of motorcycle use and emissions. Although sensitive to geography and economic prosperity, motorcycle populations are quite significant in many areas. For example, motorcycles outnumber four-wheeled vehicles in a number of Asian countries and growth in motorcycle populations is dramatic. The majority of the global motorcycle population utilizes small displacement engines, generally on the order of 50-150cc, which complicates emissions control issues due to the low cost and simple design characteristics of the basic engine technology. Motorcycle emissions can be quite significant, estimated to contribute as much as 40 percent of PM and CO_2, 50 percent of CO, and 70 percent or more of VOC in some Asian cities.[8] However, emissions controls with the potential to greatly reduce this significance are currently available (as well as under continuing development).

3.1 *Motorcycle Populations*

Although vehicle sales statistics are available, vehicle registration requirements and enforcement techniques are still under development in many countries. As a result, it is somewhat difficult to derive precise estimates of in-use motorcycle populations. Nevertheless, several informative statistics are available from data collected by the International Road Federation (IRF), a non-governmental, non-profit organization that compiles global road and vehicle statistics used for program development by agencies such as the United Nations and World Bank.[9]

For this report, IRF data for 2002 were used to generate several informative statistics. [1] Table 1 presents the number of motorcycles per thousand people for countries or regions where the IRF dataset included both motorcycle and population data. Figure 1 presents the same statistic aggregated by geographic group.[10] This oft-used statistic clearly illustrates the predominance of per-capita motorcycle ownership in Asia and Europe. It is clear from these data that Asian and European countries exclusively exhibit the top ownership rates. On a geographic group basis, Asia and Europe exhibit ownership rates two to forty times larger than other geographic groups. Taiwan province of China, in particular, exhibits an ownership rate over twice that of any other country or region (in the IRF dataset).

While per-capita ownership data is informative, it should be recognized that ownership rates can be greatly affected by the degree of urbanization of each country or region. Motorcycles are far more viable as an urban transportation option where travel distances and cargo carrying requirements are comparatively small relative to rural requirements. Therefore, countries or

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[8] See Section 3.4 for additional discussion and references for these data. These data are not intended to indicate that motorcycle emissions are similarly significant in all Asian cities. The significance of motorcycle emissions in any given city will depend entirely on local conditions. Instead, these data are intended to show that motorcycle can play a significant, and sometimes dominant, role in the total emissions loads of some cities.

[9] http://www.irfnet.org

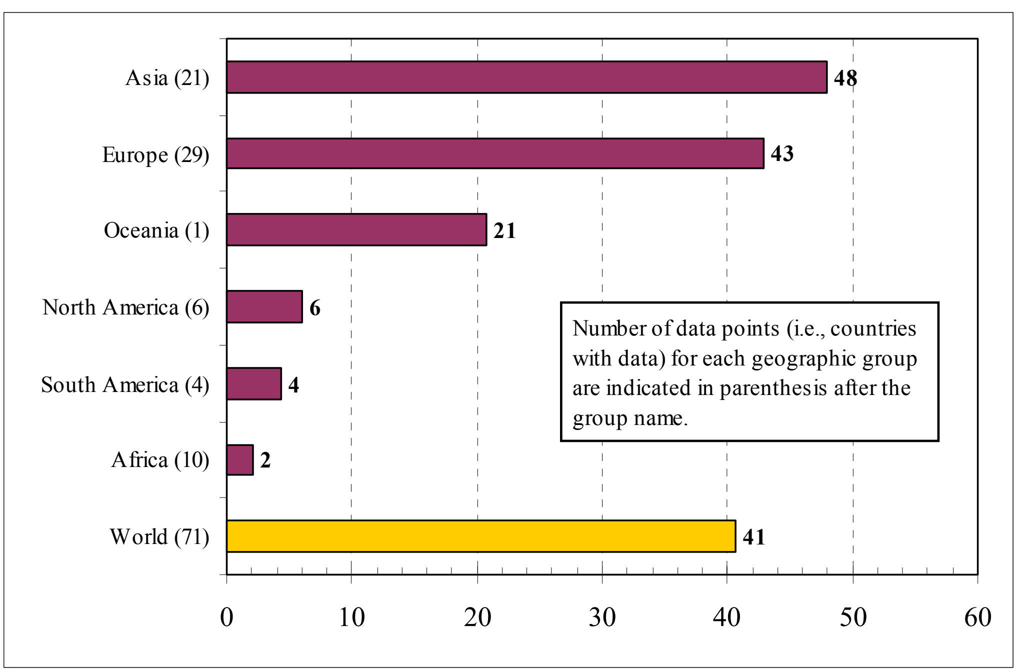
[10] With the exception of Oceania, geographic groups are defined as continents. Oceania consists of Australia, New Zealand, Papua New Guinea, and thousands of smaller Pacific islands.

Table 1. Motorcycles per Thousand People by Country (or Region)

Size Group	Countries (or Region) in Group
200 or More	Taiwan province of China (533, Asia), Malaysia (241, Asia), Greece (230, Europe)
100-199	Macao, China (141, Asia), Japan (106, Asia), Switzerland (102, Europe), Mauritius (101, Africa)
50-99	Czech Republic (74, Europe), Austria (74, Europe), Norway (61, Europe), Belarus (53, Europe), Cyprus (53, Europe)
25-49	Sri Lanka (49, Asia), Finland (43, Europe), mainland China (40, Asia), Spain (37, Europe), South Korea (36, Asia), Ukraine (36, Europe), Sweden (34, Europe), Malta (34, Europe), Poland (33, Europe), Singapore (31, Asia), Belgium (31, Europe), Bulgaria (28, Europe), Luxembourg (27, Europe), Slovenia (25, Europe), *also India (33-41, Asia): see footnote 12*
10-24	Costa Rica (23, North America), New Zealand (21, Oceania), Croatia (19, Europe), Philippines (18, Asia), Turkey (15, Asia), Denmark (15, Europe), Israel (12, Asia), Canada (11, North America), Pakistan (11, Asia), Mongolia (10, Asia), Bhutan (10, Asia), Hungary (10, Europe)
1-9	Latvia (9, Europe), Iceland (9, Europe), Slovak Republic (9, Europe), Peru (9, South America), Barbados (7, North America), Qatar (7, Asia), Netherlands Antilles (6, North America), Lithuania (6, Europe), Syria (6, Asia), Nicaragua (5, North America), Kazakhstan (5, Asia), Estonia (5, Europe), Zimbabwe (4, Africa), Mexico (4, North America), South Africa (4, Africa), Bahrain (3, Asia), Moldova (3, Europe), Swaziland (3, Africa), Kyrgyzstan (2, Asia), Ecuador (2, South America), Namibia (2, Africa), Brunei Darussalam (2, Asia), Chile (2, South America), Albania (1, Europe), Azerbaijan (1, Europe)
<1	Morocco (0.72, Africa), Tunisia (0.62, Africa), Botswana (0.61, Africa), Georgia (0.54, Europe), Sierra Leone (0.32, Africa), Bolivia (0.13, South America), Occupied Palestinian Territory (0.089, Asia), Ethiopia (0.038, Africa)

Source data were not available for unlisted countries. [1]

Figure 1. Motorcycles per Thousand People by Geographic Group



regions with large rural populations can exhibit relatively modest per-capita ownership rates while simultaneously being home to urban areas with significant motorcycle populations.

Additionally, while motorcycle ownership rates provide a broad indication of countries or regions where motorcycle emissions may be an important contributor to local air quality issues, they do not provide an indication of how motorcycle ownership compares to other motor vehicle ownership. For example, motorcycle emissions contributions may be limited in countries or regions with significant ownership rates if those rates are but a fraction of the ownership rates for other motor vehicles. Conversely, air quality in a country or region with only a modest motorcycle ownership rates may be quite sensitive to motorcycle emissions performance in high density areas if ownership rates for other motor vehicles are low.

In an effort to overcome the limitations of strict per-capita ownership rates, two additional statistics were generated using the IRF data. Table 2 presents the ratio of motorcycles per four-wheel vehicles for individual countries or regions, while Figure 2 presents corresponding data aggregated by geographic group.[11] Table 3 presents the number of motorcycles per kilometer of roadway for individual countries or regions, while Figure 3 presents the same data aggregated by geographic group. The four-wheel to motorcycle ownership ratios provide an indication of the significance of the motorcycle population relative to that of other motorized vehicles, while the motorcycle per kilometer statistic indicates the relative density of motorcycle use. Together, these statistics provide an indication of how significant a role motorcycles might play in local air quality.

From Figure 2, it is clear that Asian motorcycle ownership is much more significant relative to Asian ownership of other motorized vehicles than is the case in any other geographic area. In total, there are only about 1.6 non-motorcycles (four-wheeled vehicles) per motorcycle in Asia, as compared to 8 four-wheeled vehicles per motorcycle in Europe and 15-45 four-wheeled vehicles per motorcycle in all other geographic groups. Moreover, as shown in Table 2, five Asian countries or regions exhibit higher motorcycle than non-motorcycle ownership, with ratios in both mainland China and Taiwan province of China indicating about two motorcycles per non-motorcycle. It is reasonable to expect that motorcycles in such countries or regions play a critical role in determining the overall significance of motor vehicle emissions.[12]

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[11] In this report, the term "four-wheel" signifies any motorized vehicle with four *or more* wheels. Generally, this includes automobiles and trucks.

[12] The contrast in the motorcycle to four-wheeled vehicle and per-capita motorcycle statistics is perhaps most demonstrable for India. Because IRF does not report the 2002 motorcycle population for India, the country does not appear in Tables 1, 2, or 3. However, the corresponding statistics for 1999 were 33 motorcycles per 1000 people, 3.0 motorcycles per four-wheeled vehicle, and 13 motorcycles per kilometer of road. Similarly, 2002 data provided in the TERI (The Energy Resources Institute) Energy Data Directory and Yearbook (TEDDY), 2004/05 indicates that India had 41 motorcycles per 1000 people, 2.4 motorcycles per four-wheeled vehicle, and 17 motorcycles per kilometer of road. While the per-capita motorcycle ownership ratio would rank the country just below the top quartile of counties included in Table 1, the motorcycle to four-wheeled vehicle ratio would place India even above Taiwan (and by a substantial margin) on the list of counties included in Table 2. Clearly, it is important to look beyond per-capita statistics in determining the significance of motorcycle ownership.

Table 2. Motorcycles per Four (or More) Wheeled Motor Vehicle by Country (or Region)

Size Group	Countries (or Region) in Group
1 or More	Taiwan province of China (2.0, Asia), mainland China (1.9, Asia), Pakistan (1.3, Asia), Sri Lanka (1.2, Asia), Macao, China (1.1, Asia), *also India (2.4-3.0, Asia): see footnote 12*
0.5-1	Malaysia (0.9, Asia), Mauritius (0.9, Africa), Bhutan (0.6, Asia), Philippines (0.5, Asia), Greece (0.5, Europe)
0.2-0.49	Belarus (0.3, Europe), Ukraine (0.3, Europe), Mongolia (0.2, Asia), Singapore (0.2, Asia), Czech Republic (0.2, Europe), Switzerland (0.2, Europe), Peru (0.2, South America), Japan (0.2, Asia), Turkey (0.2, Asia), Syria (0.2, Asia), Costa Rica (0.2, North America)
0.1-0.19	Nicaragua (0.1, North America), Austria (0.1, Europe), South Korea (0.1, Asia), Norway (0.1, Europe), Finland (0.1, Europe)
0.04-0.099	Cyprus (0.099, Europe), Poland (0.095, Europe), Sierra Leone (0.087, Africa), Bulgaria (0.086, Europe), Zimbabwe (0.080, Africa), Sweden (0.068, Europe), Spain (0.066, Europe), Kyrgyzstan (0.065, Asia), Croatia (0.061, Europe), Kazakhstan (0.061, Asia), Belgium (0.059, Europe), Malta (0.054, Europe), Slovenia (0.053, Europe), Moldova (0.045, Europe), Israel (0.042, Asia)
0.02-0.039	Luxembourg (0.038, Europe), Ecuador (0.037, South America), Swaziland (0.035, Africa), Denmark (0.034, Europe), Hungary (0.032, Europe), Slovak Republic (0.032, Europe), New Zealand (0.028, Oceania), Latvia (0.028, Europe), South Africa (0.024, Africa), Ethiopia (0.021, Africa), Barbados (0.021, North America), Namibia (0.020, Africa), Mexico (0.020, North America)
<0.02	Canada (0.019, North America), Azerbaijan (0.017, Europe), Netherlands Antilles (0.017, North America), Lithuania (0.016, Europe), Morocco (0.016, Africa), Albania (0.015, Europe), Estonia (0.015, Europe), Iceland (0.014, Europe), Bolivia (0.013, South America), Chile (0.012, South America), Qatar (0.012, Asia), Occupied Palestinian Territory (0.010, Asia), Georgia (0.009, Europe), Bahrain (0.009, Asia), Tunisia (0.007, Africa), Botswana (0.007, Africa), Brunei Darussalam (0.005, Asia)

Source data were not available for unlisted countries. [1]

Figure 2. Motorcycles per Four (or More) Wheeled Motor Vehicle by Geographic Group

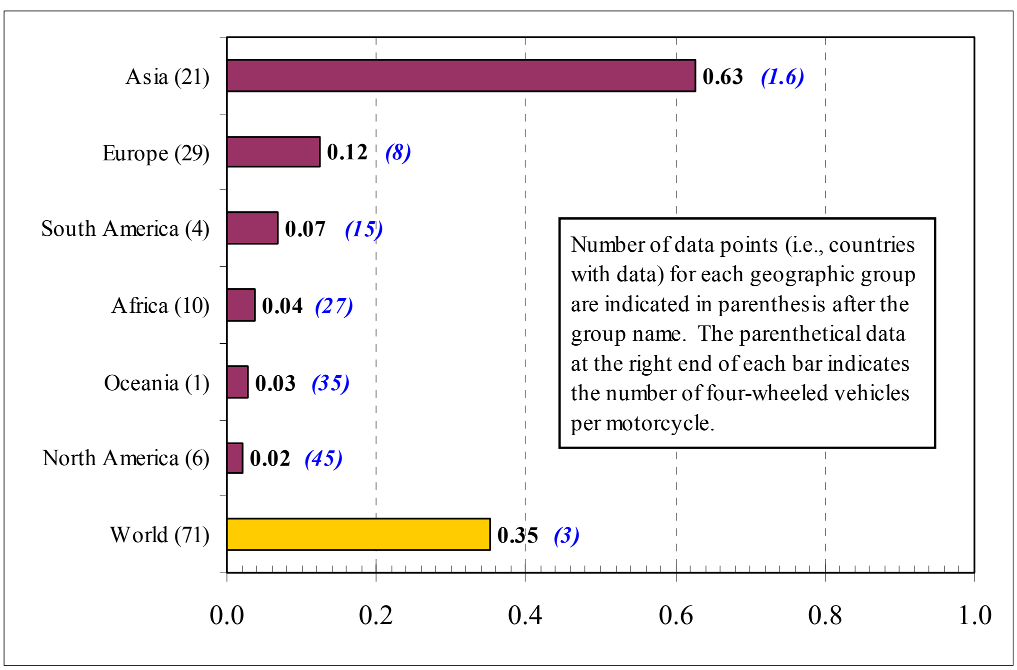
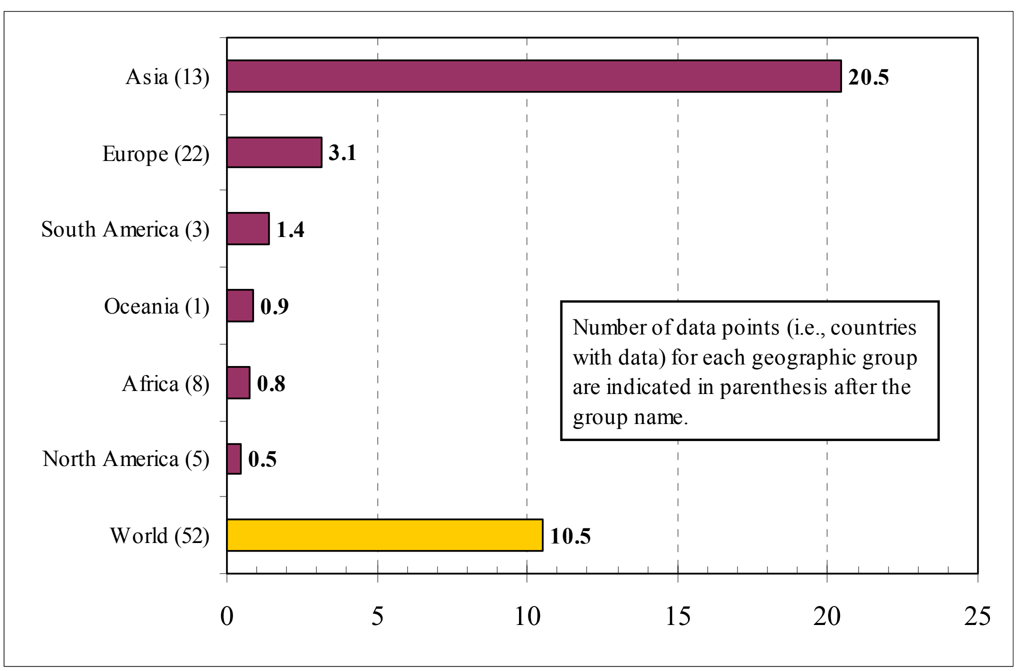


Table 3. Motorcycles per Kilometer of Roadway by Country (or Region)

Size Group	Countries (or Region) in Group
100 or More	Taiwan province of China (321, Asia), Macao, China (182, Asia)
50-99	Mauritius (61, Africa)
25-49	Singapore (42, Asia), mainland China (29, Asia)
10-24	South Korea (18, Asia), Japan (12, Asia), Switzerland (10, Europe), Ukraine (10, Europe) *also India (13-17, Asia): see footnote 12*
5-9	Philippines (7, Asia), Malta (6, Europe), Czech Republic (6, Europe), Israel (5, Asia)
1-4	Austria (4, Europe), Cyprus (3, Europe), Norway (3, Europe), Croatia (3, Europe), Turkey (3, Asia), Peru (3, South America), Finland (3, Europe), Costa Rica (3, North America), Spain (2, Europe), Bulgaria (2, Europe), Belgium (2, Europe), Nicaragua (2, North America), Barbados (1, North America), Mexico (1, North America), Slovak Republic (1, Europe), Denmark (1, Europe), Moldova (1, Europe)
<1	New Zealand (0.89, Oceania), Swaziland (0.86, Africa), Bahrain (0.66, Asia), Hungary (0.61, Europe), Zimbabwe (0.55, Africa), Ecuador (0.55, South America), Mongolia (0.52, Asia), Morocco (0.37, Africa), Kazakhstan (0.32, Asia), Latvia (0.31, Europe), Lithuania (0.27, Europe), Canada (0.25, North America), Iceland (0.20, Europe), Albania (0.19, Europe), Sierra Leone (0.15, Africa), Georgia (0.14, Europe), Estonia (0.13, Europe), Namibia (0.081, Africa), Ethiopia (0.077, Africa), Occupied Palestinian Territory (0.072, Asia), Botswana (0.043, Africa), Bolivia (0.019, South America)

Source data were not available for unlisted countries. [1]

Figure 3. Motorcycles per Kilometer of Roadway by Geographic Group



Similar Asian motorcycle significance is apparent from Figure 3, with over 20 motorcycles per kilometer of roadway -- almost double the global average motorcycle density, and nearly seven times higher than the next densest area, Europe. Two regions in particular, Taiwan province of China and Macao special administrative region of China, exhibit density statistics of over 100 motorcycles per kilometer, as compared to North American countries with density statistics of less than one motorcycle per kilometer. Combined, the density (motorcycle per kilometer of road) statistic and the non-motorcycle per motorcycle ownership statistic demonstrate the primacy of Asia as the geographic area most sensitive to motorcycle emissions performance.

Table 4 shows the annual growth in motorcycle ownership between 1989 and 2002 for 17 Asian countries or regions. [2] With the exception of Japan and Singapore, annual growth rates have been five percent or more -- with seven countries or regions exhibiting annual growth above 10 percent. Mainland China, in particular, has demonstrated an astounding annual growth rate of 25 percent. As shown in Figure 4, the growth rate in mainland Chinese motorcycle ownership far exceeds population growth as well as GDP growth over the last decade. [2,3] It is not clear how long such growth can be sustained, but on a nationwide basis, current motorcycle ownership per 1000 people is still below that of other Asian countries or regions (e.g., 40 in mainland China versus 533 in Taiwan province of China, 241 in Malaysia, and 106 in Japan). However, it is possible that the growth rate will decline in the near future as urban demand saturates and continuing economic expansion shifts vehicle interest toward passenger cars.

While it is not possible to do more than speculate about continuing motorcycle ownership growth, Asia already accounts for almost 85 percent of new motorcycle sales. As indicated in Figure 5, sales in Europe are a distant second at about 8 percent. [4] These data, combined with comparatively lower Asian per-capita automobile and truck ownership, clearly demonstrate that Asian air quality will be substantially more sensitive to motorcycle emissions impacts than is the case in non-Asian markets.

The global average per-capita motorcycle ownership statistics presented in Figure 1 above, in conjunction with global population estimates for 2002, implies that the global motorcycle population in 2002 was about 255 million units. [5] Corresponding data for 1989 imply a global motorcycle population of about 125 million units. [5,6] Together, these data imply an (average) annual increase in the global motorcycle population between 1989 and 2002 of about ten million units. This estimate is a bit higher, but generally consistent with other independent estimates of seven million additional units per year. [7] Moreover, these data imply that since 1989, the global per-capita ownership of motorcycles has increased from about 24 units per 1000 people to about 41 units per 1000 people. During the same period, the number of four-wheeled vehicles per motorcycle has decreased from about six to about four and the number of motorcycles per kilometer of roadway has increased from about four to about eleven. Based on the data presented above, it is clear that this growth has been fueled almost exclusively by growth in Asian motorcycle ownership, but the implications are also clear -- namely that the global motorcycle population is growing faster than the human population, the population of four-wheeled vehicles, and roadway mileage.

Table 4. Growth in Asian Motorcycle Populations (1989-2002)

Country (or Region)	Annual Growth Rate	Estimated 2002 Population	Years for Population to Double
Mainland China	25%	62,105,412	3
Nepal	16%	204,121	5
Vietnam	15%	9,436,024	5
Philippines	14%	1,735,814	5
Cambodia	13%	333,663	6
Laos	11%	201,948	7
India	10%	41,760,670	7
Indonesia	9%	16,775,380	8
Thailand	9%	16,886,204	8
Bangladesh	7%	285,895	10
Sri Lanka	7%	710,356	10
Pakistan	7%	2,729,155	11
Hong Kong, China	5%	39,099	14
Taiwan, China	5%	12,459,333	14
Malaysia	5%	5,378,127	15
Japan	3%	1,404,074	26
Singapore	1%	134,799	70
Aggregate	**15%**	**172,580,075**	**5**

Figure 4. Chinese Motorcycle Growth Versus Population and GDP

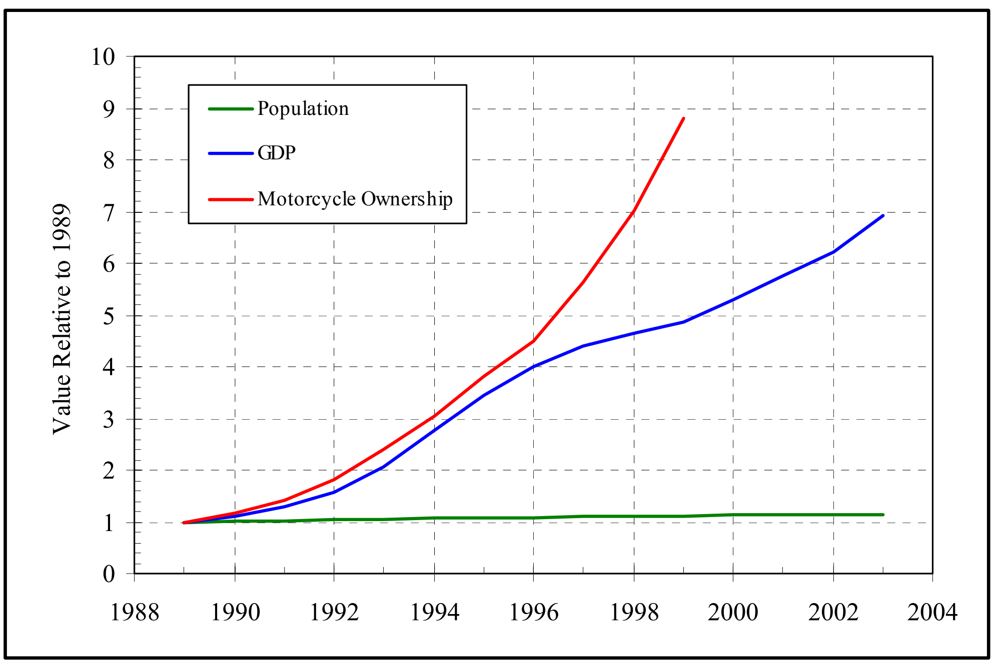
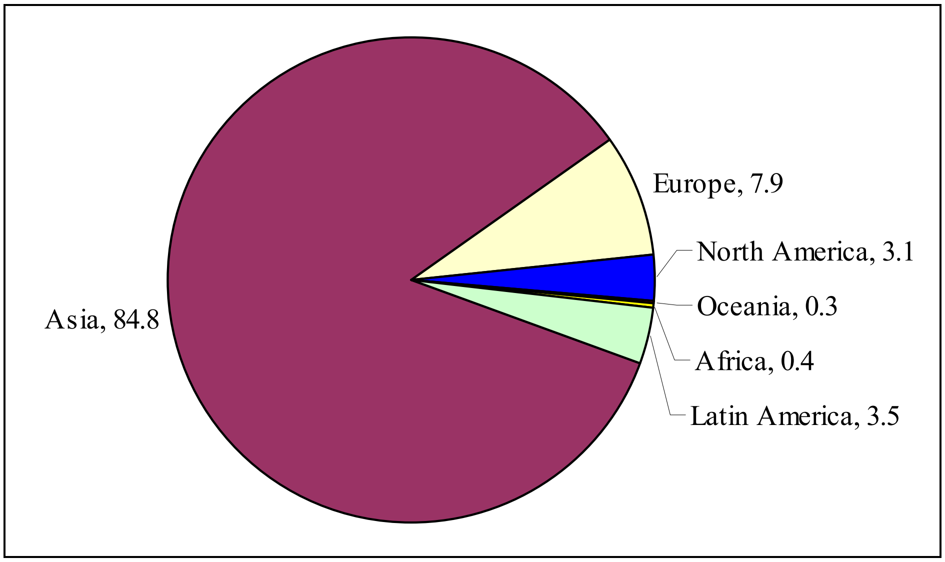


Figure 5. Share of Global Market for New Motorcycles (%)



3.2 *Motorcycle Size*

Motorcycles are marketed in a wide range of size distributions, from less than 50cc mopeds to over 2000cc touring bikes. Although engine technology and emissions performance can (and does) vary somewhat over such a wide range, the predominant engine size on a global basis is concentrated on the lower end of the range, from less than 50cc to about 150cc -- comprised of mopeds, scooters, and small motorcycles. For example, Figure 6 shows the distribution of displacements for motorcycles sold in Taiwan province of China between 1996 and 2000. [8] Although some variation is observed in the dominant engine displacement from country to country, all Asian markets reflect a pronounced bias toward small displacement engines.[13]

The dominance of small motorcycles in Asia is in dramatic contrast to the distribution of motorcycles in the United States and Northern Europe, where 500cc and larger engines dominate sales. For example, Figure 7 illustrates the motorcycle size distributions for Taiwan province of China and the United States in calendar year 2000. [10] As indicated, small motorcycles play only a minor role in the U.S., and thus the emissions performance of larger motorcycles is of greater concern in the U.S. market. However, given the dominant role of Asia in the global motorcycle market, the bias found in Asian markets translates directly into a global primacy for small motorcycles.

In light of the lesser importance of large motorcycles on a global basis, the emissions-related discussions that follow in the remainder of this report are biased toward small displacement

[13] For example, while 50, 90, 100, and 125cc models dominate motorcycle sales in China, the dominant engine size is 100cc (as compared to 125cc in Taiwan). [9]

Figure 6. Distribution of Motorcycle Sizes in Taiwan Province of China

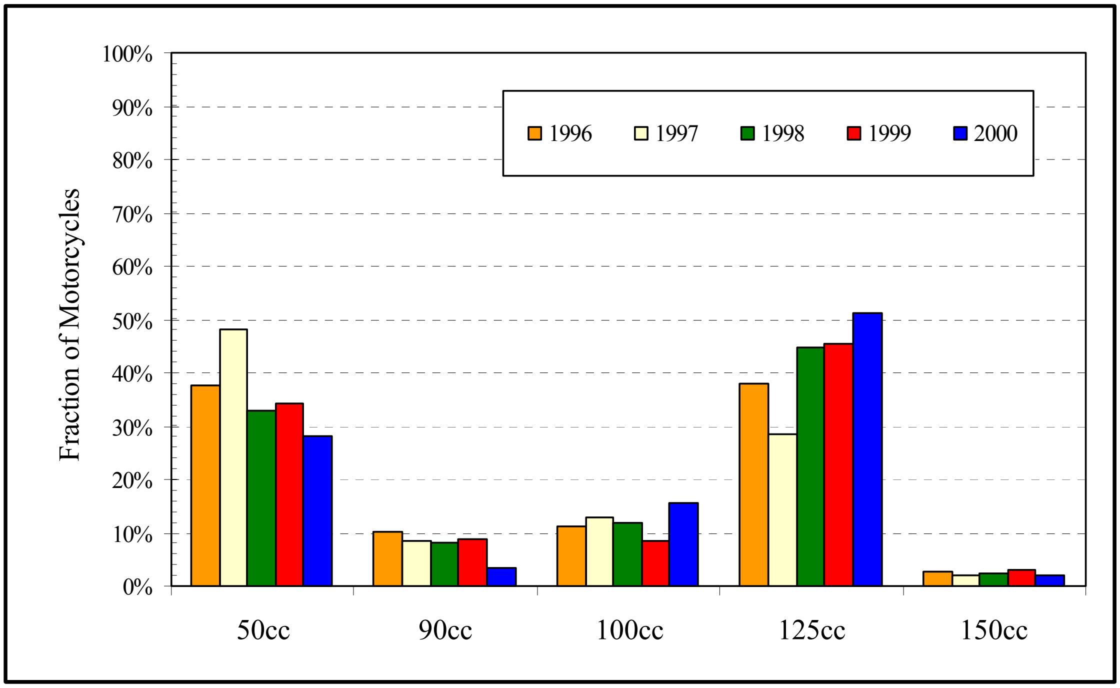
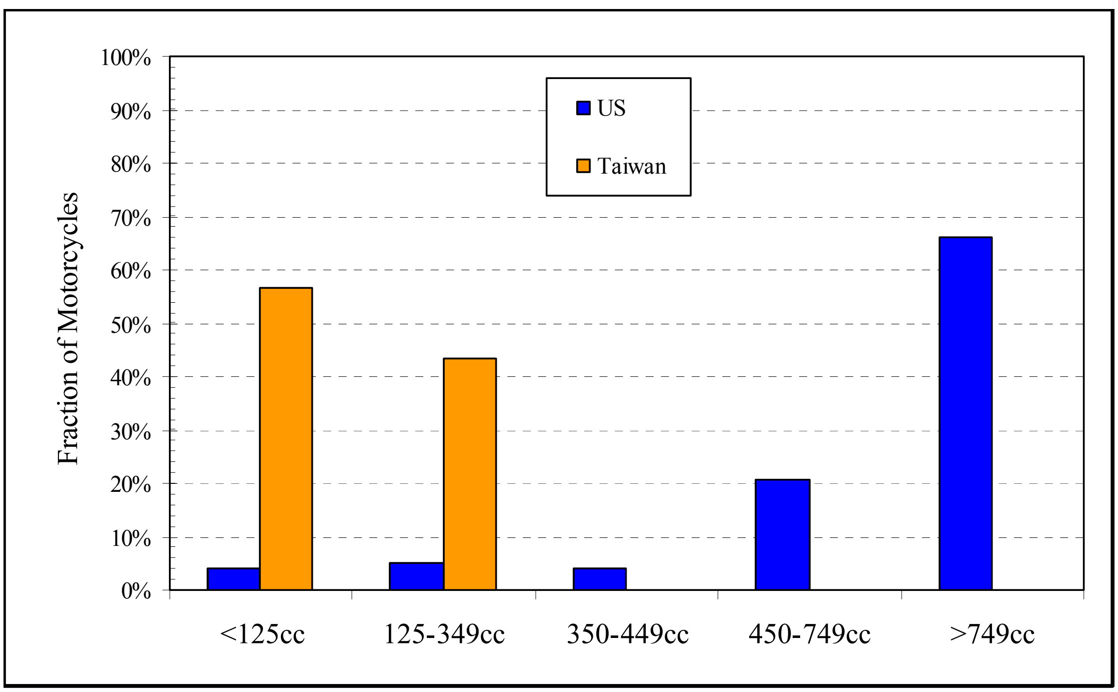


Figure 7. Comparison of Taiwan, China and U.S. Motorcycle Size Distributions



motorcycles (i.e., those with displacements of up to about 250cc). While many of the issues discussed can be extended to larger motorcycles, there are differences in both performance and cost that can affect the design and viability of emissions control options. For example, as compared to small displacement motorcycles, the cost of control equipment for larger motorcycles is likely to represent a smaller fraction of overall vehicle costs -- which can facilitate more aggressive control options. From both a design and relative cost standpoint,[14] small displacement motorcycles present a more difficult emissions control target, so that the small motorcycle bias that follows throughout the remainder of this report not only better reflects the overall global situation, but also is likely to reflect emissions control issues from their most challenging perspective. However, it should also be recognized that automotive-type emissions control technology is more easily transferred to larger displacement motorcycles, so that the small displacement bias that follows will not provide a complete description of the control options that might be viable for larger displacement engines.

3.3 *Motorcycle Engine Technology*

A basic understanding of the fundamental engine technology employed in motorcycles is necessary to understand motorcycle emissions characteristics. Like other motor vehicles, virtually all existing production motorcycles utilize internal combustion engine (ICE) designs, which utilize the energy released by burning fuel to turn a crankshaft (and ultimately propel the vehicle). Almost all large automotive internal combustion engines are of a four-stroke design and this is true for larger motorcycles as well. Smaller motorcycles have historically utilized two-stroke engine designs due to their generally high power-to-weight ratio, lower production and maintenance complexity, and lower purchase and maintenance cost. However, existing emission standards have had a significant impact on engine design and four-stroke technology now dominates new motorcycle production for displacements as low as 100cc.[15] Nevertheless, it is important to understand the general emissions differences between two-stroke and four-stoke designs as a substantial number of two-stroke motorcycles remain in service and emerging technologies such as direct injection fueling could result in the continuing production of two-stroke engines.

With a few exceptions, all ICE engines rely on a piston-in-cylinder design wherein movement of the piston is brought about by expanding gases created through the combustion of a compressed air/fuel mixture. The energy associated with piston movement is used to perform work. There are four components to an ICE combustion cycle. First, air and fuel are introduced into the cylinder, in a process commonly known as “intake.” Second, the air and fuel are compressed in the cylinder through the movement of the piston, a process commonly known as “compression.” Third, the air and fuel are ignited creating expanding gases that act against the piston, a process commonly known as “expansion.” Fourth, the combustion gases are forced out of the cylinder in

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[14] Where relative cost signifies the cost of emissions control relative to the cost of an uncontrolled motorcycle. When relative control costs increase, larger percentage changes in motorcycle cost are observed.

[15] In some cases, most notably that of India, consumer preference for higher fuel efficiency motorcycles in the face of rising fuel costs has also contributed to the rapid introduction of four-stroke technology.

the final "exhaust" component of the cycle, following which the cycle begins anew with a fresh intake action.[16]

Two-stroke engine designs accomplish the entire combustion cycle each time the piston cycles through the cylinder, whereas four-stroke designs require two piston cycles for every one combustion cycle. In effect, for engines running at the same speed, a two-stroke design will produce work twice as often as a four-stroke design. This allows two-stroke designs to offer greater power for a given size and weight engine -- with the trade off being a greater challenge to control the combustion process. In contrast, four-stroke designs offer greater combustion control as each of the four combustion cycle components occurs during a distinct movement of the piston through the cylinder.

From a cost and performance standpoint (i.e., in the absence of emissions and fuel efficiency concerns), two-stroke engine design is favored for small motorcycles. Relative to four-stroke engines, two-strokes offer several advantages for size restricted applications. Two-stroke designs rely on relatively simple cylinder sidewall ports (opened and closed in accordance with piston position in the cylinder) while four-stroke engines require comparatively complex mechanical valve systems to control intake and exhaust port function (since those ports are only opened once for every two cycles of the piston through the cylinder). In addition, since two-stroke engines generate one power stroke per crankshaft revolution as compared to one power stroke per two crankshaft revolutions in a four-stroke engine, two-stroke engines are smaller and more compact than equivalent-output four-stroke engines. These simplified design elements also make two-stroke engines both less costly and generally easier to maintain.

However, from an emissions and fuel efficiency standpoint, two-stroke simplicity comes at a cost. While a four-stroke engine utilizes piston movement to force combustion products out of the cylinder, a two-stroke engine relies on the pressurized flow created by the compressed intake charge to force combustion products out of the cylinder. In effect, intake and exhaust gasses are entering and leaving the cylinder simultaneously. This allows a portion of the intake charge to escape through the exhaust port without being combusted. Since the simplest two-stroke designs rely on a carbureted air/fuel intake charge, a portion of the escaping charge is unburned fuel. These so-called scavenging emissions represent the major emissions difference between two-stroke and four-stroke engines. In worst case operating modes (low speed, high load), up to 40 percent of the intake charge can be lost through the exhaust port prior to combustion. [11] Scavenging emissions of unburned fuel result directly in high HC emissions and increased fuel consumption relative to four-stroke engines.[17]

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[16] It should be noted that advanced combustion technologies can alter the generalized combustion cycle described herein. For example, in direct injection engines, air and fuel are treated separately during the intake stroke. These technologies do not fundamentally alter the four -step cycle, but can affect the specific characteristics of each cycle component.

[17] It should be noted that improvements in two-stroke engine design can significantly reduce scavenging emissions. For example, Indian motorcycle manufacturers have reduced the loss of intake charge to approximately 15 percent, which not only resulted in a significant improvement in fuel efficiency but simultaneous improvements in engine power and torque. [36]

Scavenging also results in high PM emissions due to the lubrication technology employed on basic two-stroke engines. In four-stroke engines, the lubricating oil is essentially contained within a (nearly) sealed system that utilizes the engine crankcase as a collection sump. As a result, only a very small fraction of lubricating oil is consumed during the combustion process. Conversely, the crankcase is used in a two-stroke engine to compress the intake charge during the power stroke of the piston. Moreover, piston rings cannot serve as efficient lubricating system seals in a two-stroke engine since the intake, transfer, and exhaust ports all penetrate the cylinder wall. As a result, two-stroke engines generally rely on "total loss" lubricating systems, wherein oil is mixed with the fuel or introduced into the fuel-air mixture and consumed during the combustion process.

During the two-stroke scavenging process, a portion of the lubricating oil escapes without being combusted. This oil manifests itself in motorcycle exhaust as condensed organics and represents the bulk of PM emissions from two-stroke engines. Various studies have estimated that unburned lubricating oil constitutes 80-95 percent of total two-stroke PM. [12-15] Depending on the specific fuel-to-oil mixing ratio employed, unburned oil often manifests itself as white smoke emissions that are synonymous with two-stroke motorcycles in some Asian cities. Manufacturer recommended fuel-to-oil ratios are typically about 50:1, while in-use ratios as low as 12:1 are common in some cities. [16] Moreover, the use of inferior quality oil exacerbates two-stroke PM emissions. Oils specifically formulated to control smoke and PM emissions from two-stroke motorcycles have been developed and are available, but some vehicle owners, especially those operating three-wheeled motorcycles, often substitute poorer quality oils in an effort (albeit, a misguided one) to save on lubricating oil expenditures. Fuel-to-oil ratios need to approach 400:1 before lubrication-related PM becomes insignificant relative to combustion-related PM. Such ratios approach the oil consumption rate of a four-stroke engine. [13]

Two-stroke scavenging inefficiency does result in a NO_x emissions benefit. Just as some of the intake charge escapes through the exhaust port prior to combustion, some combustion products remain in the cylinder during subsequent combustion cycles (rather than being expelled through the exhaust port). This effectively results in what is commonly known as "internal" exhaust gas recirculation (EGR), which constrains peak cylinder combustion temperatures and limits NO_x formation. While internal EGR results in an inherently low NO_x emissions characteristic for two-stroke engines, it also necessitates the use of a rich intake charge[18] to ensure combustion stability. This further controls peak combustion temperatures and suppresses NO_x formation, but results in significant emissions of carbon monoxide (due to insufficient oxygen in the intake charge to promote complete combustion) -- as well as partially combusted HC and lubricating oil.

In contrast, four-stroke engines offer finer intake charge and exhaust control since the exhaust and intake portions of the combustion cycle occur sequentially rather than simultaneously. In four-stroke engines, exhaust scavenging is primarily controlled by exhaust system pressure pulsations and piston movement (i.e., the upward motion of the piston forces exhaust gases out of an overhead port), during which time the intake port is closed. As a result, scavenging losses are eliminated -- reducing both HC emissions and fuel consumption relative to two-stroke

[18] More fuel than can be fully combusted for a given quantity of intake air.

designs. The intake charge of small four-stroke engines is usually set rich to control peak combustion temperatures (and increase engine life), which results in high CO emissions, similar to those of two-stroke engines. Since four-stroke engines do not offer the internal EGR effects associated with two-stroke charge scavenging, NO_x emissions are higher than those of two-strokes -- but still are relatively low compared to larger motor vehicles due to the suppression of peak combustion temperatures brought about by the rich-bias of the combustion charge.[19]

The net effect is that relative to four-stroke engines, two-stroke engines exhibit increased fuel consumption, increased emissions of HC and PM, substantially reduced emissions of NO_x, and similar emissions of CO. Increased fuel consumption translates directly into increased emissions of carbon and, ultimately, increased GHG emissions. In general, four-stroke engines offer some advantage relative to two-stroke engines in regard to an ability to implement effective emissions control aftertreatment (i.e., post-combustion emissions reduction). This advantage stems primarily from the ability to more finely control both intake and exhaust characteristics with four-stroke engine designs, allowing for more stable exhaust flows tailored to promote effective aftertreatment. However, effective emission reduction options have been demonstrated for both two-stroke and four-stroke motorcycles.

Existing motorcycle emission standards (see Section 4) have effectively already shifted the small motorcycle market to a considerable extent. While four-stroke engine technology has been the dominant technology for large motorcycles for decades, four-stroke technology now dominates new motorcycle production for displacements as low as 100cc. Significant research has also been devoted to developing economical 50cc four-stroke designs, and some four-stroke designs of this size are currently being marketed. Additionally, significant development of improved two-stroke designs, relying on technologies such as air assisted fuel injection, that minimize scavenging losses have attained production level reliability and continue to undergo refinement to reduce cost and complexity. Catalytic aftertreatment is currently marketed on many models of both small and large displacement motorcycles. Nevertheless, significant emission reduction opportunities remain, as discussed in Section 5 below.

3.4 *General Emissions Characteristics*

As described in Section 3.1, there are substantially more four-wheel vehicles on a global basis than motorcycles. However, regulatory emission control strategies targeting four-wheel vehicles have been in place for over 40 years and are quite advanced, while strategies targeting motorcycles are relatively more recent and generally reflect initial control efforts. This is not meant to imply that aggressive regulatory efforts targeting motorcycle emissions in countries or regions such as India, Taiwan province of China, and Thailand have been without success, but rather that the evolution of motorcycle emissions control, especially for in-use motorcycles, has not yet reached the state of the four-wheel vehicle market where manufacturers are subject to both stringent new and in-use vehicle requirements. While reducing new vehicle emissions is important and reflects admirable advances in the promotion of emission reduction technology,

[19] It should be noted that in India, due to consumer demand for fuel efficiency even at the cost of a loss in torque and horsepower, four-stroke engine manufacturers generally employ very lean air/fuel mixtures. This has added effect of increasing NO_x formation relative to two-stroke motorcycles (due to increased combustion temperature).

the true key to motorcycle emissions control is the assurance that low emissions are maintained during consumer use.

This report is not intended to provide a robust emissions inventory from which the precise global significance of motorcycle emissions can be derived, but it is possible to generate a reasonable estimate of that significance from existing emission rate information. As might be expected, there are a wide range of reported emission rates for small motorcycles. For this report, representative emission rates were developed by taking a simple arithmetic average of a series of reported rates from in-use two-stroke and four-stroke motorcycles, generally in the 90-125cc size range. [17-24] The specific emission rate information used to develop representative motorcycle emission rates for this report is presented in some detail in the attached appendix. It should be recognized that the resulting emission rates are generally higher than would be implied by existing motorcycle emission standards (see Section 4), but this is to be expected given the fact that such standards are, in many cases, relatively new and generally impose few, if any, durability requirements. This is adequately demonstrated by the wide-range in reported in-use emission rates, which generally masks any model year-specific emissions trends.

To translate emission rates into total mass emissions, an estimate of the distance motorcycles travel per year is required. For this report, the requisite estimate was derived by averaging annual travel distance estimates from several sources. [6,25-28] Generally, these sources present travel estimates (or allow travel estimates to be derived) in either of two fashions. Some reports present model year and odometer data from which annual average travel distances can be derived, while others present total motorcycle travel and motorcycle registration populations from which similar per-motorcycle estimates can be calculated. So long as the number of registered motorcycles equals the number of in-use motorcycles, the two approaches should produce equivalent travel estimates. However, there is evidence to indicate that there is a substantial difference between the number of registered motorcycles and the number of in-use motorcycles in Asia. [24] To account for the fact that not all registered motorcycles are used, a correction factor (0.54) is applied to travel estimates derived through odometer readings to produce registration-equivalent estimates.[20]

Using this approach, per-motorcycle travel estimates of 3,000-5,000 kilometers (1,850-3,100 mi) per year were developed -- with a simple arithmetic average across sources of 4,261 kilometers (2,648 mi). Based on the motorcycle population data presented in Section 3.1, the 2005 global motorcycle population is estimated to be about 283.4 million. Combining the population and annual per-motorcycle travel estimates yields an overall annual motorcycle travel estimate of 1207.5 billion kilometers (750.3 billion miles). This estimate is then combined with the estimated emission rates for two-stroke and four-stroke motorcycles to derive total annual motorcycle emission estimates. The report's appendix provides additional details on the

[20] Shah and Harshadeep [24] report a total of about 2.05 million in-use motorcycles in Bangkok relative to a registered population of about 3.8 million motorcycles, implying an in-use to registered correction factor of about 0.54. Although this is only a single datapoint, its general accuracy is believed to be validated by the fact that when the factor is applied to odometer-based annual usage rates (which average about 8,000 km per year in Asia), the resulting "registration-corrected" annual usage rate (about 4,300 km per year) is quite consistent with independent registration-based annual usage rates (determined as total motorcycle travel distance divided by the number of registered motorcycles).

methodology used to estimate the global emission factors. As more stringent motorcycle emission standards are adopted and enforced, the emission rates for motorcycles should correspondingly decline. However, since the purpose of this report is to provide a general estimate of the potential significance of motorcycle emissions and since there is little demonstrative data to show that the in-service emission rates of recent model year motorcycles are significantly different than those of the motorcycles used to derive the emission rates used for this report (combined with the fact that the overall percentage of older vehicles in the global fleet continues to be quite high), it is believed that the emission estimates developed for this report are generally representative. Nevertheless, motorcycle emission rates will almost assuredly decline over the coming years as more stringent regulatory requirements continue to be adopted.

Of course, one also needs to know the share of overall travel accumulated by two-stroke and four-stroke motorcycles individually to derive an aggregate emissions estimate. While two-stroke motorcycles were the dominant small engine technology though the early 1990s, that is no longer the case in much of the global motorcycle market. Figure 8 presents the market share of four-stroke motorcycles in Taiwan province of China between 1996 and 2000. [8] As indicated, four-stroke sales increased from 40 percent to over 60 percent in the five year period. Figure 9 presents the corresponding data for India, where as indicated four-stroke sales increased from just over 10 percent to over 70 percent between 1996 and 2004. [36] Similarly, four-strokes accounted for over 70 percent of motorcycles produced in mainland China in 2000. [29] Clearly, much of the market is moving to four-stroke engines, although a substantial number of two-stroke engines continue to be sold and many more remain in-use. This report assumes that the overall travel share is split equally between two-stroke and four-stroke engines, a split that discounts the higher recent four-stroke sales share to account for the higher historic two-stroke sales shares that still influence the in-use motorcycle population. Although this is a gross assumption, readers can easily investigate the impact of alternative splits using the provided emission rate and travel data.

Table 5 presents the estimated global motorcycle emissions mass as well as the underlying emission rates for both two-stroke and four-stroke motorcycles. For comparative purposes, Table 5 also expresses motorcycle emissions as a fraction of total estimated global emissions for various pollutants based on overall global inventories developed by the Intergovernmental Panel on Climate Change (IPCC). [30] As indicated, motorcycle emissions of NO_x and CO_2 are generally modest relative to total global emissions, while emissions of VOC and, to a lesser extent, CO are significant.[21]

However, as indicated in Section 3.1, motorcycle populations are most significant in Asia. This is especially true in Asian metropolitan areas, where in some cases, motorcycles represent 70 percent or more of the motor vehicle fleet. [24] As a result, motorcycle emissions are much more significant on a regional and local basis than implied by the global emission fractions presents in Table 5. Table 6 presents a sampling of significance estimates reported in other research, while Figure 10 illustrates the difference between the global and local significance of

[21] No estimate of total global or total Asian PM emissions is available to determine the significance of estimated motorcycle PM emissions on a global or total Asian basis.

Figure 8. Four-Stroke Motorcycle Sales in Taiwan Province of China

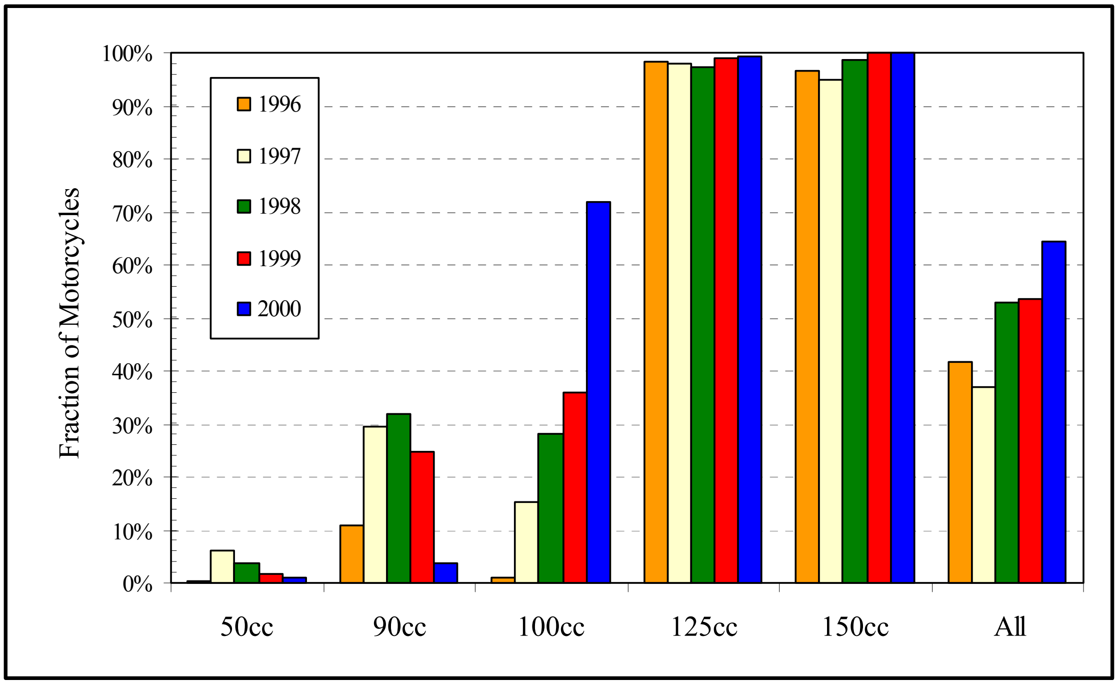


Figure 9. Four-Stroke Motorcycle Sales in India

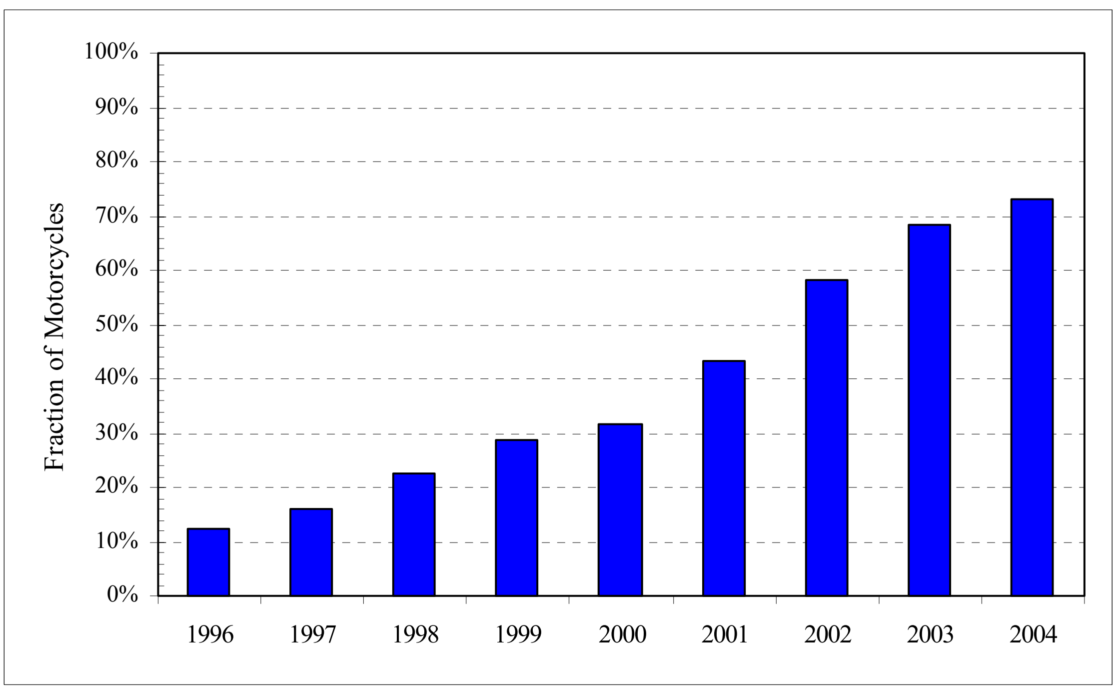


Table 5. Estimated Global Motorcycle Emissions (2005)

Emissions Metric	Exh VOC	Evap VOC	Total VOC	CO	NO_x	PM	CO_2	Max CO_2	N_2O	CH_4
2-Stroke Motorcycle Emission Rate (g/km)	15.5	1.25	16.75	18	0.05	0.5	40	118	0.002	0.15
4-Stroke Motorcycle Emission Rate (g/km)	1	1.25	2.25	12.5	0.15	0.1	55	77	0.002	0.20
2-Stroke Motorcycle Emission Rate (g/mi)	*24.9*	*2.0*	*27.0*	*29.0*	*0.08*	*0.80*	*64.4*	*189.9*	*0.003*	*0.24*
4-Stroke Motorcycle Emission Rate (g/mi)	*1.6*	*2.0*	*3.6*	*20.1*	*0.24*	*0.16*	*88.5*	*123.9*	*0.003*	*0.32*
Motorcycle Emissions (Tg)	**10.0**	**1.5**	**11.5**	**18.4**	**0.1**	**0.4**	**57.4**	**117.7**	**0.002**	**0.2**
Share of Global Emissions			7.6%	2.0%	0.2%		0.2%	0.4%		

See the included appendix for more detail on the derivation of the presented emission rates.

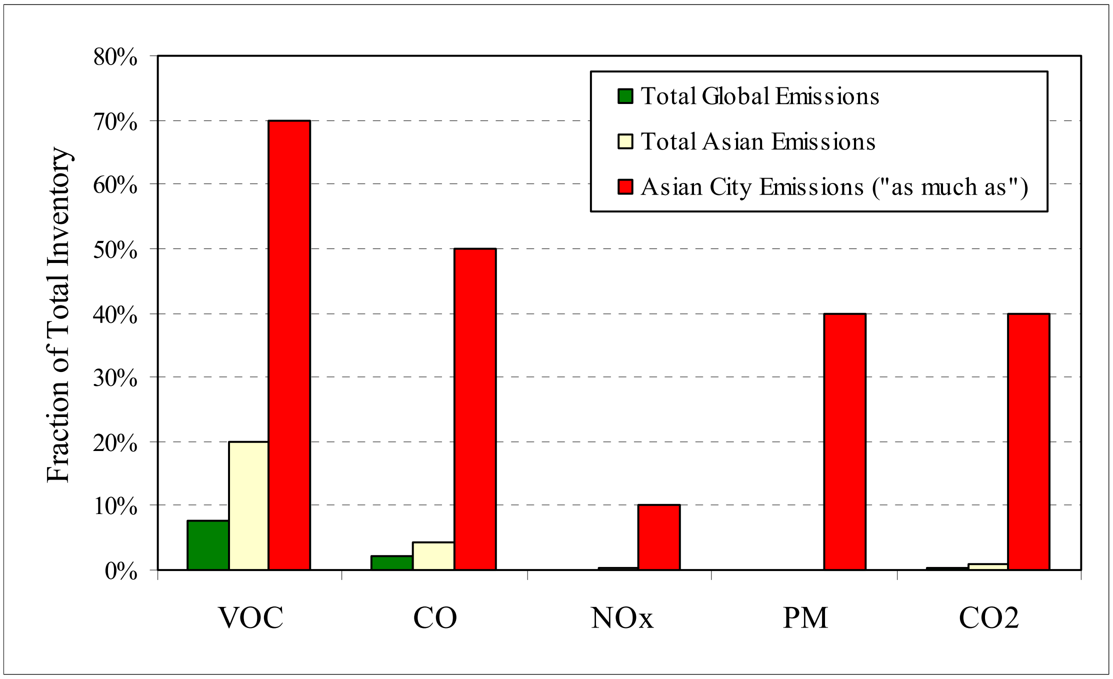
Table 6. Motorcycle Share of Total Transportation Emissions

City	VOC	CO	PM	NO_x	CO_2
Ho Chi Minh City, Vietnam [31]	90%	70%	no estimate	12%	40%
Delhi, India [32]	70%	50%	no estimate	no estimate	no estimate
Bangkok, Thailand [33]	70%	32%	4%	<1%	no estimate
Dhaka, Bangladesh [34]	60%	26%	42%	4%	no estimate

motorcycle emissions. [30,31-34] Clearly, motorcycle emissions can be important contributors to local air quality issues.

As indicated in Table 5, CO_2 emissions have been estimated using two approaches. The first approach (denoted simply as "CO_2") relies on current CO_2 emission rates derived from existing in-use motorcycle testing, as described above (and in more detail in the included appendix). The second approach (denoted as "Max CO_2") reflects the potential CO_2 emission rate that would result from a significant reduction in VOC and CO emissions, without an offsetting increase in motorcycle efficiency. In the absence of increased efficiency, VOC and CO are controlled by minimizing incomplete in-cylinder combustion or through post-combustion oxidation -- either of which effectively trades the carbon from VOC and CO for carbon as CO_2. In effect, current motorcycle CO_2 emission rates are "artificially" low as a result of high VOC and CO emissions. As those emissions are controlled, CO_2 emissions will increase. The "Max CO_2" emission

Figure 10. Significance of Estimated Motorcycle Emissions (2005)



See Table 6 for the specific Asian cities and associated emissions references.

estimates attempt to quantify the potential increase (which would be associated with very low VOC and CO emissions).

It is perhaps again worth noting that the emission rates used for this report are considerably higher than would be expected given the emission standards that are in effect in many of the countries or regions from which the reference motorcycles were recruited (see the included appendix). However, this is not indicative of the fact that the motorcycles are older pre-control models. Quite the contrary, the reference motorcycles generally reflect in-use models of 1993-2003 vintage and the underlying cause of the elevated emission rates (relative to those that would be implied by existing emission standards) is the differential between in-use and certification (i.e., new vehicle) emissions.

Figure 11 provides additional perspective on the magnitude of the generalized motorcycle emission rates, through its depiction of the number of *in-use* U.S. Tier 2 Bin 5 vehicles that produce the same mass of emissions per kilometer *on a lifetime average basis* as a single motorcycle.[22] As indicated, it takes about 200 Tier 2 Bin 5 passenger cars to produce the same

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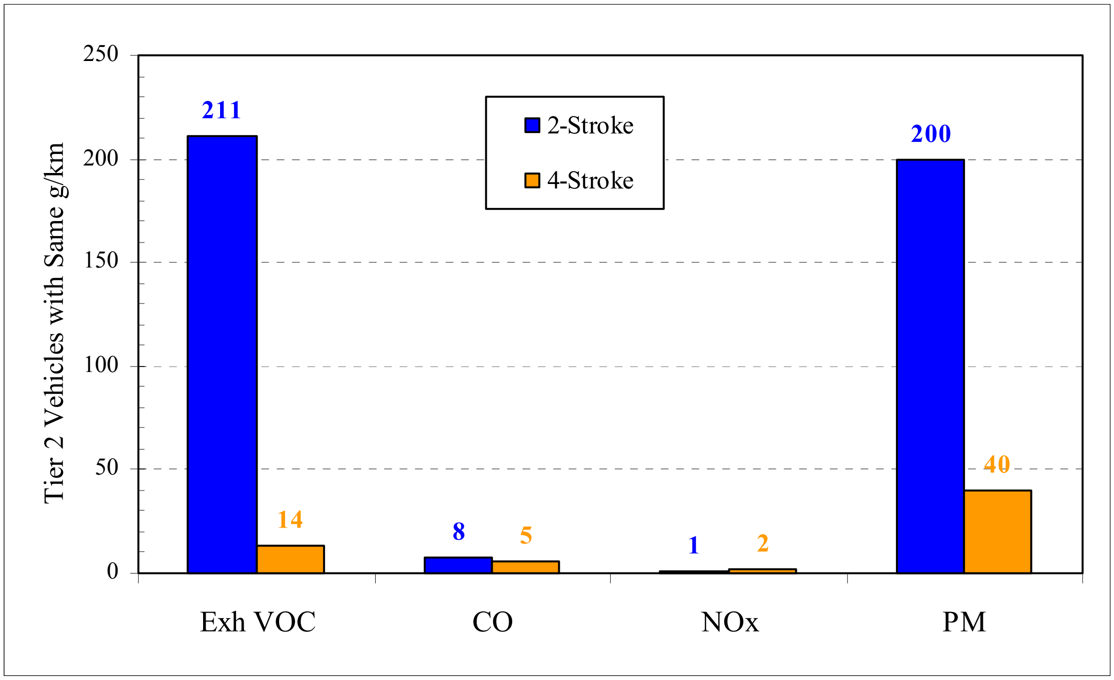
[22] Tier 2 Bin 5 is a set of U.S. emission certification standards applicable to passenger cars and light duty trucks. The Bin 5 standards represent one of eight alternative sets of standards (not including transitional standards) that took effect with the latest U.S. certification program (denoted as Tier 2) in model year 2004. The Bin 5 standards were selected as the basis for comparison because they roughly represent the fleet average certification requirements for post-2004 passenger cars and light trucks in the U.S., and thus provide a reasonable representation of advanced technology emissions performance in the light duty sector.

Figure 11. Number of Tier 2 Vehicles with a Total Emission Rate Equal to the Emission Rate of a Single Motorcycle

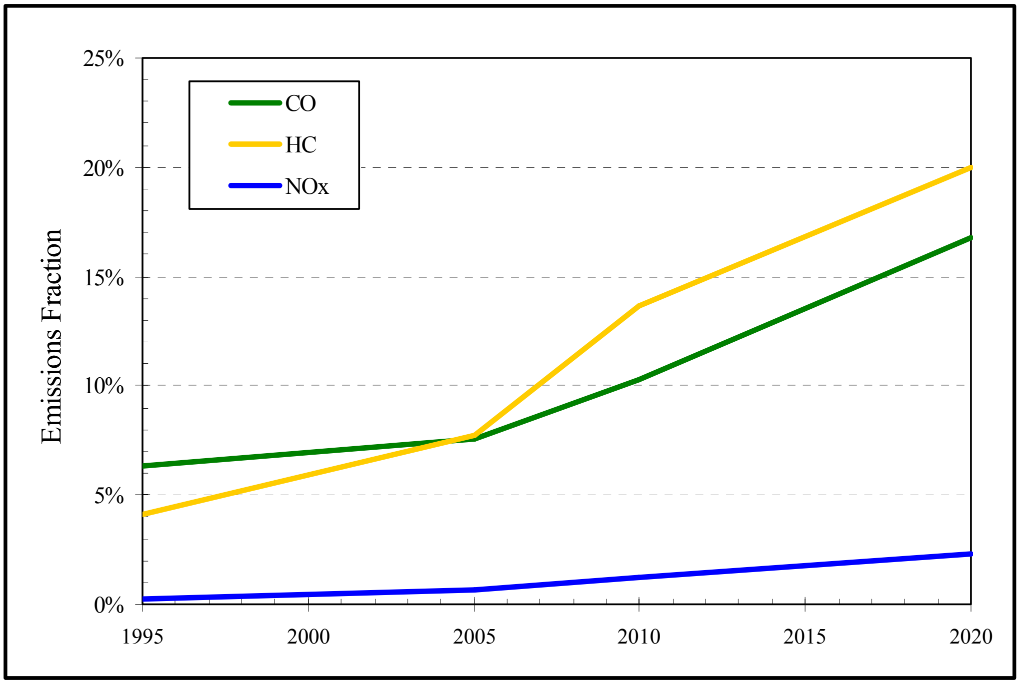


amount of exhaust VOC and PM emissions as one two-stroke motorcycle. Comparatively, four-stroke motorcycles are much cleaner, but still emit at substantially greater rates than advanced technology passenger cars.

It is also important to recognize that because stringent emission standards are in place and continue to evolve for four-wheeled vehicles, that the contribution of motorcycles to total emissions in all locations will increase from current levels until such time as emission control performance becomes comparable to that of four-wheeled vehicles. For example, a recent European Union (EU) analysis concluded that the contribution of motorcycles to total transport sector VOC and CO emissions in 9 EU countries[23] for which detailed transport sector emissions were available, will increase from about 5 percent in 1995 to 15-20 percent by 2020 given existing emission control regulations (as depicted in Figure 12). [37] This is despite the fact that the EU analysis assumes that motorcycles will be responsible for only 2-3 percent of travel in 2020. Due to the fact that NO_x emissions of current motorcycle engines are inherently low due to rich engine tuning and internal EGR (in the case of two-strokes), motorcycle NO_x emissions are less significant and growth is generally proportional to growth in travel. Conversely, motorcycle VOC and CO emissions grow in significance as emissions from other transportation sources decline more rapidly than those of motorcycles, due to more stringent emissions control regulations.

[23] Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Spain, and the United Kingdom.

Figure 12. Motorcycle Share of Transport Emissions in Nine EU Countries.



Finally, it should be reiterated that the presented emissions estimates are intended only to serve as indicators of the significance of motorcycle emissions. As is the case for determining emission rates from any motorized vehicle, there is considerable uncertainty in measured emissions due to factors that include not only the accuracy of the measurement procedure, but the representativeness of the test method, test vehicle, and test fuel. This is particularly an issue for motorcycles since they cover such a wide range of performance and usage characteristics. Uncertainty in motorcycle activity rates (i.e., kilometers of travel, number of evaporative events, two-stroke versus four-stroke activity shares, etc.) also translates directly into mass emissions uncertainty.

The magnitude of potential uncertainty can be inferred by comparing motorcycle emission rates over various test cycles. Figures 13 and 14 present a comparison of such data for two driving cycles relative to the ECE R40 test cycle, which is by far the predominant motorcycle certification cycle on a global basis. [23] The presented data cover a wide range of motorcycle size and design technologies. The ECE R40 cycle is a warm start test cycle that generally reflects urban travel, with a maximum speed of 50 km/hr (31 mi/hr). In contrast, the ECE R40+EUDC test cycle associated with the data presented in Figure 13 adds an "extra-urban" portion to the ECE R40 cycle, as well as initiating emissions measurement immediately after a cold engine start. The maximum speed over the extra-urban portion of the cycle is 120 km/hr (75 mi/hr). Both the basic R40 and R40+EUDC test cycles were originally designed for passenger car and light truck testing. The World Motorcycle Test Cycle (WMTC) associated with the data presented in Figure 14, represents an attempt to design a test cycle specifically for

Figure 13. ECE R40+EUDC (with Cold Start) Motorcycle Emissions

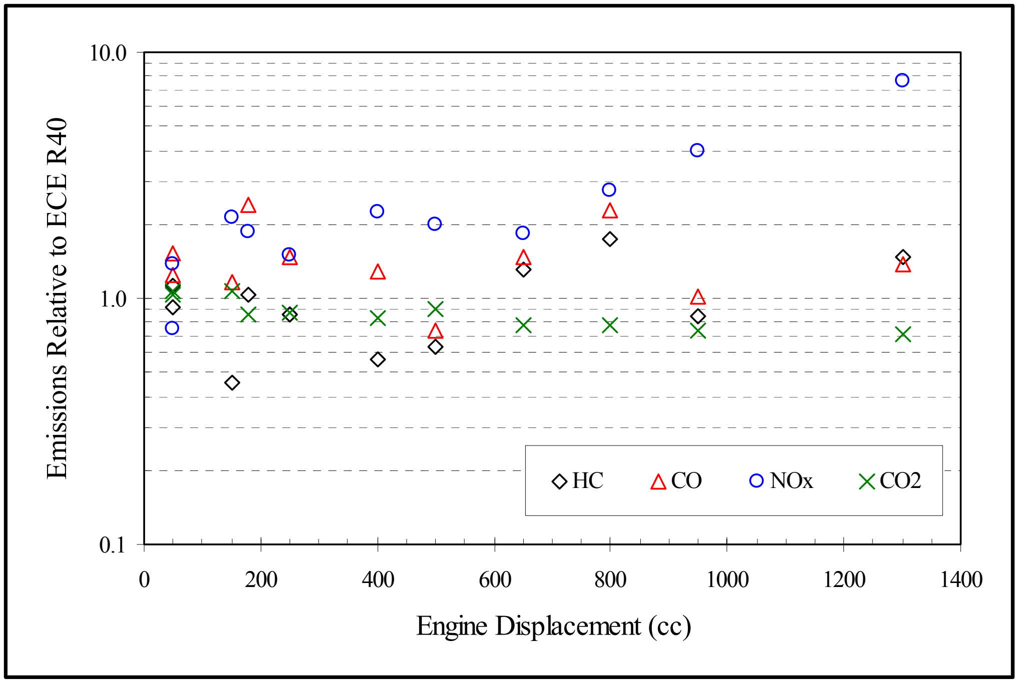
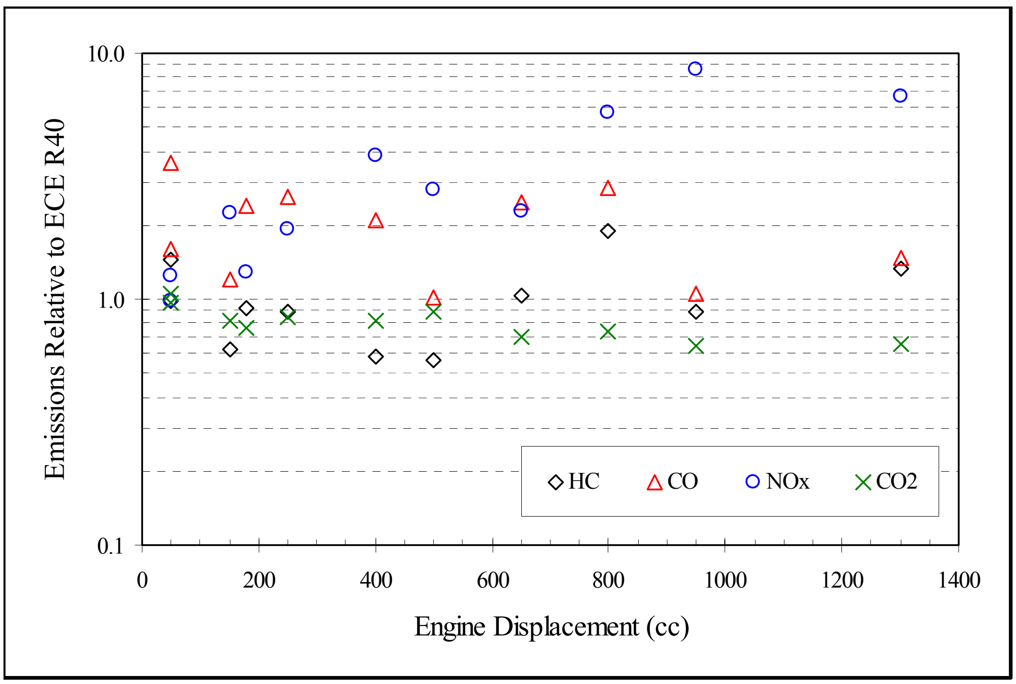


Figure 14. World Motorcycle Test Cycle (with Cold Start) Emissions



motorcycles that can be applied on a global basis. The WMTC generally consists of three portions, one each designed to represent urban, rural, and highway travel -- with maximum speeds of about 60, 95, and 125 km/hr (37, 59, and 78 mi/hr) respectively. It also includes emissions measurement from a cold engine start.

As indicated in Figures 13 and 14, emissions measured over the alternative test cycles vary by roughly a factor of two from those measured over the ECE R40 cycle for motorcycles up to about 200cc displacement. For larger engines, NO_x emissions can be up to an order of magnitude higher than those measured over the ECE R40 cycle. Thus, while emission rates can vary significantly from those used to estimate emissions mass in this report, the dominance of small (less than 200cc) motorcycles in the global fleet implies that the generalized emission rates used in this report are likely to be accurate to within perhaps a factor of two. Of course, localized emission rates could vary by more in accordance with the character of the local motorcycle fleet.

3.5 *Overview of Emissions Control Issues*

While motorcycle emission control options are discussed in detail in Section 5 below, it is important to recognize that there are available control options. Some of these options have already been implemented to various degrees in many areas, while others have not yet been required to meet existing emission standards. Generally, options can be categorized as either technology options that apply to motorcycle engines or the fuel consumed by those engines, or activity-based controls that attempt to influence motorcycle usage, usually through regulatory prohibitions or incentives. Examples of the former are improvements in basic engine design, the introduction of catalytic aftertreatment devices, the replacement of carburetors with fuel injection systems, the introduction of direct injection technology, the replacement of two-stroke engine designs with four-stroke designs, and the replacement of conventional fuel designs with designs based on alternative fuels such as compressed natural gas (CNG), liquefied petroleum gas (LPG), or electricity. As discussed in Section 5, the emission reduction potential of such options is significant.

Ideally, such technologies would be introduced into the market in response to technology-neutral emission standards implemented by regulatory authorities -- as opposed to the imposition of requirements mandating specific technologies. Technology-neutral standards allow market forces to dictate the lowest cost solutions, whereas technology mandates remove market flexibility and often lead to cost inefficient solutions. However, for technology-neutral standards to be both effective and truly neutral, the emissions certification process must be sufficiently robust to ensure that a certification technology is effective not only during certification, but also during the period the motorcycle is in-use. If the in-use emissions performance of certification technologies is not equivalent, both consumers and air quality will suffer.

Similarly, fuel and lubricating oil quality standards are quite important to the optimum emissions performance of motorcycles. At a minimum, the quality of both fuel and lubricating oil should be sufficiently controlled to allow for both efficient combustion and the efficient use of catalytic aftertreatment technology. Generally this means that minimum octane rating requirements should be established and enforced, along with strict controls on lead, metals, sulfur, and phosphorus -- all of which serve to diminish the effectiveness of aftertreatment technology. Ideally, the certification fuel and lubricating oil used to demonstrate compliance with motorcycle emission standards should be representative of the fuel and oil used during the in-use operation of the motorcycle. It may be necessary, however, to undertake strict lubricating oil enforcement since it is difficult for motorcycle manufacturers to control in-use lubrication practices.

Restrictions on motorcycle use, either through outright prohibitions or disincentives (e.g., usage fees), can be effective means to limit motorcycle emissions, but such policies inherently include socioeconomic implications that introduce concerns not associated with technology-forcing emission standards. Prohibitions have the potential to treat motorcycles differently than other motor vehicles, even in instances where both have equivalent emissions. Emissions-based prohibitions can be effective, but administrative requirements to distinguish the emissions profile of a particular motorcycle will be a challenge. Disincentives offer a more market-based approach, but balancing the magnitude of the incentive against emission reduction technology cost is a significant challenge. There is no question but that motorcycles represent an economical transportation solution for a large number of global citizens. Regulatory policies should be set to minimize the impact of emissions reduction options on this citizenry. Certainly prohibitions and disincentives represent a larger burden on the low income population and, therefore, it is essential that the complete implications of such policies be understood prior to implementation. Due to the wide variety of potential approaches to motorcycle usage restrictions, along with the significant influence local transportation alternatives can play in the ultimate effectiveness of such restrictions, usage control policies are discussed only briefly in this report. Individual policy options should be subjected to detailed local evaluation before implementation to ensure that negative socioeconomic impacts are minimized.

4. Existing Emission Standards

Certification[24] emission standards for motorcycles have been implemented in many countries and regions. Table 7 presents an overview of the motorcycle emission standards that are in effect in a cross-section of such countries or regions. [8,33,38-51] In the interest of brevity, not all global emission standards are included in Table 7 -- but those presented include most of the major motorcycle markets and those that are not presented are generally derived from, or are similar to, one of the presented standards. As indicated, standards often vary with motorcycle configuration and size, so that it is difficult to derive an accurate characterization of differences across countries or regions without considering the data presented in Table 7 in detail. Nevertheless, in an effort to facilitate at least a rudimentary comparison, Figure 15 presents an overview the CO and HC+NO_x certification standards for 100cc two-wheeled motorcycles. Figures 16 and 17 graphically depict the evolution of CO and HC emission standards for a 100cc two-stroke two-wheel motorcycle.[25]

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[24] Certification indicates the process of demonstrating compliance with emission standards, a process that must be completed before a motorcycle can legally be offered for sale. The term “certification” is generally used for U.S. compliance demonstrations, while the term “type approval” is more generally used for equivalent demonstration processes in Europe and Asia.

[25] To aid in clarity, standards for China have been excluded from Figures 16 and 17 as they are identical to the EU 1999 and 2003 standards, but delayed by four years and one year respectively.

Table 7. Motorcycle Emission Standards

Location	Year Began	Engines Covered	Cycle Strokes	Wheel Config	CO g/km	HC g/km	NO_x g/km	$HC+NO_x$ g/km	PM g/km	Driving Cycle	Cold Start	Durability (km)
Taiwan Province of China	1988	All	2 & 4	2 & 3	8.8			5.5		ECE R40	No	None
	1991				4.5			3.0				6,000
	1998				3.5			2.0				15,000
	2003		2		7.0			1.0			Yes	
			4					2.0				
EU	pre-99	<50cc	2 & 4	2	8	5				ECE R47	No	None
				3	15	10						
	1999			2	6			3				
				3	12			6				
	2002			2	1			1.2				
				3	3.5			1.2				
Switzerland	1988	<50cc	2 & 4	2 & 3	0.5	0.5	0.1			ECE R47	No	None
EU	pre-93	50+cc	2	2 & 3	16-40	10-15				ECE R40	No	None
	1993				12.8-32	8-12						
	1999			2	8	4	0.1					
				3	12	6	0.15					
	pre-93		4	2 & 3	25-50	7-10						
	1993				17.5-35	4.2-6						
	1999			2	13	3	0.3					
				3	19.5	4.5	0.45					
EU	2003	50-150cc	2 & 4	2	5.5	1.2	0.3			ECE R40	No	None
	2006				2.0	0.8	0.15				Yes	30,000
	2003		2 & 4 SI	3	7.0	1.5	0.4				No	None
			2 & 4 CI		2.0	1.0	0.65					
EU	2003	150+cc	2 & 4	2	5.5	1.0	0.3			ECE R40	No	None
	2006				2.0	0.3	0.15			R40+EUDC	Yes	30,000
	2003		2 & 4 SI	3	7.0	1.5	0.4			ECE R40	No	None
			2 & 4 CI		2.0	1.0	0.65					
Thailand	1997	All	2 & 4	2 & 3	13	5				ECE R40	No	None
	1999	<110cc			4.5			3				12,000
	2000	<125cc										
	2001	All										
	2003	<110cc			3.5			2				
	2004	All										
Japan	1998	<50cc	2	2 & 3	8	3	0.1			ISO 6460	No	6,000
	1999	50-125cc										8,000
		125-250cc										12,000
Japan	1998	<50cc	4	2 & 3	13	2	0.3			ISO 6460	No	6,000
	1999	50-125cc										8,000
		125-250cc										12,000
Mainland China	2003	50+cc	2	2	8	4	0.1			ECE R40	No	None
			4		13	3	0.3					
	2004		2 & 4		5.5	1.2	0.3					
Mainland China	2003	<50cc	2 & 4	2	6			3		ECE R47	No	None
	2005				1			1.2				

- continued -

Table 7. Motorcycle Emission Standards (continuation)

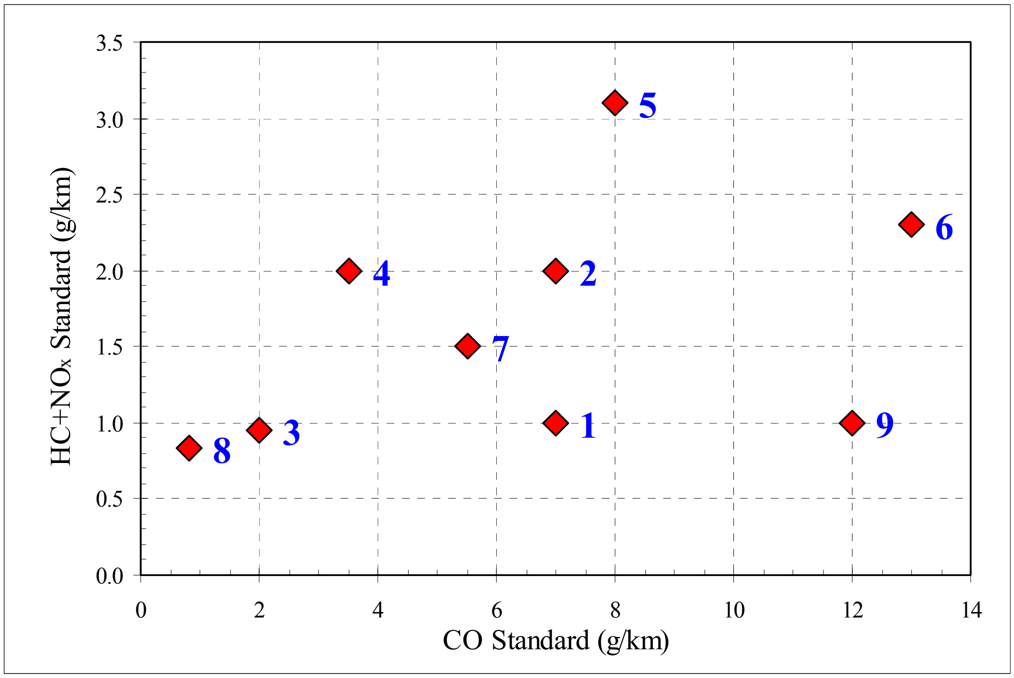
Location	Year Began	Engines Covered	Cycle Strokes	Wheel Config	CO g/km	HC g/km	NO_x g/km	$HC+NO_x$ g/km	PM g/km	Driving Cycle	Cold Start	Durability (km)
	1991			2 & 3	12-30	8-12					No	
	1996				4.5			3.6				None
India	1998	All	2 & 4							IDC		
	2000			2	2			2			Yes	
	2005				1.50 (a)			1.50 (a)				30,000
	2008/10				1.0 (a)			1.0 (a)				
	1996				6.75			5.4			No	
	1998		2 & 4		6.75			5.4				None
	2000				4			2				
India	2005	All	2 & 4 SI	3	2.25 (b)			2.00 (b)		IDC	Yes	
			2 & 4 CI		1.00 (c)			0.85 (c)	0.10 (c)			30,000
	2008/10		2 & 4 SI		1.25 (b)			1.25 (b)				
			2 & 4 CI		0.50 (c)			0.50 (c)	0.05 (c)			
	1978				17	5						
U.S. California	1980	50-169cc	2 & 4	2 & 3						Modified FTP-75	Yes	12,000
	1982				12	1						
	1978				17	5-6.7						
U.S. California	1980	170-279cc	2 & 4	2 & 3	17	5				FTP-75	Yes	18,000
	1982				12	1						
	1978	280-749cc			17	6.7-14						
		750+cc				14						
	1980				17	5						
	1982	280+cc				2.5						
U.S. California	1985		2 & 4	2 & 3		1.4				FTP-75	Yes	30,000
	1988	280-699cc			12	1						
		700+cc				1.4						
	2004	280+cc						1.4				
	2008							0.8				
		50-169cc								Mod FTP75		12,000
U.S. Federal	1980	170-279cc	2 & 4	2 & 3	12	5				FTP-75	Yes	18,000
		280+cc										30,000
		<50cc								Modified FTP-75		6,000
		50-169cc				1						12,000
U.S. Federal	2006	170-279cc	2 & 4	2 & 3	12						Yes	18,000
		280+cc						1.4		FTP-75		30,000
	2010	280+cc						0.8				

(a) Manufacturers can either demonstrate compliance with the indicated standards after accumulating 30,000 durability kilometers, or apply a standard deterioration factor of 1.2 to "zero kilometer" motorcycle emission measurements, in which case "zero kilometer" motorcycles would be required to have measured emissions at or below 1.25 g/km for CO and $HC+NO_x$ in 2005 and 0.83 g/km for CO and $HC+NO_x$ in 2008/10.

(b) Manufacturers can either demonstrate compliance with the indicated standards after accumulating 30,000 durability kilometers, or apply a standard deterioration factor of 1.2 to "zero kilometer" motorcycle emission measurements, in which case "zero kilometer" motorcycles would be required to have measured emissions at or below 1.88 g/km for CO and 1.67 g/km for $HC+NO_x$ in 2005 and 1.04 g/km for CO and $HC+NO_x$ in 2008/10.

(c) Manufacturers can either demonstrate compliance with the indicated standards after accumulating 30,000 durability kilometers, or apply a standard deterioration factor of 1.1 for CO, 1.0 for $HC+NO_x$, and 1.2 for PM to "zero kilometer" motorcycle emission measurements, in which case "zero kilometer" motorcycles would be required to have measured emissions at or below 0.91 g/km for CO, 0.85 g/km for $HC+NO_x$, and 0.08 g/km for PM in 2005 and 0.45 g/km for CO, 0.50 g/km for $HC+NO_x$, and 0.04 g/km for PM in 2008/10.

Figure 15. Emission Standards for 100cc Two-Wheel Motorcycles



Data Point Key for Figure 15

Data Point	Country (or Region)	Effective Year	Engine Type	Driving Cycle	Other Issue(s)
1	Taiwan, China	2003	2-Stroke	ECE/R40	
2	Taiwan, China	2003	4-Stroke	ECE R40	
3	EU	2006	2 & 4-Stroke	ECE R40	
4	Thailand	2004	2 & 4-Stroke	ECE R40	
5	Japan	1999	2-Stroke	ISO 6460	
6	Japan	1999	4-Stroke	ISO 6460	
7	Mainland China	2004	2 & 4-Stroke	ECE R40	
8	India	2010	2 & 4-Stroke	IDC	
9	U.S. California	1982	2 & 4-Stroke	Mod FTP75	No NO_x Standard
9	U.S. Federal	2006	2 & 4-Stroke	Mod FTP75	No NO_x Standard

As indicated in Figures 15 through 17, there is a rather substantial difference in the numerical value of emission standards across countries or regions. However, like emission standards for passenger cars and trucks, it can be difficult to compare the relative stringency of differing numerical standards due to differences in the stringency of associated test procedures and enforcement techniques. For example, as indicated in Table 7 (and the key to Figure 15), several different driving cycles are employed. There can also be substantial differences in engine conditions during certification testing and emissions durability requirements. Most of the emission standards through the mid- to late-1990s were based on warm start emissions testing with no, or only limited, durability requirements -- and these requirements have become progressively more stringent on different schedules in different countries and regions. Regardless, it is apparent from Figures 16 and 17 that motorcycle emission standards have become, on the whole, substantially more stringent since the first standards were adopted by California in the late 1970s.

Figure 16. CO Standards for 100cc Two-Stroke Motorcycles (2-wheelers)

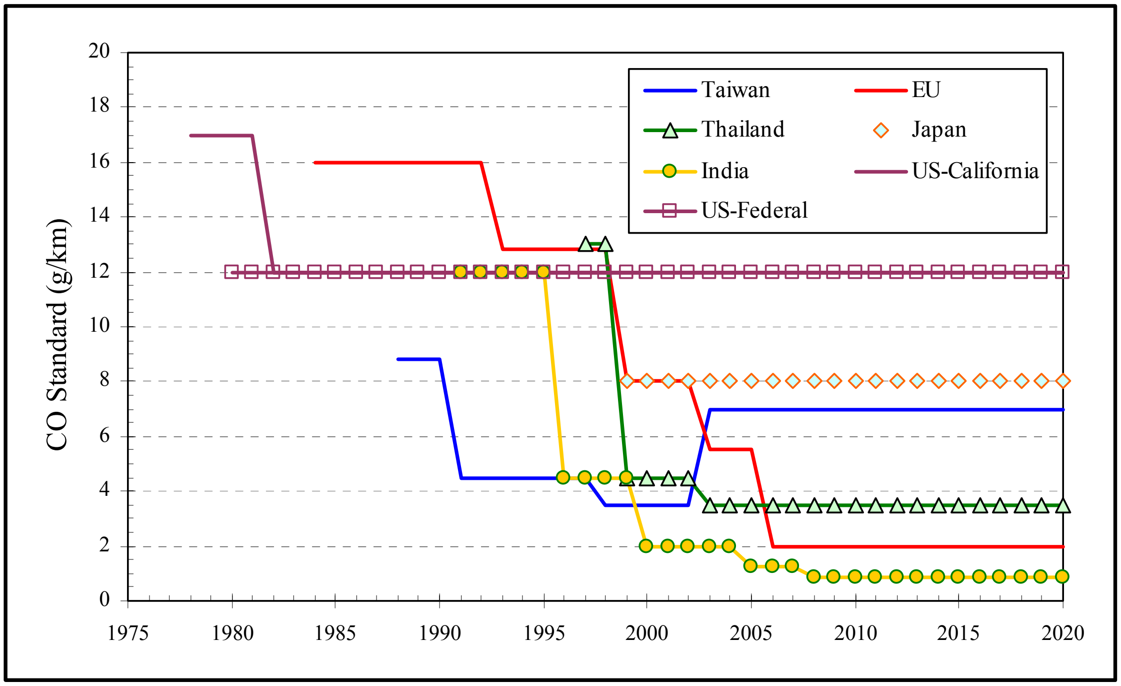
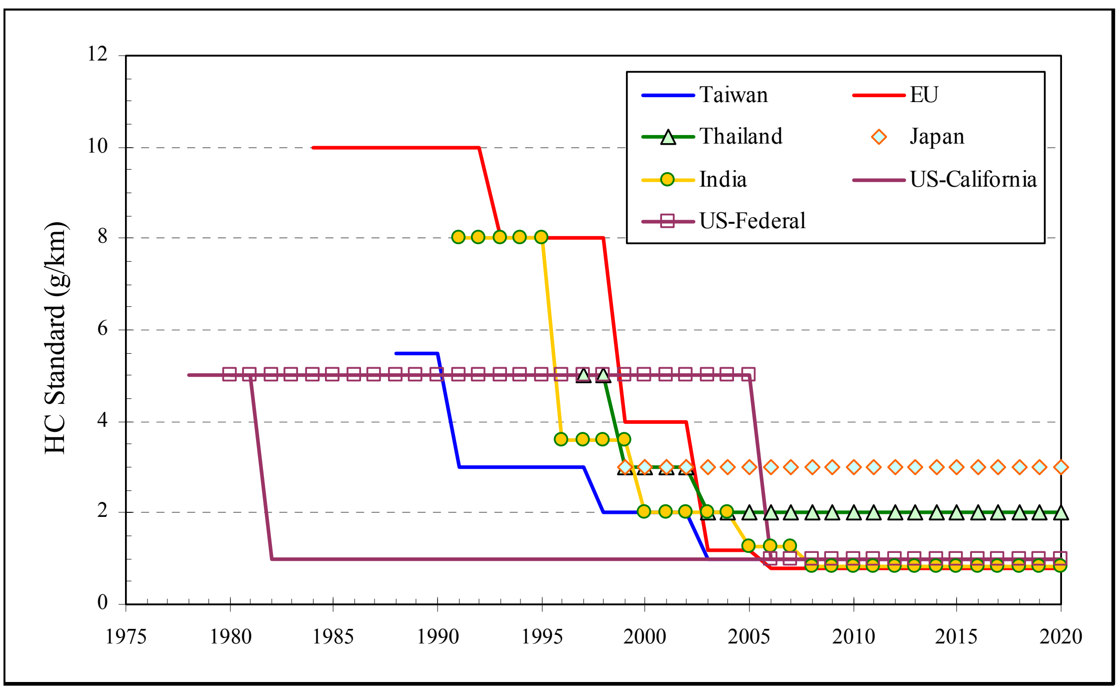


Figure 17. HC Standards for 100cc Two-Stroke Motorcycles (2-wheelers)



Note: In this figure, emission standards that are expressed in terms of HC plus NO_x are treated as though they were an HC-only standard. Because NO_x emission rates from two-stroke engines are inherently low, the error associated with this simplification is minor.

Without question, the evolution in emission standards has resulted in emission reductions from motorcycles. In conjunction with 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. Additionally, virtually all two-stroke motorcycles currently sold in countries or regions such as India, Taiwan province of China, and Thailand come equipped with catalytic converters, while emerging standards may spur an additional movement toward fuel injected engines. For example, Honda, the worlds largest motorcycle manufacturer, has eliminated two-stroke technology from all new models introduced in Japan, as well as expanded the use of its programmed fuel injection (PGM-FI) technology to engines as small as 50cc. [52]

However, it is also important to recognize that substantial issues continue to exist with regard to certification emissions performance and that attained during real-world driving. In addition, there continue to be important emissions aspects that are not addressed by current emission standards.

Current motorcycle emission standards continue to focus primarily on CO and HC. NO_x standards are also common (either alone or in combination with HC), but motorcycles are currently low NO_x emitters. However, with the exception of a standard for compression ignition (i.e., diesel) motorcycles in India and Europe, there are no motorcycle PM standards -- despite the fact that two-stroke PM emissions can be very significant, as discussed in Section 3.4 above. While it is likely that existing HC emission standards have served as a surrogate for PM to some extent, the efficacy of this approach is uncertain as in-use emissions measurements have demonstrated (see Section 3.4).[26]

Perhaps most important to the relationship between certification and in-use emissions, however, is the lack of full life durability requirements and in-use compliance requirements. Motorcycle emissions durability testing is generally limited to between 6,000 and 15,000 kilometers (3,750 to 9,300 miles) during certification, although 30,000 km (18,650 mi) requirements are being applied in some instances (see Table 7). These durability requirements pale in comparison to real-world travel data that show annual average accumulations for in-use two-wheel motorcycles of 8,000-10,000 km (4,950-6,200 mi).[27] [25,26] In-use three-wheelers accumulate on the order of 40,000 km (24,850 mi) per year. [25,53] Clearly, most motorcycles will exceed certification

[26] It is worth noting that there are several issues that are currently under debate with regard to the reliable measurement of motorcycle PM. Among these are whether the PM test procedure used for other motor vehicles is adequate for motorcycle testing from both a detection and reproducibility standpoint. Other issues unrelated to actual measurement include a desire for better understanding of two-stroke PM health effects and whether the large organic fraction of two-stroke PM can be adequately controlled through evolving HC standards.

[27] The annual average accumulation of 8,000-10,000 km per year should not be confused with the average accumulation of 4,260 km per year used elsewhere in this report. The latter figure is based on the number of *registered* motorcycles, a figure that, as described in Section 3.4, has been shown to be substantially different than the number of *in-use* motorcycles. Since the global emissions estimates presented in this report are based on the number of registered motorcycles, the 4,260 km per year figure is the appropriate average travel distance for that calculation. To be conservative, the 4,260 km per year figure is also used for cost effectiveness calculations. However, the actual mileage of in-use motorcycles in Asia has been shown to be on the order of 8,000-10,000 km per year.

durability requirements in one-to-three years. This compares to passenger car and light truck durability requirements of 10 years or more in the US. [35] Imposition of a realistic useful life durability requirement is critical to ensuring that adopted emissions control systems are effective with a reasonable deterioration rate when operated and maintained properly. The importance of this is perhaps best illustrated by the generalized emission rates developed for this report (see Section 3.4) which indicate that the in-use emission rates of motorcycles are considerably higher than associated certification emission rates. Clearly, low certification emissions do not necessarily imply low in-use emissions.

Equally important to the effectiveness of current motorcycle emission standards is the general lack of in-use emission testing requirements. Such 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 (i.e., mass) emissions test on a selected sample of well-maintained vehicles to ensure that certification emission 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. Along with the certification durability requirements, in-use emissions testing ensures that emissions control systems are effective when motorcycles are used as recommended.

Of course, since not all motorcycles are used and maintained as recommended by manufacturers, emissions inspection and maintenance (I/M) requirements are also an important part of in-use emissions control. Both India and Taiwan province of China currently administer 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, which would allow for a more rigorous investigation of in-use emissions. Other countries or regions administer random smoke tests. I/M requirements are generally distinguished from certification emission standards, however, since their design goal is to promote consumer maintenance rather than manufacturer design. Accordingly, I/M is discussed further in Section 5 below.

It is perhaps important to recognize that many countries do administer in-use manufacturer-based idle test standards for CO and HC. Such standards are, however, substantially less informative than mass-based emissions tests and are generally only capable of detecting emissions failures that are well above the mass-based standards that apply during certification. For example, standards of 4.5 percent CO and about 8,000 ppm HC are common for two-stroke engines. While it is not possible to compare these standards to mass-based standards, there is no question that such idle test standards are substantially less stringent than current mass-based emission standards and intended solely for the identification of only gross emissions problems.

It is encouraging to note the 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. In an era of non-catalyst equipped motorcycles, cold start emissions impacts were likely to be minor -- so that hot start emissions testing was adequate for determining overall motorcycle emissions performance. However, catalyst applications are widespread in the motorcycle industry and increasing annually, so that cold start emissions characteristics will increasingly dominate overall motorcycle emissions profiles and, thus, cold start emissions testing should be considered an integral component of any effective certification testing program.[28]

In addition to the lack of an explicit standard for PM, it is also important to note that with the exception of the Taiwan province of China, Thailand, and the U.S., there are no motorcycle standards for evaporative HC. In the U.S., the California Air Resources Board enforces 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.[29] [54] Similar requirement are in effect in Taiwan province of China and Thailand. Motorcycle certification data for California indicates that model-specific evaporative emissions range from about 0.1-1.7 grams. [55] The U.S. Environmental Protection Agency recently adopted fuel system permeation limits that take affect beginning in model year 2008. The adopted limits restrict fuel tank permeation to 1.5 g/m^2/day (gram per square meter of tank surface area per day) and fueling system hose permeation to 15 g/m^2/day (gram per square meter of hose surface area per day). The limits are expected to reduce fuel tank and hose permeation by 85-95 percent. [41] Given that evaporative emissions are important contributors to air quality issues and that such importance increases as exhaust emissions decline, certification emission standards should include appropriate evaporative emission limits.

Although there are a significant number of local motorcycle manufacturers throughout Asia, almost all have entered into cooperative agreements with one of the four major Japanese manufacturers -- Honda, Kawasaki, Suzuki, and Yamaha. Thus, these four manufacturers, combined with Harley-Davidson, BMW, and Ducati in the large motorcycle market, are responsible for all but a small percentage of global motorcycle production. Given this global nature of the motorcycle market, it would be ideal if motorcycle emission standards and certification requirements were globally uniform. This would allow for substantial cost savings to both industry and government as certification resources could be optimized on the manufacturing side, while compliance and enforcement efforts could potentially be pooled and, as a result, greatly expanded. For example, enforcement activities in one country or region operating under a global emission standard might be used to support emissions determinations on a regional or even global basis, allowing for efficient and greatly expanded in-use compliance activities.

[28] Catalytic aftertreatment systems do not function until exhaust temperatures are sufficiently high to promote emissions conversion. After a cold start, it takes some time for catalysts to reach their "light-off temperature" and emissions during this period are substantially higher than emissions after light-off. Catalytic efficiencies in the passenger car and light truck markets are approaching 100 percent so that emissions during the period before light-off dominate the overall emissions profile of the vehicle. It is likely that catalyst applications in the motorcycle market will result in a similar situation should the electronic engine controls that facilitate finely resolved control of the intake air/fuel mixture be introduced.

[29] SHED is an acronym for Sealed Housing for Evaporative Determination and is essentially a sealed enclosure in which the motorcycle is placed so that evaporative emissions collected over a specified period can be measured. The diurnal portion of the test consists of a one hour heat build designed to simulate a daily diurnal temperature variation. The hot soak consists of a ten minute soak performed immediately after a hot stabilized exhaust emissions test is completed, and is designed to simulate emissions that would occur during the ten minute period after a motorcycle is shut down. These tests have been revised for passenger cars and light trucks to include more representative (real-time, multi-day) diurnal characteristics, but have been maintained at the one-hour heat build requirements for motorcycles.

Of course, for such efficiencies to be gained, motorcycle emissions requirements must be identical across countries and regions. Not only must numeric standards be the same, but also test procedures, durability requirements, etc. Significant effort in developing a global motorcycle test cycle has been undertaken over the last decade under the auspices of the United Nations Economic Commission for Europe, and the so-called World Motorcycle Test Cycle (WMTC) has been finalized, although amendments in response to concerns raised by India are under consideration. [56] In an attempt to define a test cycle that could be used for the entire range of available motorcycles, the WMTC includes three test components characteristic of urban, rural, and highway driving, with different weighting factors for each component based on motorcycle size and design.

India, has expressed serious reservations about the WMTC based on difficulties replicating the cycle with local small displacement motorcycles and substantial differences between WMTC emissions values and those measured over the Indian Driving Cycle (IDC) currently employed in that country. [57] India has specifically cited issues related to the inability of motorcycles designed for high fuel economy (over roadways that do not allow for high speed and acceleration rates) to adhere to the speed and acceleration characteristics of the WMTC. Moreover, India finds that fuel consumption and emission rates measured over the WMTC do not reasonably correlate with corresponding values from either the IDC or in-use testing. As one of the largest motorcycle markets in the world, India has requested that the WMTC be amended to include an additional test cycle, more representative of conditions in India and other developing areas.

Regardless of the ultimate characterization of the WMTC, it is important to recognize that no driving cycle can represent all vehicles, and it is not uncommon for in-use emission rates to vary from certification emission rates, due both to driving cycle issues and differences between certification and real-world performance (e.g., differences in maintenance, driving behavior, fuel quality, etc.). In fact, it is common practice in the U.S. to conduct independent certification and in-use emission factor testing programs for precisely these reasons. Thus, while emission factors for in-use vehicles could ideally be derived from certification test data, that ideal is rarely, if ever, approached in practice. It is almost certain that even under a global test regimen, such as the WMTC, local emission factors will still need to be developed on the basis of local test data collected over locally-applicable conditions and, most importantly, using actual in-use motorcycles tested in an as-received condition (i.e., tested without any repairs or other adjustments).

5. Control Technologies

As alluded to throughout the preceding sections of this report, various emission control technologies have been introduced into the motorcycle market over the last decade or so in response to adopted emission standards. As might be expected, the effectiveness of these technologies has advanced over time -- so that conclusions derived on the basis of initial market introductions are unlikely to reflect present realities. For example, early catalytic converter applications for two-stroke motorcycles were prone to very quick performance deterioration and in-use emissions control was seldom on par with implied certification emissions reductions.

However, significant progress has been made over the last few years in regard to both emissions control effectiveness and cost impacts.

This section provides an overview of some of the motorcycle emission control technologies that might be employed to meet current and future emission standards. As discussed in the introduction to this report, a detailed analysis of any one of the discussed technologies might well be the focus of an extensive separate report -- so the reader is cautioned to view the included material as introductory in nature and necessarily subject to a number of qualifications that can only be fully explored in the context of specific applications.

As with any emissions control program, potential control measures span both the design and in-use arenas. Design controls imply emissions control technologies implemented by the motorcycle manufacturer as an integral component of vehicle development and manufacture. These are controls that affect the consumer in no way other than that they are present on a motorcycle that is purchased. Ideally, they are transparent to the consumer -- although in some cases they can require the purchase of a specific fuel (e.g., unleaded fuel for catalyst-equipped vehicles). Conversely, in-use controls specifically target the consumer and can include strategies such as purchase prohibitions, retrofit requirements, maintenance requirements, usage restrictions, etc. The potential design of in-use controls in boundless and, as a result, such controls typically require application-specific design and evaluation. For example, usage restrictions may be quite acceptable and effective in a city with adequate transport alternatives, while entirely unacceptable in a city where motorcycles are the primary or sole means of motorized transport. As a result, this report discusses in-use controls only on a general basis, leaving more in-depth analysis to subsequent focused reports.

It is also important to recognize that all emission impact and cost estimates presented in this section are necessarily generalized given the global scope of this report. Differences, perhaps significant, can be expected on a local basis due to differences between the global "average" characteristics assumed in this report and corresponding local characteristics, including fuel prices, motorcycle usage rates, current baseline emission rates, etc. In *all* cases, locally specific estimates should be developed as a necessary precondition to the establishment of any regulatory requirements.

5.1 *Catalytic Converters for Two-Stroke Engines*

Advances in aftertreatment catalyst technology are responsible in large part for the remarkable and continuing emission reductions observed in the automobile and light truck markets over the last three decades. Catalysts in these markets routinely provide conversion efficiencies approaching 100 percent for HC, CO, and NO_x, over a durability period that extends for 160,000 km (100,000 mi) or more. However, while the challenges overcome by catalyst manufacturers in developing systems for the auto and truck markets should not be underestimated, there are a range of development issues associated with catalyst application in the motorcycle sector that prohibit the simple transfer of auto and truck catalyst technology. Many of the lessons learned in the auto and truck sectors can be applied to the development of effective catalyst technology for the motorcycle sector, but those lessons must be incorporated into a technology response that is specific to the unique aspects of motorcycle emissions control.

Cost, space, and backpressure constraints substantially different from those of the four-wheel market are among the issues that must be considered in the development of a motorcycle catalyst. For example, a $100 catalyst investment represents only one-half of one percent of the cost of a $20,000 vehicle. However, many motorcycles sold in the Asian market have retail costs of $1,000 or less, so that the same $100 catalyst would represent a 10 percent surcharge (thus, catalyst costs in the small motorcycle market must be much lower). Similarly, small motorcycles present significant space limitations and, as a result, allowable catalyst size (and configuration) is constrained. A typical catalyst for a small motorcycle might have a space velocity that is two-to-three times greater than that of an automobile.[30] To compound this problem, small (single cylinder) motorcycle engines are significantly more sensitive to exhaust backpressure than are larger automobile engines. This sensitivity affects not only emissions, but power and driveability as well. As a result, catalyst flow restriction must be minimized, so that a small motorcycle catalyst is typically constrained to a cell density of 100 cells per square inch (CPSI) -- as compared to the 400-1200 CPSI catalyst designs commonly used in current four-wheel applications. Combined with the greater space velocity, this means that the time during which exhaust gas from a small motorcycle will be in contact with active catalyst surface area is only about one-tenth that of a typical automobile or light truck. [58] Such constraints impose clear (and significant) design issues for the small motorcycle catalyst industry.

Another factor limiting the maximum effectiveness of motorcycle catalysts is the fact that most small motorcycles continue to utilize low-cost carbureted fueling systems. It is significantly more difficult to control intake air/fuel ratios with such systems than is possible with the electronic computer control systems universally installed in the automobile and light truck markets. As a result, the near-100 percent conversion efficiencies exhibited by catalysts in these markets is unlikely to be met in the motorcycle market without the enabling replacement of carbureted fueling technologies with electronic fueling technologies.

Two-stroke engines in particular pose significant additional design issues. The high efficiency simultaneous conversion of HC, CO, and NO_x (oxidation of HC and CO to water and CO_2 and reduction of NO_x to nitrogen) achieved in four-wheel applications requires very precise, near stoichiometric,[31] intake charge control -- not possible for typical two-stroke motorcycle engines, both due to less sophisticated (more variable) designs and the need for a rich intake charge for combustion stability. Nevertheless, catalytic aftertreatment is possible on two-stroke motorcycle engines as evidenced by an extensive research database and the introduction of two-stroke motorcycle catalysts in Asia in the early 1990s. [8,11,12,20,21,29,44-46,58-62]

As described in Section 3.3, NO_x emissions from two-stroke engines are inherently low due to a rich intake charge in combination with significant internal EGR. As a result, a two-stroke motorcycle catalyst need not be designed for effective NO_x control, instead focusing primarily on

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[30] Residence time is inversely proportional to space velocity. So, as space velocity increases, the time available to promote exhaust aftertreatment declines. For example, gas flowing through a catalyst system with a space velocity three times that of another has a 67 percent shorter residence time.

[31] Stoichiometric refers to the condition in which the mixture of air and fuel is precisely metered so that the amount of air contained in the mixture is exactly the amount necessary to completely combust the fuel -- no more, no less.

the effective oxidation of HC and CO. Normally, such an "oxidation" catalyst would have only limited effectiveness when operated in conjunction with a rich intake charge -- unless a secondary source of oxygen were provided -- but typical two-stroke scavenging losses provide a significant source of oxygen (in the form of unreacted air that has passed through the cylinder without supporting combustion). While this oxygen supply is not sufficient to promote 100 percent conversion of HC and CO (since the net intake charge is rich), it is adequate to allow significant post-combustion catalytic activity. Additionally, in countries such as India that have deployed high fuel efficiency two-stroke designs, oxygen availability is improved through the use of a relatively lean intake charge. Alternatively, a simple passive secondary air injection system can be introduced upstream of the catalyst to both provide excess air to the catalyst as well as increase exhaust gas temperatures to promote quicker catalyst light-off. However, since two-stroke engines typically have high engine-out HC and CO emissions, secondary air injection can result in temperature exotherms within the catalyst (due to the large quantities of HC and CO undergoing conversion) that are potentially damaging to catalyst durability.

Additionally, because CO is an intermediate product of two of the three HC conversion reactions typically observed in an oxidation catalyst,[32] CO conversion effectiveness can be quite sensitive to catalyst formulation and exhaust conditions. [58] In effect, while CO is undergoing oxidation, it is also being formed by the oxidation of HC -- so that the apparent conversion effectiveness for CO is equal to the net difference between the destruction and formation rates. If catalyst formulations are not optimized, the net conversion efficiency for CO can be negative across the catalyst.

Given these challenges, it is not surprising to find that many early catalyst systems for two-stroke motorcycles were less effective than desired. Those that did function effectively when new, often demonstrated rapid deterioration during use, even when there was no evidence of catalyst poisoning. For example, Figure 18 illustrates the effective average conversion efficiencies measured over 20,000 km (12,450 mi) for three properly maintained 150cc two-stroke motorcycles in Thailand. [20] As indicated, HC conversion efficiencies of about 60 percent were observed during the first 5,000 km (3,100 mi), but those efficiencies declined to near-zero by 15,000 km (9,300 mi). In contrast, CO emissions actually increased through the catalyst throughout the entire test period, with post-catalyst CO being about 20 percent higher than engine-out CO. Clearly, such systems were of little value as an in-use emissions reduction strategy.

Later systems, however, show clear advantages. Figure 19 is a reproduction of Figure 18, upon which is imposed emissions measurements collected over 30,000 km (18,650 mi) for an optimized two-stroke catalyst installed on three scooters representative of those found in Europe, India and mainland China. [58] As indicated, all three show little to no deterioration for HC -- with conversion efficiencies ranging from about 50-60 percent -- and not only positive conversion efficiencies for CO, but efficiencies which remain positive over the full 30,000 km (18,650 mi) measurement period. Emissions testing has also demonstrated two-stroke catalyst PM conversion efficiencies that are about 10 percentage points lower than HC conversion

[32] HC is fully oxidized to CO_2 and water, partially oxidized to CO and hydrogen, or converted to CO and hydrogen via a reaction with water (steam reforming).

Figure 18. Conversion Efficiency of Early Two-Stroke Catalysts [20]

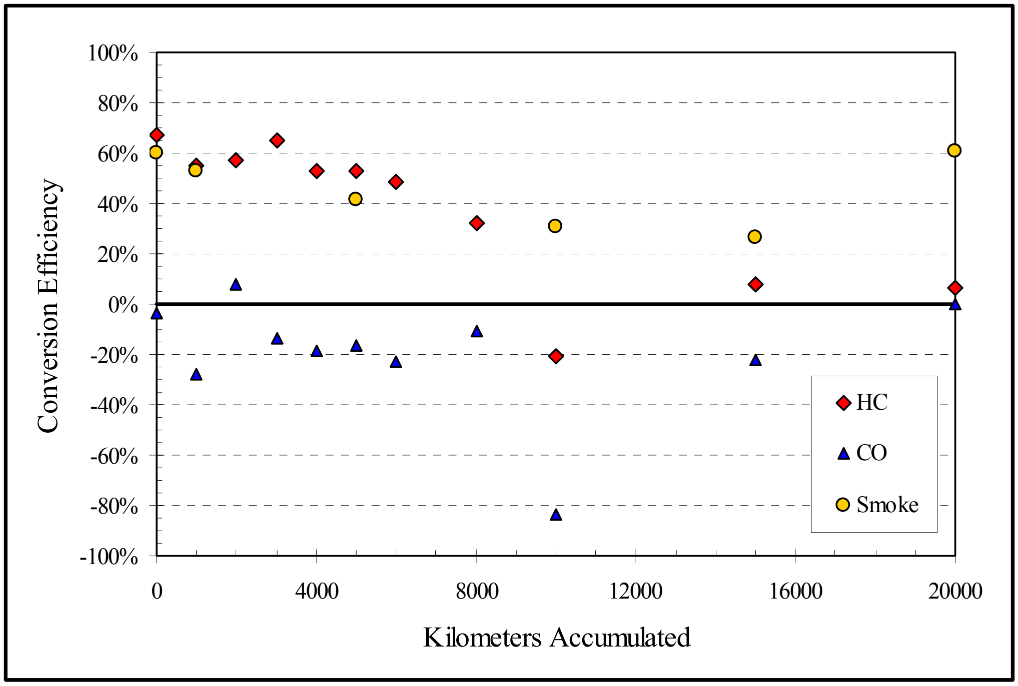
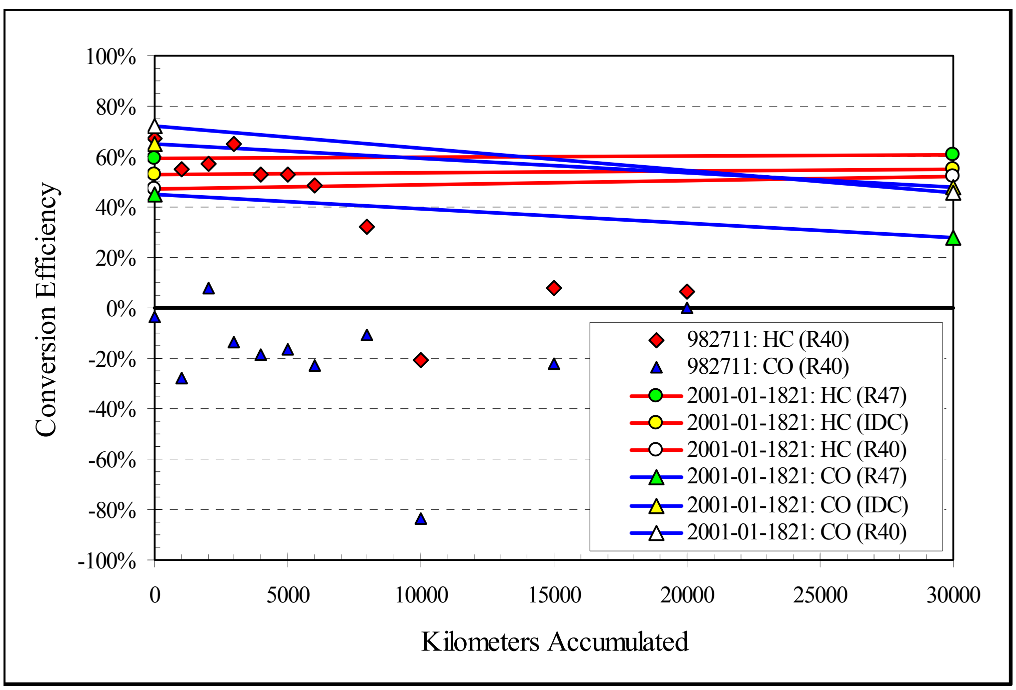


Figure 19. Improved Conversion Efficiency of Two-Stroke Catalysts [20,58]



efficiencies, as well as an approximate 25 percentage point increase in HC and CO conversion efficiencies with secondary air injection. [12,45] Clearly, the technology is much improved and quite effective in reducing two-stroke emissions.

While it is reasonable to expect that continuing improvements to two-stroke catalyst design and effectiveness are likely, the cost-effectiveness of two-stroke catalyst technology is estimated in this report assuming a 30,000 km (18,650 mi) catalyst life and effective average conversion efficiencies of 55 percent for HC, 50 percent for CO, and 45 percent for PM for a system without secondary air. A catalyst system with secondary pulse air is estimated to increase average conversion efficiencies over the same period to 80 percent for HC, 75 percent for CO, and 70 percent for PM.

Retail cost estimates for two-stroke catalysts span a rather wide range, from about $20 to as much as $171. [53,63-66] Generally, however, most estimates are in the $20-$50 range.[33] Throughout this report, all cost data are reported in 2005 U.S. dollars. Cost data from the EU, expressed in euros, have been converted to U.S. 2005 dollars using an exchange rate of 0.8 euros per U.S. dollar, which is roughly equal to the average January through August 2005 exchange rate. [67]

Where possible, the cited cost estimates have been adjusted for consistency with the catalyst volume and metal loading expected for a 100cc engine. Specifically, a 0.1 liter catalyst with a total precious metal loading of 0.141 grams, at a platinum/palladium/rhodium ratio of 18:0:1 was assumed since a catalyst of that formulation produced the emissions test data presented in Figure 19 -- data which are consistent with the catalyst conversion efficiencies assumed in this report. [58] Applying precious metal market price data to this formulation yields a total precious metal cost of $4.26. [68] This cost and volume data are used to adjust reference catalyst costs in instances where appropriate comparative assumptions are provided.

Without exception, technology cost estimates reported by the European Union average 4-8 times higher than average costs reported by other researchers. [66] While some differences are to be expected given the generally larger displacement motorcycles marketed in Europe, the reported estimates are significantly larger than estimates reported by U.S. researchers for large displacement motorcycles. [64,65] One possible explanation is that the reported EU data are based, at least partially, on estimates reported in a survey of motorcycle manufacturers. Regardless, the EU found cost-effectiveness estimates based on these costs and associated HC emission reductions to be within the range of cost-effectiveness for other recently adopted control measures. Nevertheless, since the reported costs are so inconsistent with other cost estimates reviewed for this report, the EU cost data have been excluded from the cost-effectiveness analysis for this report.

[33] It should be noted that one cited cost reference provided information only on costs relative to a conventional carbureted engine without aftertreatment. [63] These relative costs were converted into absolute incremental costs by assuming a cost of $42 for a conventional single cylinder two-stroke carbureted engine, as derived from cost estimates reported by the U.S. Environmental Protection Agency. [65]

Based on the remaining cost estimates, an average incremental cost of $34 has been assumed for a two-stroke oxidation catalyst system. A cost of $46 has been assumed for a two-stroke oxidation catalyst system with secondary pulse air injection. These estimates, combined with the baseline emission rates presented in Section 3.4 and the emission reduction estimates described above, yield cost-effectiveness estimates (per metric ton) of:

	Based on HC-Only Impacts	Based on $HC+NO_x$ Impacts	Based on $HC+CO+NO_x+PM$ Impacts
Catalyst	$136	$136	$65
Catalyst + Secondary Air	$124	$124	$59

As described above, these estimates assume a useful catalyst life of only 30,000 km (18,650 mi). If systems of improved durability are developed, cost-effectiveness would improve further.

It should also be recognized, however, that the presented cost-effectiveness estimates assume an uncontrolled emissions baseline. If, instead, catalyst systems were applied to an already controlled motorcycle, the systems would be marginally less cost-effective (since some portion of emissions would have already been controlled prior to the application of the catalyst). One indication of the potential impact of such an "ordered" control approach can be derived by noting that the cost-effectiveness of an oxidation catalyst/secondary air system on a four-stroke uncontrolled engine is nearly $900 per ton of HC (see Section 5.4), due to the substantially reduced HC emissions of four-stroke engines. Another example might assume the application of a catalyst system to a two-stroke engine previously converted to direct fuel injection (see Section 5.2). In such an application, the cost-effectiveness estimates for the catalyst system are:

	Based on HC-Only Impacts	Based on $HC+NO_x$ Impacts	Based on $HC+CO+NO_x+PM$ Impacts
Catalyst (DI Base)	$678	$678	$320

As both examples illustrate, the cost-effectiveness of the catalyst system depends largely on the emissions characteristics of the engine upon which it is installed. However, all of these estimates compare quite favorably to the cost-effectiveness of other emission control options. For example, in a recently compiled list of measures that could be considered to meet the U.S. ozone air quality standard, the U.S. Environmental Protection Agency found the average cost of control to be about $5,500 per metric ton of HC. [69]

It is perhaps also important to note that exhaust CO_2 emissions will increase by about 100 percent for non-secondary air systems and about 150 percent for catalyst systems with secondary air. This increase is the direct result of the conversion of HC and CO emissions to CO_2 and reflects the artificially low CO_2 emissions of a high HC and CO emitting base engine. Total emissions of carbon are unchanged -- carbon previously emitted as HC and CO is now emitted as CO_2. To the extent that emissions of HC and CO ultimately undergo oxidation in the atmosphere to form CO_2, the overall contribution to atmospheric CO_2 is unchanged. As stated, the emission reduction and cost-effectiveness estimates are based on an assumed useful life of 30,000 km (18,650 mi). Although it seems reasonable to expect more durable catalyst designs will continue to be introduced, existing research does not support a longer useful life for two-stroke catalyst systems at this time. Thus, regulatory programs should be structured to ensure that either full useful life durability demonstrations are required at the time of initial compliance certification or that adequate mid-life requirements are established to ensure continued emissions control effectiveness (e.g., replacement catalyst requirements).

Finally, it is critical that the fuel quality requirements for effective catalytic converter operation be recognized. Generally, this means that catalyst-equipped vehicles should be fueled only with an unleaded, low phosphorus gasoline -- with as low a sulfur content as practical. All of these compounds inhibit catalyst function. In countries or regions where leaded gasoline is still available, regulatory efforts to prevent misfueling will have to be implemented. Phosphorus limits should be on the order of 0.001 grams per liter (0.005 gram per gallon), with sulfur not exceeding 500 parts per million (by weight) -- although sulfur limits will ideally be 50 parts per million or lower. In addition to lead, gasoline should also be free of other metals such as manganese.

With proper precautions, catalysts can be applied as retrofit technology to existing motorcycles. Due to the sensitivity of engine performance to changes in exhaust backpressure, retrofit technology would ideally be designed and made available by original-equipment motorcycle manufacturers. Although adopted to ensure adequate performance of replacement catalysts rather than newly-added catalysts, recent EU regulatory language establishing type-approval requirements for catalyst systems could serve as the basis for an effective catalyst retrofit program. [70] Whether this or another approach is taken, local regulatory authorities will need to ensure that retrofit technology is properly designed and effective to avoid negative consumer impacts.

5.2 *Direct Injection for Two-Stroke Engines*

As described in Section 3.3, two-stroke engines offer substantial advantages over four-stroke engines in regard to cost and available power per unit size and weight. However, these advantages are offset from an environmental standpoint by the high emissions associated with exhaust scavenging. In response to emission reduction efforts directed at motorcycles, considerable research has been devoted to reducing scavenging emissions. [13,63,71-77] For scavenging reduction technologies to be viable in the market, the associated cost must be sufficiently low relative to the cost of an equivalent performance four-stroke engine.

Conventional two-stroke scavenging is accomplished using exhaust system pressure pulses in combination with the positive pressures created by the pressurized air/fuel mixture entering the cylinder. Through this process, a substantial portion of the air/fuel mixture can escape through the exhaust port prior to combustion. This results in high emissions of unburned HC and lubricating oil. Various techniques have been developed to reduce these scavenging losses, but all involve the fundamental separation of the air and fuel intake strategies so that scavenging can be accomplished using only air. For convenience, this report focuses on the specific technology developed by Orbital Engine Company of Australia, as this technology has successfully entered the two-stroke market in volume. [77] However, the fundamental emissions benefits of other air scavenging technologies will be similar.

Under the Orbital process, the fundamental separation of the air and fuel intake processes is accomplished by adding a direct fuel injection (DI) system to the engine, so that air-only is transferred through the conventional two-stroke intake and scavenging process. Fuel is injected directly into the combustion chamber only after the exhaust port has closed. This effectively reduces scavenging HC emissions to zero. Additionally, lubricating oil consumption rates can be reduced by about 50 percent since oil is no longer mixed with fuel. [73]

The critical breakthrough that allows the DI system to be implemented economically is the use of compressed air to reduce required fuel injection system pressures. Through this air-assisted process, DI can be accomplished using low pressure fuel injectors. Moreover, the use of compressed air improves both the quality of the fuel spray and the degree of fuel atomization. This allows for further emissions improvement by enabling lean stratified combustion over substantial portions of the engine operating cycle, with air/fuel ratios as high as 30:1. [73]

Various emissions testing has demonstrated emission reductions, relative to a conventional carbureted two-stroke engine, of about 80 percent for HC and CO and 50 percent for PM. Simultaneous reductions in fuel consumption of about 40 percent accrue through both reduced scavenging losses and increased efficiency. The stratified combustion process does result in about a 50 percent increase in NO_x, but this is due to the fact that NO_x emissions from a conventional two-stroke engine are very low (as described in Section 3.4). Thus, even though a 50 percent NO_x increase is observed, the absolute increase in NO_x is small.

It is important to note that DI technology has moved beyond the laboratory to mass market application. It is currently marketed on seven European motorcycle models (with engine displacements as low as 49cc) produced by Aprilia, Piaggio, and Peugeot. [77] In addition, Bajaj (India) has entered into a joint agreement to introduce DI technology on three-wheel motorcycles. [78]

Retail cost estimates for two-stroke DI systems range from $42 to as much as $250. [63,66,79] For this report, the higher costs estimates have been dismissed as unrealistic for the market application of two-stroke DI. To be marketable, the cost of DI has to be competitive with the cost of switching to a four-stroke engine design, which is estimated to be less than $50 (see Section 5.3). For DI technology, the higher cost estimates come from an EU report and a report related to retrofit DI technology. [66,79] As mentioned in Section 5.1, the costs from the EU report are 4-8 times higher than average costs from other sources -- and have, therefore, been discounted. The costs from the retrofit report [79] are more reasonable, but include non-OEM overhead and installation costs and do not include the savings that will accrue by not having to install the original carbureted engine. Thus, they are considerably higher than OEM costs. In contrast, the $42 estimate is based on an original equipment installation as developed by a DI OEM. As a result, the $42 estimate is used as the basis for all small motorcycle DI cost calculations in this report.

The assumed cost of DI technology, combined with the baseline emission rates presented in Section 3.4 and the emission reduction estimates described above, yields cost-effectiveness estimates (per metric ton) of:

	Based on HC-Only Impacts	Based on $HC+NO_x$ Impacts	Based on $HC+CO+NO_x+PM$ Impacts	Payback
DI (Retail Cost)	$39	$39	$18	
DI (with Savings)	$-1,074	$-1,077	$-493	0.5 years

Two separate estimates are provided to illustrate the impacts of the reduced fuel consumption benefits of DI technology. On a retail cost basis alone (i.e., assuming no improvement in fuel consumption), DI technology is very cost-effective as an emissions reduction control measure at less than $50 per metric ton of emissions avoided. When reduced fuel consumption is considered, the cost-effectiveness estimates turn negative indicating that emissions are avoided at a negative cost -- in effect, reduced fuel expenditures exceed technology costs and the consumer recoups the technology investment cost in less than one year. It is perhaps interesting to note that even if initial costs were $250, the technology would still pay for itself in less than three years.

The cost-effectiveness estimates assume average annual travel of 4,260 km (2,650 mi), an average useful life of 20 years, and average fuel costs of $1.06 per liter ($4.00 per gallon).[34] The estimates do not include any savings for reduced lubricating oil consumption, even though oil expenditures should be reduced by about half in-use. Motorcycles with higher annual usage rates will recoup the initial investment quicker, as will motorcycles operated in areas with higher fuel prices.[35] Motorcycles operated in areas with lower fuel prices will have longer payback periods. The assumed fuel price is intended to represent a rough approximation of the average global gasoline price in 2005, with country-specific prices ranging from a low of about $0.03 per liter ($0.12 per gallon -- Venezuela) to about $1.72 per liter ($6.50 per gallon -- Netherlands). [80] The bulk of countries exhibit prices in the range of $0.53-$1.59 per liter ($2.00-$6.00 per gallon).

As described in Section 5.1, the marginal cost of adding an oxidation catalyst on an DI-equipped motorcycle is also quite cost-effective, at about $700 per ton of HC (or $HC+NO_x$) and about $300 per ton of combined HC, CO, NO_x, and PM. Under a combined DI plus catalyst scenario, the consumer payback period increases by about four months, but is still less than one year for the assumed gasoline price and motorcycle usage rate.

As was the case with catalyst systems, exhaust CO_2 emissions will increase -- but only by about 40 percent (as opposed to 100-150 percent for catalyst systems alone). This increase is the direct result of the reduction in HC and CO emissions and reflects the artificially low CO_2 emissions of a high HC and CO emitting base engine. With DI, total emissions of carbon are actually reduced

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[34] All cost savings estimates in this report are discounted at an annual rate of 5 percent. At that rate, discounted savings over a 20 year useful life are equal to 65.4 percent of undiscounted savings.

[35] The higher annual usage rate is particularly important as the payback analysis is based on a conservative annual travel rate of 4,260 km, derived for an average *registered* motorcycle as described in Section 3.4. The average usage rate for typical *in-use* motorcycles can be considerably higher at 8,000-10,000 km per year, implying a payback period for such motorcycles that is only half that calculated on the basis of registered motorcycle statistics.

by about 40 percent, but carbon previously emitted as HC and CO is now emitted as CO_2. To the extent that emissions of HC and CO ultimately undergo oxidation in the atmosphere to form CO_2, the overall contribution to atmospheric CO_2 is therefore reduced by about 40 percent with DI technology (as opposed to no change with catalyst-only systems).

DI technology is also quite durable and should be able to demonstrate very low emissions deterioration over the full useful life of the motorcycle. Equally important is the fact that emission reductions accrue in all operating conditions, including cold start. In addition, because the system includes an electronic control module, it also provides important self-diagnostic features that can be useful to repair shop operators. Therefore, in many respects, DI technology provides important safeguards to ensuring that certification emission reductions are achieved in-use, regardless of the specific requirements of the certification program (e.g., durability requirements, cold start emissions requirements, etc.).

As alluded to above, retrofit DI systems have been developed and can be applied to existing motorcycles. [79] Consumer payback periods will be longer since both the original and replacement fueling system must be purchased, and installation costs for the replacement system must be paid. However, at an estimated retrofit cost of \$200-\$300 per motorcycle (including installation), investment costs would be recouped in 2.5-3.8 years at average motorcycle usage rates.[36]

5.3 *Replace Two-Stroke Engines with Four-Stroke Engines*

While two-stroke engines offer substantial advantages over four-stroke engines in regard to cost and available power per unit size and weight, these advantages are offset from an environmental standpoint by the high emissions associated with exhaust scavenging. Although substantial research has been devoted to improving the emissions performance of two-stroke engines and has resulted in significant successes, such as the direct injection technology discussed in Section 5.2, other research devoted to extending four-stroke engine performance and reducing four-stroke engine cost for applications in the small motorcycle market has also been successful. Whereas two-stroke motorcycles once dominated global sales -- four-stroke production now exceeds two-stroke production in all segments of the market except for units under about 100cc.

It appears likely that the shift toward four-stroke designs will continue. Honda, the world's largest motorcycle manufacturer, has established a near-term goal of 100 percent four-stroke production. [52] The four-stroke share of annual motorcycle output in mainland China, the largest national producer and consumer of small motorcycles, was 90 percent in 2002. [47] In 2003, the four-stroke share in Taiwan province of China was 98 percent. [81] Clearly, the application of four-stroke engines to small motorcycles is not only possible, but practical.

In addition to emission benefits, four-stroke designs are also much quieter than two-strokes, have a smoother idle, and offer the advantage of substantially reduced oil consumption. Novel approaches are available for low-cost four-stroke engines. For example, rotating cylinder

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[36] The lower bound of the retrofit costs estimate is from reference 79, the upper bound from Willson, B. et al., Envirofit International, Ltd., *New Solutions to Global Challenges*, presented at BAQ 2006, Yogyakarta, Indonesia, December 13-15, 2006.

engines that offer otherwise conventional two-stroke engine construction in combination with a cylinder liner that rotates at half engine speed to allow four cycle operation have been used for several years in the model aircraft market. Adaptation of such designs to the motorcycle market has been investigated. [82] However, it appears that the major cost issues associated with conventional "poppet valve" four-stroke designs have been successfully overcome as such designs have now entered the small motorcycle market. For example, the 2006 Yamaha Vino Classic scooter is powered by a 49cc liquid-cooled four-stroke engine -- replacing the air-cooled two-stroke engine offered on the 2005 model. [83]

The emissions benefits of an uncontrolled four-stroke versus an uncontrolled two-stroke design can be readily assessed by comparing the emission factors for the two designs as presented in Section 3.4 above. HC reductions are on the order of 95 percent, while CO reductions are more modest at about 30 percent. NO_x emissions increase by about 200 percent, but this is relative to very low two-stroke NO_x -- so absolute increases are modest and can be controlled using EGR or aftertreatment technology. PM emission reductions on the order of 80 percent can be expected, along with a reduction in fuel consumption of about 35 percent.

Of course, emissions reductions would be smaller relative to advanced or controlled two-stroke designs, but the intent is to provide a fundamental framework upon which additional emissions relations can be inferred. For example, basic four-stroke emissions relative to advanced two-stroke designs can be determined directly through a comparison of the emissions relations presented in this section with those in previous Section 5.2. It is not practical to specifically detail all possible technology substitutions in a broad-scoped report such as this, but it should be possible to derive reasonably accurate relationships by comparing emission impacts across the specific reported technology substitutions.

Incremental retail cost estimates for small four-stroke designs relative to a two-stroke baseline range from $28 to $100, although most estimates appear to range from $25-$50. [7,53,63,65] Since the $25-$50 range is also consistent with the price differential for the four-stroke Yamaha scooter cited above, the average of three estimates within the restricted range -- $36 -- is used as the basis for all small motorcycle four-stroke replacement cost calculations in this report.[37]

The assumed incremental cost of four-stroke technology, combined with the baseline emission rates presented in Section 3.4 and the emission reduction estimates described above, yields cost-effectiveness estimates (per metric ton) of:

	Based on HC-Only Impacts	Based on $HC+NO_x$ Impacts	Based on $HC+CO+NO_x+PM$ Impacts	Payback
Four-Stroke (Retail Cost)	$29	$29	$21	
Four-Stroke (with Savings)	$-792	$-797	$-571	0.5 years

[37] The MSRP for the 2006 Yamaha is $50 more than the 2005 two-stroke MSRP. While there is no question that factors other than component technology cost are reflected in an MSRP, the comparison nonetheless provides a fundamental benchmark for consideration.

Two separate estimates are provided to illustrate the impacts of the reduced fuel consumption benefits of four-stroke technology. On a retail cost basis alone (i.e., assuming no improvement in fuel consumption), the technology is very cost-effective as an emissions reduction control measure at less than $50 per metric ton of emissions avoided. When reduced fuel consumption is considered, the cost-effectiveness estimates turn negative indicating that emissions are avoided at a negative cost -- in effect, reduced fuel expenditures exceed technology costs and the consumer recoups the technology investment cost in less than one year. It is perhaps interesting to note that even if initial costs were on the high end of the range cited above ($100), the technology would still pay for itself in less than one and one-half years.

As with all calculations discussed in this report, cost-effectiveness estimates assume average annual travel of 4,260 km (2,650 mi), an average useful life of 20 years, and average fuel costs of $1.06 per liter ($4.00 per gallon). The estimates do not include any savings for reduced lubricating oil consumption, even though oil expenditures should be reduced substantially. Motorcycles with higher annual usage rates will recoup the initial investment quicker, as will motorcycles operated in areas with higher fuel prices.[38] Motorcycles operated in areas with lower fuel prices will have longer payback periods.

Exhaust CO_2 emissions increase by about 35 percent as a result of the reduction in HC and CO emissions -- an increase which is solely associated with the artificially low CO_2 emissions of a high HC and CO emitting base engine. Total emissions of carbon are actually reduced by about 35 percent, but carbon previously emitted as HC and CO is now emitted as CO_2. To the extent that emissions of HC and CO ultimately undergo oxidation in the atmosphere to form CO_2, the overall contribution to atmospheric CO_2 is therefore reduced by about 35 percent with four-stroke technology.

Since the basic four-stroke engine has no associated emissions control equipment, it should be able to maintain its emissions performance over the full useful life of the motorcycle. It may be possible to introduce four-stroke engines as retrofit technology in some cases, but space and mounting considerations will likely limit the scope of such applications. In cases where retrofit is possible, consumer expenditures will be higher and consumer payback periods will be longer since the consumer will have borne both the cost of the original two-stroke engine and the replacement four-stroke engine, as well as associated installation costs. Assuming an estimated retrofit cost of $125 per motorcycle (including installation), investment costs would be recouped in just over 1.5 years for average motorcycle usage rates.

5.4 *Secondary Air and Oxidation Catalysts for Four-Stroke Engines*

As described in Section 5.1, oxidation catalyst systems can provide substantial emission reductions for two-stroke motorcycles, and this same technology can be equally effective for four-stroke designs. [7,45,47,60,84-86] Four-stroke engine-out HC is much lower than that of

[38] The higher annual usage rate is particularly important as the payback analysis is based on a conservative annual travel rate of 4,260 km, derived for an average *registered* motorcycle as described in Section 3.4. The average usage rate for typical *in-use* motorcycles can be considerably higher at 8,000-10,000 km per year, implying a payback period for such motorcycles that is only half that calculated on the basis of registered motorcycle statistics.

conventional two-stroke engines, providing for lower exotherms across the catalyst and reduced potential for thermal deactivation. In addition, four-stroke exhaust temperatures are generally higher than those of two-strokes, allowing for quicker catalyst light-off. However, like small two-stroke engines, small four-stroke engines are generally calibrated for a rich-biased air/fuel mixture to maximize power and control peak combustion temperatures. This limits the availability of oxygen required to promote post-combustion HC and CO oxidation.[39] To provide the oxygen required for effective conversion of HC and CO, four-stroke motorcycles must utilize a secondary air injection system upstream of the catalyst. These are usually passive one-way valves that rely on exhaust system pressure pulsations to pull air into the exhaust stream.[40]

Because uncontrolled four-stroke exhaust emissions are generally lower than those of two-stroke engines -- excluding NO_x -- and since most existing emission standards do not require significant NO_x control, many four-stroke designs have been able to demonstrate compliance (with historic) with only secondary air systems (without a catalyst). [45] The injection of air into a hot exhaust stream results in the oxidation of some exhaust HC and CO without any catalytic activity. This would be somewhat equivalent to the exhaust stream oxidation that would occur in a lean-calibrated four-stroke design such as those in use in India. For this reason, this report includes secondary air as a potential stand-alone aftertreatment technology, even though it is unlikely (on its own) to allow for compliance with emerging motorcycle emission standards.

Based on various emissions testing demonstration programs, emission reduction potential for secondary air alone is estimated to be on the order of 20 percent for HC and 40 percent for CO. In contrast, control efficiencies for secondary air in conjunction with an oxidation catalyst are estimated to be about 80 percent for HC and 90 percent for CO. Although both systems will also result in the oxidation of a portion of the soluble organic fraction of PM, this report assumes no "credit" for that reduction since the soluble fraction of four-stroke gasoline PM emissions is small (as opposed to two-stroke engine PM, which is dominated by soluble lubricating oil emissions). [15]

Retail cost estimates for four-stroke secondary air systems range from $12-$100. [53,63,64,66] The $100 estimate is from an EU report and is not considered reliable given than all cost estimates from the report are 4-8 times higher than average costs from other sources. As a result, the average of the other estimates -- $26 -- has been used for this report. Retail cost estimates for a secondary air and oxidation catalyst system range from $46-$275. [53,63,64,66] As with the secondary air only system, the $275 estimate has been discounted and the average of the other estimates -- $61 -- has been used for this report.

The assumed technology costs, combined with the baseline emission rates presented in Section 3.4 and the emission reduction estimates described above, yield cost-effectiveness estimates (per metric ton) of:

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[39] Despite similar rich-biasing, substantial oxygen for two-stroke aftertreatment is available due to scavenging losses, which result in the presence of a significant quantity of air and unburned gasoline in the exhaust stream.

[40] India serves as an exception in that consumer demand for fuel efficiency has resulted in a market where manufacturers have calibrated engines to operate lean (at a cost of reduced power and acceleration). In such cases, sufficient exhaust oxygen should be available for effective four-stroke oxidation catalysis even without secondary air injection.

	Based on HC-Only Impacts	Based on $HC+NO_x$ Impacts	Based on $HC+CO+NO_x+PM$ Impacts
Secondary Air	$1,522	$1,522	$59
Secondary Air + Catalyst	$891	$891	$59

Unlike the catalyst system evaluated in Section 5.1, which assumed a useful life of only 30,000 km (18,650 mi), the cost-effectiveness of the four-stroke systems is based on a full useful life of 85,200 km (52,950 mi) -- 4,260 km (2,650 mi) per year over 20 years. Given the reduced potential for thermal deactivation, the reduced consumption of lubricating oil, and experience with four-stroke oxidation catalysis in the automotive market, four-stroke control systems should be able to achieve good in-use durability. Nevertheless, regulatory programs should be structured to ensure that full useful life durability demonstrations are required at the time of initial compliance certification.

Although the presented cost-effectiveness estimates assume an uncontrolled four-stroke emissions baseline, it is clear that they differ substantially from the cost-effectiveness estimates for two-stroke catalyst systems, as presented in Section 5.1 above. This results primarily from the fact that uncontrolled four-stroke emissions are substantially lower than uncontrolled two-stroke emissions, so that emissions avoided through catalyst installation are lower (despite the extended useful life of the four-stroke system). It should also be recognized that the cost-effectiveness estimates also represent the marginal cost-effectiveness of adding an oxidation catalyst system to a four-stroke engine conversion as described in Section 5.3 above.

The cost-effectiveness estimates compare quite favorably to the cost-effectiveness of other emission control options. For example, in a recently compiled list of measures that could be considered to meet the U.S. ozone air quality standard, the U.S. Environmental Protection Agency found the average cost of control to be about $5,500 per metric ton of HC. [69]

As was the case with the other emission control options discussed in this report, exhaust CO_2 emissions will increase in response to secondary air or catalyst installation -- by about 15 percent for secondary air systems alone and about 35 percent for catalyst systems with secondary air. This increase is the direct result of the conversion of HC and CO emissions to CO_2 and reflects the artificially low CO_2 emissions of a high HC and CO emitting base engine. Total emissions of carbon are unchanged -- carbon previously emitted as HC and CO is now emitted as CO_2. To the extent that emissions of HC and CO ultimately undergo oxidation in the atmosphere to form CO_2, the overall contribution to atmospheric CO_2 is unchanged.

Finally, the fuel quality requirements for effective catalytic converter operation must be recognized. Catalyst-equipped vehicles should be fueled only with an unleaded, low phosphorus gasoline -- with as low a sulfur content as practical. All of these compounds inhibit catalyst function. In countries or regions where leaded gasoline is still available, regulatory efforts to prevent misfueling will have to be implemented. Phosphorus limits should be on the order of 0.001 grams per liter (0.005 gram per gallon), with sulfur not exceeding 500 parts per million (by weight) -- although sulfur limits will ideally be 50 parts per million or lower. Gasoline should also be free of metals such as manganese.

With proper precautions, catalysts can be applied as retrofit technology to existing four-stroke motorcycles. Due to the sensitivity of small engine performance to changes in exhaust backpressure, retrofit technology would ideally be designed and made available by original-equipment motorcycle manufacturers. Although adopted to ensure adequate performance of replacement catalysts rather than newly-added catalysts, recent EU regulatory language establishing type-approval requirements for catalyst systems could serve as the basis for an effective catalyst retrofit program. [70] Whether this or another approach is taken, local regulatory authorities will need to ensure that retrofit technology is properly designed and effective to avoid negative consumer impacts.

5.5 *Three-Way Catalyst for Four-Stroke Engines*

A three-way catalyst system allows for the simultaneous conversion of HC, CO, and NO_x. Such systems have demonstrated remarkable efficiencies in the automotive sector and are largely responsible for the very low emission rates achievable with advanced technology vehicles. However, the simultaneous conversion of HC, CO, and NO_x requires that the engine operate under an air/fuel mixture strategy that exhibits only small, precisely managed oscillations about stoichiometry. Effective NO_x conversion generally requires a stoichiometric-to-rich air/fuel mixture, while effective HC and CO conversion generally requires a stoichiometric-to-lean air/fuel mixture. Three-way catalyst systems achieve maximum efficiency by storing oxygen during lean operating periods and releasing stored oxygen during rich operating periods, so that oxygen availability within the catalyst is always near optimum.

A high efficiency system requires very precise electronic controls, not generally found on small, typically carbureted, motorcycles. For this reason, the cost effectiveness of high efficiency three-way catalysts is presented in the next section that addresses fuel injection for four-stroke engines. Such a system would facilitate the required level of air/fuel mixture control. However, it has also been demonstrated that three-way catalysts can be effective in oxidizing HC and CO and reducing NO_x even in the absence of electronic fueling controls (albeit at lower overall conversion efficiencies). Engines tuned to a rich-bias (i.e., most small motorcycles) tend to exhibit modest HC and CO reductions and NO_x reductions of 50 percent (or more). [47,60,84] In contrast, engines tuned to a lean-bias (i.e., generally limited to small motorcycles in India) tend to exhibit greater HC and CO reductions and less significant NO_x reductions. [60] Generally, conversion efficiencies for three-way catalyst systems installed without appropriate air/fuel mixture controls can be expected to perform similarly to oxidation catalysts for HC and CO, while providing for modest NO_x reductions. It therefore appears that reductions on the order of 55 percent for HC, 50 percent for CO, and 25 percent for NO_x may be generally achievable with three-way catalyst systems without associated air/fuel mixture controls.

Three-way catalyst systems installed in conjunction with associated oxygen sensors (mounted before and after the catalyst to monitor catalyst oxygen conditions) and an air/fuel management system that adjusts the intake mixture in response to oxygen sensor output can be expected to provide greater conversion efficiencies, but even these are unlikely to approach the 90-plus percent conversion efficiencies commonly observed in the automotive sector.[41] Given motorcycle space constraints as well as the sensitivity of single cylinder engines to exhaust backpressure, catalysts in the motorcycle market are of smaller volumes and smaller cell densities relative to those is the automotive market. As a result, space velocities are likely to be considerably larger than those in the automotive market (see Section 5.1) -- limiting conversion efficiencies below levels observed in that sector. [58,87] Based on available research, it appears that reductions on the order of 75 percent for HC, 50 percent for CO, and 50 percent for NO_x may be achievable with current systems incorporating air/fuel mixture controls. [7,47]

Retail cost estimates for three-way catalyst systems range from $36-$605. [53,64,66] The high estimate is from an EU report and is not considered reliable given than all cost estimates from the report are 4-8 times higher than average costs from other sources. As a result, the average of the other estimates -- $39 -- has been used for this report. Note that this cost is for a three-way catalyst alone, without associated air/fuel mixture control hardware. Cost and cost effectiveness estimates related to three way catalysts with associated air/fuel mixture controls are discussed in Section 5.6.

For three-way catalysts without associated air/fuel mixture controls, the assumed technology cost, combined with the baseline emission rates presented in Section 3.4 and the emission reduction estimates described above, yields cost-effectiveness estimates (per metric ton) of:

	Based on HC-Only Impacts	Based on $HC+NO_x$ Impacts	Based on $HC+CO+NO_x+PM$ Impacts
Three-Way Catalyst	$832	$779	$67

As with the four-stroke oxidation catalyst system discussed in Section 5.4, the cost-effectiveness estimates are based on a full useful life of 85,200 km (52,950 mi) -- 4,260 km (2,650 mi) per year over 20 years. Given the reduced potential for thermal deactivation due to the lower engine-out emissions of four-strokes, and the reduced consumption of lubricating oil, four-stroke catalyst systems should be able to demonstrate good in-use durability. Nevertheless, regulatory programs should be structured to ensure that full useful life durability demonstrations are required at the time of initial compliance certification.

The presented cost-effectiveness estimates assume an uncontrolled four-stroke emissions baseline, so that they do not reflect the marginal cost of upgrading from an oxidation catalyst system. The two systems should be evaluated as alternatives in the context of NO_x reductions, rather than as incremental control systems. The cost-effectiveness estimates do, however, represent the marginal cost-effectiveness of adding a three-way catalyst system to a four-stroke engine design conversion as described in Section 5.3 above.

As was the case for the four-stroke oxidation catalyst, the three-way catalyst cost-effectiveness estimates compare quite favorably to the cost-effectiveness of other emission control options. For example, in a recently compiled list of measures that could be considered to meet the U.S.

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[41] Engine construction modifications may also be required to tolerate the increased temperatures associated with stoichiometric combustion.

ozone air quality standard, the U.S. Environmental Protection Agency found the average cost of control to be about $5,500 per metric ton of HC. [69]

As with other HC and CO reduction technologies, exhaust CO_2 emissions will increase in response to three-way catalyst installation -- by about 20 percent relative to an uncontrolled four-stroke engine. This increase is the direct result of the conversion of HC and CO emissions to CO_2 and reflects the artificially low CO_2 emissions of a high HC and CO emitting base engine. Total emissions of carbon are unchanged -- carbon previously emitted as HC and CO is now emitted as CO_2. To the extent that emissions of HC and CO ultimately undergo oxidation in the atmosphere to form CO_2, the overall contribution to atmospheric CO_2 is unchanged.

As with all other catalyst options, the fuel quality requirements for effective catalytic converter operation must be recognized. Catalyst-equipped vehicles should be fueled only with an unleaded, low phosphorus gasoline -- with as low a sulfur content as practical. All of these compounds inhibit catalyst function. In countries or regions where leaded gasoline is still available, regulatory efforts to prevent misfueling will have to be implemented. Phosphorus limits should be on the order of 0.001 grams per liter (0.005 gram per gallon), with sulfur not exceeding 500 parts per million (by weight) -- although sulfur limits will ideally be 50 parts per million or lower. Gasoline should also be free of metals such as manganese.

With proper precautions, three-way catalysts can be applied as retrofit technology to existing four-stroke motorcycles. However, due to the sensitivity of small engine performance to changes in exhaust backpressure as well as the fact that three-way systems require associated engine management changes, retrofit technology would ideally be designed and made available by original-equipment motorcycle manufacturers. Retrofit of a three-way system is greater challenge than retrofit of an oxidation catalyst system, and it is not clear that the additional NO_x reductions justify the added risk given that similar HC and CO reductions can be derived from the simpler oxidation catalyst system. Regardless, if such retrofits are envisioned, local regulatory authorities will need to ensure that retrofit technology is properly designed and effective to avoid negative consumer impacts.

5.6 *Fuel Injection for Four-Stroke Engines*

Like their two-stroke counterparts, conventional small four-cylinder engines traditionally utilize inexpensive carbureted fueling technology. However, fuel injection (FI) technology has been the focus of considerable recent research and is becoming more prevalent in the motorcycle market. [63,87-91] In fact, FI technology has achieved commercialization even in the small engine sector. For example, Honda now offers their programmed fuel injection (PGM-FI) technology on four-stroke engines as small as 50cc. [52]

Even though four-stroke engines do not suffer from the exhaust scavenging losses that led to the development of direct injection technology for two-stroke engines (see Section 5.2), fuel injection still offers considerable fueling control advantages that make it attractive for application on four-stroke engines. These same advantages led to the complete replacement of carbureted fueling in the automotive sector and are likely to do the same in the motorcycle markets. As costs for FI decline, this shift is likely to occur in response to performance advantages alone, even in the absence of additional emissions regulation. For this reason, it is somewhat unfair to assess the costs of FI technology on the basis of their emissions benefits alone, but that approach has been undertaken in this report.[42] Accordingly, the cost-effectiveness estimates presented below are likely to be conservative.

It is perhaps appropriate to distinguish direct injection (DI) technology from FI technology. Whereas DI technology involves the injection of fuel directly into the combustion chamber, FI technology generally involves the injection of fuel into the cylinder intake port, which allows additional time for vaporization and allows for the use of lower pressure (and less costly) injectors (a technique commonly referred to as port fuel injection, or PFI). Since there is no conventional intake port in two-stroke engines, DI is the only viable fuel injection technology (although so-called "semi-direct" transfer port injection technology has also been investigated). Four-strokes, however, utilize a conventional poppet valve intake system which allows for either FI or DI technology. While DI technology has been investigated for small four-stroke engines, FI is generally a cheaper alternative. [92,93] DI does allow for a potentially more responsive fueling system with a 10-15 percent higher fuel efficiency potential, but both systems allow for high efficiency lean-burn operation, so that FI appears to be the more cost-effective solution at this time. For this reason, FI is evaluated in this report -- but readers should recognize that DI is also a potential four-stroke solution, especially in cases where maximum fuel efficiency is desirable. Since both systems offer similar emissions performance for conventional pollutants, the cost-effectiveness of four-stroke DI will be equal to (ideal case) or worse than that of FI systems and can only be evaluated fairly in terms of CO_2 reduction potential.

The stratified lean-burn opportunities enabled with FI technology have demonstrated emission reductions on the order of 40 percent for HC and 80 percent for CO relative to a conventional carbureted four-stroke engine. Fuel consumption reductions are on the order of 20 percent. However, NO_x emissions increases of about 50 percent accrue in conjunction with increasing combustion efficiency. Generally these NO_x increases would be offset through the inclusion of a three-way catalyst as an integral component of a four-stroke FI system -- so the marginal cost-effectiveness associated with three-way catalyst inclusion is also evaluated. With a three-way catalyst, a four-stroke FI system should allow for emission reductions on the order of 85 percent for HC, 90 percent for CO, and 25 percent for NO_x relative to a conventional carbureted four-stroke engine -- while retaining the same 20 percent reduction in fuel consumption.

Retail cost estimates for four-stroke FI systems range from $84-$177 without a catalyst and $104-$257 with a catalyst. [63-65] For this report, the average of the available cost estimates has been used to estimate emissions reduction cost-effectiveness -- $111 for a non-catalyst system and $166 for a catalyst-equipped system.

The assumed costs of FI technology, combined with the baseline emission rates presented in Section 3.4 and the emission reduction estimates described above, yield cost-effectiveness estimates (per metric ton) of:

[42] The U.S. Environmental Protection Agency, for example, allocates one-half of the cost of FI technology to performance and one-half to emission control. [65]

	Based on HC-Only Impacts	Based on $HC+NO_x$ Impacts	Based on $HC+CO+NO_x+PM$ Impacts	Payback
FI Alone (Retail Cost)	$3,266	$4,019	$127	
FI Alone (with Savings)	$-8,180	$-10,067	$-317	4.1 years
FI+Catalyst (Retail Cost)	$2,289	$2,192	$160	
FI+Catalyst (with Savings)	$-3,097	$-2,967	$-217	6.5 years
Catalyst (Marginal Cost)	$1,420	$1,136	$353	

Two separate estimates are provided to illustrate the impacts of the reduced fuel consumption benefits of FI technology. On a retail cost basis alone (i.e., assuming no improvement in fuel consumption), cost-effectiveness estimates for FI technology range from $100-$4,000 per metric ton depending on the pollutants for which reductions are valued. When reduced fuel consumption is considered, the cost-effectiveness estimates turn negative indicating that emissions are avoided at a negative cost -- in effect, reduced fuel expenditures exceed technology costs and the consumer recoups the technology investment cost in just over four years.

If the FI and three-way catalyst are evaluated as a system, cost-effectiveness estimates range from $150-$2,200 per metric ton depending on the pollutants for which reductions are valued, indicating that the catalyst installation is relatively economical (the FI system is more cost-effective with the catalyst than without). This is further illustrated by the fact that the marginal cost-effectiveness of the three-way catalyst system, which, while greater than the cost-effectiveness of a three-way catalyst relative to a carbureted engine (see Section 5.5), is still more cost-effective than the FI system alone. For the combined system, the cost-effectiveness estimates still turn negative when fuel consumption reductions are considered, but the additional cost of the catalyst extends the consumer payback period to 6.5 years.

The cost-effectiveness estimates assume average annual travel of 4,260 km (2,650 mi), an average useful life of 20 years, and average fuel costs of $1.06 per liter ($4.00 per gallon). Motorcycles with higher annual usage rates will recoup the initial investment quicker, as will motorcycles operated in areas with higher fuel prices.[43] Motorcycles operated in areas with lower fuel prices will have longer payback periods.

Although the FI system is by far the least cost-effective option evaluated based on equipment costs alone, the technology still compares favorably to the cost-effectiveness of other emission control options. For example, in a recently compiled list of measures that could be considered to meet the U.S. ozone air quality standard, the U.S. Environmental Protection Agency found the average cost of control to be about $5,500 per metric ton of HC. [69] Of course, when both

[43] The higher annual usage rate is particularly important as the payback analysis is based on a conservative annual travel rate of 4,260 km, derived for an average *registered* motorcycle as described in Section 3.4. The average usage rate for typical *in-use* motorcycles can be considerably higher at 8,000-10,000 km per year, implying a payback period for such motorcycles that is only half that calculated on the basis of registered motorcycle statistics.

technology costs and operating cost savings are considered, FI technology is very cost-effective since the entire investment cost is recouped by the consumer.

Although exhaust CO_2 emissions will increase due to significant reductions in HC and CO, the increase associated with the FI system is by far the smallest of the various technologies evaluated in this report. For the FI system alone, an increase of only about 3 percent would accrue (relative to a carbureted four-stroke engine), while the combination FI plus catalyst system would lead to an approximate 10 percent increase. Both are the direct result of the reduction in HC and CO emissions and reflect the artificially low CO_2 emissions of a high HC and CO emitting base engine. With FI, total emissions of carbon are actually reduced by about 20 percent, but carbon previously emitted as HC and CO is now emitted as CO_2. To the extent that emissions of HC and CO ultimately undergo oxidation in the atmosphere to form CO_2, the overall contribution to atmospheric CO_2 is therefore reduced by about 20 percent with FI technology. Since DI technology is capable of providing even greater fuel consumption reductions, it would lead to even larger reductions in emitted carbon (on the order of 30 percent as compared to the 20 percent reduction associated with FI).

FI (and DI) technology is quite durable and should be able to demonstrate very low emissions deterioration over the full useful life of the motorcycle. Equally important is the fact that emission reductions accrue in all operating conditions, including cold start. Both FI and DI technology provide important safeguards to ensuring that certification emission reductions are achieved in-use, regardless of the specific requirements of the certification program (e.g., durability requirements, cold start emissions requirements, etc.).

Retrofit FI (and DI) systems for four-strokes could be applied to existing motorcycles, but consumer payback periods will be longer than indicated for an OEM-installed system since both the original and replacement fueling system must be purchased, and installation costs for the replacement system must be paid. Given the 5-7 year payback period associated with the OEM-system, it is unlikely that most consumers will view retrofits as an acceptable option. Due to accelerated payback, it is possible that owners of high usage equipment, such as three-wheeler taxi operators, might view an FI retrofit as viable. However, many of these same owners have already demonstrated an unwillingness to even accept basic four-stroke engine technology due to its higher purchase price and increased repair complexity and cost.

5.7 *Evaporative Emission Controls*

Like all gasoline-powered vehicles, there are evaporative HC emissions from motorcycles. With the exception of California requirements in the U.S., provincial requirements in Taiwan, China, and, more recently, requirements in Thailand and federally in the U.S., existing motorcycle emission standards focus solely on exhaust emissions performance. As a result, there is little information available on global evaporative emission rates, although the EU COPERT III and U.S. MOBILE6.2 emission factor models do provide evaporative emissions estimates for motorcycles. [17,94] Table 8 presents a comparison of emission factors from the two models. As indicated, evaporative emission rates are generally in the range of 0.1-1.0 g/km (0.2-1.5 g/mi), but it should be recognized that emissions for individual motorcycles can be higher.

Table 8. Motorcycle Evaporative Emission Rate Estimates (1)

Emissions Type	COPERT III < 50cc	COPERT III 50+cc	MOBILE6.2
Diurnal Emissions	0.08 (0.13)	0.17 (0.27)	0.003 (0.005)
Hot Soak Emissions - Carbureted Engines	0.50 (0.80)	0.99 (1.59)	no estimate
Hot Soak Emissions - Fuel Injected Engines	0.02 (0.04)	0.05 (0.08)	no estimate
Hot Soak Emissions - Composite	no estimate	no estimate	0.11 (0.18)
Running Loss Emissions	0.03 (0.05)	0.07 (0.11)	0.00 (0.00)
Resting Loss Emissions	no estimate	no estimate	0.22 (0.36)
Total Evaporative Emissions - Carbureted Engines	0.61 (0.98)	1.23 (1.97)	no estimate
Total Evaporative Emissions - Fuel Injected Engines	0.14 (0.22)	0.28 (0.46)	no estimate
Total Evaporative Emissions - Composite	no estimate	no estimate	0.34 (0.55)

(1) g/km (g/mi)

(2) COPERT III diurnal and hot soak emission factors are in units of g/day and g/soak respectively. For illustrative purposes, they have been converted into g/km assuming an average travel distance of 11.7 km/day (7.3 mi/day) and 2 hot soaks per day. For comparison, MOBILE6.2 assumes 6.1-21.1 km/day (3.8-13.1 mi/day) depending on motorcycle age and 0.96 hot soaks per day.

An average daily travel distance of 11.7 km/day (7.3 mi/day) and two soaks per day were assumed in deriving the COPERT III emission rates presented in Table 8.[44] MOBILE6.2 has internal defaults for these parameters, which are 6.1-21.1 km/day (3.8-13.1 mi/day) depending on motorcycle age and 0.96 hot soaks per day. Thus, the assumed mileages are reasonably consistent, while the COPERT III rates reflect about one additional soak. In addition, COPERT III provides emission rates for carbureted and fuel injected engines separately, while MOBILE6 provides a composite emission rate. Nevertheless, given the level of uncertainty and the differing assumptions, the resulting emission rates are quite consistent and should provide a reasonable approximation of evaporative emissions significance.

It is also clear from the emission rates presented in Table 8 that fuel injection (including direct injection) technology provides significant evaporative emissions benefits. Such systems eliminate the evaporation of fuel remaining in open carburetor fuel bowls after engine shutoff -- as indicated by the substantial difference in hot soak emission rates between carbureted and fuel

[44] 4,260 annual kilometers (2,650 annual miles) divided by 365 days, in conjunction with one assumed round trip (with a mid-trip stop resulting in two hot soaks).

injected engines. Since these benefits are not accounted for in the cost-effectiveness estimates previously presented in Sections 5.2 and 5.6, both fuel injection and direct injection technology will be somewhat more economical than implied by the presented cost-effectiveness estimates.

Given a lack of evaporative emissions test data, no specific evaporative emissions cost-effectiveness estimates have been developed for this report. However, analyses conducted by others can provide some insight into the efficacy of evaporative controls. California has had evaporative emission requirements for motorcycles since 1978. As described in Section 5, these standards require evaporative HC to be less than or equal to 2 grams per test as measured during a standard certification SHED test procedure. Generally, such testing is most effective in controlling diurnal and hot soak emissions. Although no specific data on pre-1978 versus post-1978 emission rates are available, motorcycles sold in California are equipped with a small carbon canister to capture and recycle (back to the engine) evaporative HC. [95] Such technology has been demonstrated to be highly effective in controlling evaporative emissions from four-wheel vehicles. However, current motorcycle certification data for California indicates that model-specific evaporative emissions range from 0.1-1.7 grams per test -- so the quality of emissions control varies across models by over an order of magnitude and a significantly tighter emission standard could be adopted. [55]

The U.S. Environmental Protection Agency recently adopted fuel system permeation limits that take affect beginning in model year 2008. The adopted limits restrict fuel tank permeation to 1.5 g/m^2/day and fueling system hose permeation to 15 g/m^2/day. The limits primarily target resting loss evaporative emissions and are expected to reduce fuel tank and hose permeation by 85-95 percent. [41] It is easy to see from the emission rates presented in Table 8, why the permeation standards were adopted. As indicated, resting loss emissions comprise about 65 percent of the total motorcycle evaporative emissions estimates by the MOBILE6.2 model. Targeting these emissions in conjunction with an exhaust emission standard that continues the market shift toward fuel injected vehicles (that provide the added benefit of lower hot soak evaporative emissions) appears to be a very effective evaporative emissions control strategy.

The U.S. Environmental Protection Agency estimated that cost of compliance with the permeations standards would be approximately $2 per motorcycle. They further estimated that the reduction in permeation losses would result in the combustion of about 8.5 gallons of gasoline -- that would have otherwise evaporated -- over the lifetime of a motorcycle. Thus, the control measure results in a net savings to the consumer as long as gasoline prices are above about $0.24 per gallon (undiscounted). If the U.S. analysis is adjusted for the higher estimated lifetime mileage of global motorcycles and combined with the estimated average global gasoline price used for this report ($1.06 per liter -- $4.00 per gallon), then discounted global average savings would be about $33 per motorcycle, equating to a cost-effectiveness estimate of *negative* $1,342 per metric ton of HC avoided and a payback period of less than one year. Even on the basis of the technology compliance cost alone (i.e., with no operating cost savings considered), the permeation controls are still very cost-effective, at about $81 per metric ton of HC avoided.

Clearly there are viable evaporative emission controls that can be adopted. While evaporative emissions were of lesser importance during an era of high exhaust HC, that era is rapidly coming to an end as more stringent motorcycle emission standards are being implemented on a global basis over the next few years. As HC exhaust emission rates decline below about 1 g/km evaporative emissions will become responsible for about half of total HC emissions. Given that global HC exhaust standards are now approaching or exceeding that level of stringency, an expansion of certification requirements to include evaporative standards is appropriate.

5.8 *Lubricating Oil/Fuel Quality Controls*

From a motorcycle manufacturer standpoint, in-use lubricating oil quality is not an issue. This is also true of four-stroke motorcycles from a consumer standpoint as four-stroke oil consumption is low and therefore lubricating oil is not a significant cost concern. However, traditional two-stroke motorcycle technology employs a "total loss" lubricating oil strategy wherein lubricating oil is mixed with gasoline and consumed in the combustion process. As a result, lubricating oil is an ongoing expenditure for two-stroke consumers, many of whom have responded with environmentally disadvantageous in-use behavior.

Effective two-stroke motorcycle oils have been developed, and when used properly result in good lubrication and low smoke emissions. Generally these oils are denoted as 2T oils and meet either the JASO (Japanese Automotive Standards Organization) FB, JASO FC, or API (American Petroleum Institute) TC specifications. The JASO FB and FC specifications are designed especially to reduce two-stroke smoke and, as a result, have gained global acceptance as preferred two-stroke engine oils. However, these oils are somewhat more expensive than traditional automotive oils and the straight mineral oils used in large stationary engines, and this, combined with serious and pervasive misunderstandings of lubricating oil quality and requirements has led to extensive consumer misuse and increased smoke and PM emissions in countries such as Pakistan and Bangladesh. [23,53]

This misunderstanding actually feeds on itself in a perverse manner that ends up not only harming the environment, but costing the consumer *more* money than if they had used the correct oil. After beginning use of the wrong lubricating oil, engine and exhaust system deposits associated with that use result in significant engine power loss and overheating. To resolve this problem, consumers increase the quantity lubricating oil used from a recommended ratio of 2-3 percent of fuel volume to 8-12 percent. This solves the overheating problem, but since 2T oil does not cost 3-6 times more than even the cheapest mineral oil, the consumer actually ends up spending more money. Additionally, to fully resolve the power loss, the consumer also removes the stock muffler and replaces it with a non-baffled aftermarket "muffler" that collects less lubricating oil deposits, but results in significant noise problems.

The practice has become so widespread in countries such as Bangladesh that fueling station attendants automatically pre-blend straight mineral oil with gasoline when three-wheel motorcycles approach the pump. In fact, a recent United Nations research program found it very difficult to purchase gasoline for even four-stroke three-wheeled motorcycles without pre-mixed straight mineral oil. Attendants often insisted that gasoline had to be sold with (excess) straight mineral oil. Thus, even if a consumer wanted to follow manufacturer recommendations and use a 2T oil, it would be virtually impossible to do so [96]. It is important to recognize that this same situation does not exist in all countries. In most countries, it is possible to purchase unmixed gasoline.

An emissions testing program conducted on three three-wheelers recruited from the Dhaka taxi fleet found that the use of an 8 percent mineral oil fuel mix increased PM emissions by nearly 160 percent compared to a 3 percent JASO FB oil mix. [21] The effects of lubricating oil misuse will only become more pronounced as motorcycle manufacturers implement catalytic aftertreatment technology. Studies have shown that the wrong lubricating oil can deactivate a motorcycle emissions control catalyst in only 500 km (310 mi). [29] Clearly, the benefits of controlled in-use lubricating oil practices are significant. Moreover, such control can actually result in a savings to consumers who switch from high mix ratio mineral oils to low mix ratio 2T oils. However, implementing such change is not straight-forward.

Options for changing consumer behavior would almost certainly be based on a ban on the use of non-2T oils in two-stroke engines, and could include requirements that only specified pre-mixed gasoline/oil mixtures can be dispensed into two-stroke vehicles. Such requirements are already in place in some areas. For example, India has both mandated the dispensing of only gasoline pre-mixed with 2T oil at refueling stations in 17 major cities and banned the sale of unmixed 2T oil. However, the key to success is effective enforcement and no program is without difficulties. For example, if pre-mixed dispensing is required, separate dispensing facilities for four-stroke and two-stroke engines must be maintained. Moreover, the non-mixed system must be also be available to direct injection two-stroke engines and any other two-stroke equipped with independent oil metering systems. The logistics should not necessarily pose problems since unmixed gasoline must also be available for other vehicles such as automobiles and light trucks, but ensuring that oil-consuming motorcycles do not access these same unmixed dispensers will require effective enforcement. Another option might be to require all pre-mix two-strokes to install (retrofit) independent oil metering systems. While such systems would not eliminate the use of the wrong lubricating oil, they would reduce the frequency of over lubricating. Pumpless lubricating oil systems were available for several years at an estimated cost of about $30, but such systems have apparently now been discontinued due to reliability issues. [53] More reliable systems that include an engine-driven oil pump would be both more expensive and pose installation issues. Nevertheless, the need for regulatory action is clear for countries where lubricating oil misuse is common.

Fuel quality enforcement is equally important. As described above, the use of gasoline with no lead, phosphorus, or manganese, and very low sulfur levels is critical to maximizing the durability of catalytic converters. In addition, proper gasoline qualities are essential to minimizing engine-out emissions. Minimum octane specifications and distillation characteristics should be established and enforced. In some countries, for example, the adulteration of gasoline with kerosene is a somewhat common practice (due to the lower cost of kerosene). [53,96] This contributes to reduced engine life and increased emissions. The potential air quality benefits of stringent motorcycle certification standards will be severely compromised by allowing the continued use of low quality fuels or lubricants by consumers.

5.9 *Alternative Fuels*

As with any motorized vehicle, alternative fueling options for motorcycles can be pursued on both an original equipment and aftermarket (i.e., retrofit) basis. Options include electrification and hybridization (although generally not as retrofits), alternative fossil fuels such as CNG and LPG, or biofuels such as ethanol. Given the localized nature of issues that can affect the viability, cost, and emissions performance of fuel-switching, this report does not attempt to assign a global "average" emission reduction or cost-effectiveness estimate to non-gasoline motorcycle policies. Issues that can affect local effectiveness include the varying emissions performance of power-generating facilities (for electric vehicles), variations in the cost of non-gasoline fuels, variations in the availability and cost of local retrofits, variations in the quality of motorcycle retrofit, and regulatory restrictions that can affect the availability of fuel. Since it is not possible to generalize these various factors in any meaningful way, this report is restricted to an overview of the basic technologies and associated issues, presented in conjunction with example analytical results reported for specific cities through other research efforts. [16,53,97-107]

The use of CNG as a motor fuel presents well-known challenges, most of which derive from the fact that as a gaseous fuel, CNG must to be compressed to allow for the storage of significant quantities of energy. Generally, this means that CNG installations involve high-pressure (on the order of 200 bar) fuel tanks that, relative to a conventional liquid fuel tank, require more space, are heavier, and more costly. Tank size serves as a prohibitive barrier to two-wheel motorcycle installation, but applications in the three-wheel motorcycle market are viable. A CNG system typically consists of a high pressure fuel tank, a pressure regulator, and a gaseous carburetor. In two-stroke applications, a lubricating oil pump must also be included since it is not possible to mix oil and fuel manually.

The incremental cost of CNG-powered motorcycles is typically on the order of \$400-\$450 relative to an equivalent gasoline-powered motorcycle, and is similar for both original equipment and retrofit applications. [53,100] The economics of CNG depend entirely on local CNG cost. CNG is currently exempted from transportation fuel taxes in many areas, so it cannot be assumed that current economic calculations will carry forward under a high demand scenario. Nevertheless, several CNG programs conducted to date have found CNG fueling to be very economical, with consumer payback periods of only about one to two years. [53,99] The lack of a refueling station infrastructure can be an impediment to widespread CNG usage, and development of the requisite infrastructure can affect CNG economics through investment and operating costs -- but in most cases this influence will be minor relative to CNG and gasoline fuel cost differentials.

Fairly wide differences are reported for the emissions performance of CNG motorcycles relative to an equivalent gasoline motorcycle. The quality of CNG retrofits may play a role in the reported differences, but significant variation is reported even for original equipment installations. In Delhi, where 100 percent of three-wheeled motorcycles are now powered by CNG in response to air quality-driven clean-fuel requirements, two-stroke CNG motorcycles are reported to reduce NMHC and NO_x emissions by about 80 percent, and CO emissions by about 60 percent -- while four-stroke CNG motorcycles are reported to reduce NMHC by about 75 percent and CO by about 60 percent, while increasing NO_x by about 30 percent. [103] In contrast, estimates for over 1000 two-stroke three-wheelers converted to CNG fueling in Dhaka imply that NMHC, CO, and NO_x have all declined by 80-90 percent. [98]

Methane emissions are perhaps the biggest emissions issue associated with CNG use. CNG is composed primarily of methane, so that methane constitutes a large fraction of any "evaporating" fuel and any unburned HC emissions. In recognition of the limited ozone reactivity of methane, CNG is universally extended a special allowance during certification, wherein HC compliance is based on NMHC emissions. As a result, methane emissions are not specifically limited and since methane is a greenhouse gas, CNG motorcycles can exhibit substantial GHG emissions increases. Methane emissions for CNG motorcycles have been estimated at about 2 g/km for four-strokes and 5-7 g/km for two-strokes (with scavenging impacts driving the larger two-stroke emissions). [53,103] Given that methane has a global warming potential 23 times that of CO_2, these emission rates translate in CO_2-equivalent emission rates of 46 g/km for four-strokes and 115-161 g/km for two-strokes. [108] For two-strokes, this means that methane emissions are 100-140 percent as high as carbon emissions from a GHG standpoint -- while for four-strokes, methane emissions are almost 60 percent as high as carbon emissions. Clearly, the GHG impacts of CNG motorcycles should be carefully evaluated in determining any future regulatory strategy.

The use of LPG in motorcycles is conceptually similar to that of CNG in that LPG is also a gaseous fuel. However, LPG can be stored as a liquid at modest pressures (4-5 bar) so that the bulky and expensive storage tanks required for CNG are not required for LPG. As a result, the incremental cost of an LPG system is about half that of a CNG system, or about $150-$200 relative to an equivalent gasoline motorcycle. [53,102] The smaller tank size also makes LPG potentially viable as a two-wheel motorcycle fuel, but the fact that LPG tanks are cylindrical for safety purposes continues to limit their application (since most available space on motorcycles is irregular in shape). Although, as was the case with CNG, most countries do not support an LPG infrastructure for transportation vehicles, a large number of LPG refueling facilities operate in support of non-transportation uses and it is likely that this infrastructure could be co-opted or expanded quite easily to support transportation refueling.

Emissions data for LPG motorcycles is relatively sparse, but available data show idle emissions to be reduced significantly for HC (about 30 percent), CO (about 35 percent), and NO_x (about 75 percent). [104] Under load, emissions estimates are much more variable. A study by Chinese researchers found HC and CO to decline between 0-70 and 75-99 percent respectively depending on specific speed and load conditions, while emissions of NO_x increased by 200-1000 percent or more, although the Chinese researchers felt that the NO_x performance of LPG could be substantially improved in an optimized application. [104] Conversely, Bajaj, a large Indian motorcycle manufacturer, has reported CO and NO_x emissions similar to those of gasoline motorcycles, with total HC increasing by 15-30 percent. [100] Other more recent data from India indicates that two-stroke LPG motorcycles reduce NMHC by about 10 percent and CO by about 40 percent, but increase NO_x emissions by about 120 percent -- while four-stroke LPG motorcycles reduce NMHC by about 50 percent and CO by about 60 percent, while increasing NO_x by about 25 percent. [36]

All three-wheelers have been powered by LPG in Bangkok for over 20 years, but this level of commitment may not be possible in all areas. For example, until very recently, LPG use as a transportation fuel was prohibited in India due to supply issues in conjunction with its extensive use as a cooking fuel. [53,109] While that prohibition has now been lifted to promote the clean air benefits of LPG use, it is indicative of the potential fuel supply issues that can arise in developing a transportation fueling strategy.

Ethanol is an alcohol that can be used to power internal combustion engines. It is typically produced by fermenting agricultural products such as corn and sugar cane, although more advanced processes allow ethanol to be produced from cellulosic biomass such as the leaves and stalks of plants (that are typically treated as waste products). If continuing reductions in the cost of cellulosic ethanol production are achieved, it is possible that future ethanol prices will be competitive with traditional petroleum-based fuels.

Ethanol is attractive as a fuel for several reasons. First, it contains a significant quantity of internal oxygen that allows for efficient combustion and reduced engine-out HC and CO emissions. Second, it is a renewable fuel for which the CO_2 emissions associated with its combustion are recycled through the respiration processes of the next generation of plants. As a result, it is possible that an efficient ethanol production industry could be GHG neutral. Although, this is not the case with the current ethanol industry due to production, transportation, and distribution energy requirements, significant efficiency improvements are possible. Finally, since ethanol can be produced from local biomass, it has the potential to significantly alter energy security issues. Significant cost and technology hurdles remain, but the potential benefits of ethanol are significant.

From an engine design standpoint, there is little difference between an ethanol engine and a gasoline engine. Modest fueling system upgrades are required to ensure that potential negative impacts on elastomers are avoided, permeation properties are addressed, and fuel delivery volumes are adequate -- but such upgrades are minor. In the automotive industry, there are a number of models available that can operate on gasoline, ethanol, or any mixture of the two.

There is little data available from an emissions standpoint for motorcycles, but it appears that, for 100 percent ethanol fuel (i.e., neat ethanol), full load HC and CO emissions could be reduced by 40-50 percent, while NO_x emissions decrease at lower engine speeds (3500 rpm and below) and increase at higher speeds. [105] Idle emissions of HC are similar to those of gasoline, while idle CO and NO_x are reduced by about 20 percent and 80 percent respectively. While additional research is necessary to fully evaluate the benefits of ethanol fueling for motorcycles, it appears that the potential for air quality benefits is significant. As with the automotive market, it is also possible to introduce ethanol as a blending component with gasoline. Such applications would tend to produce benefits that are proportional with blending volume.

Electric or hybrid electric motorcycles also have the potential to provide significant air quality benefits. For electric vehicles, the absolute potential depends largely on the emissions characteristics of the local power generating industry, but it is almost certain that the benefits would be significant. The benefits of hybrid electric motorcycles are less certain due to tradeoffs between electrical system weight and electric-only operating range, but preliminary research has demonstrated small (about 10 percent) reductions in CO and HC+NO_x in conjunction with a 15 percent reduction in fuel consumption. [106,107] While it is likely that these improvements, as well as the cost potential of electric and hybrid electric motorcycles will grow with advances in battery technology, it is not possible to foresee the timing or significance of the necessary advances.

Bajaj (India) currently estimates the cost of production electric motorcycles to be about twice that of an equivalent gasoline motorcycle. [100] Electric models under 50cc are currently available from Honda, Peugeot, and several manufacturers in Taiwan province of China -- and these have costs ranging from $1,500-$5,000. [101] This compares to 50cc gasoline scooter costs of $350-$700. All but the most expensive models use lead acid batteries with a 40-70 km (25-40 mi) range and a required recharge time of 5-8 hours.

Taiwan province of China currently has a requirement that two percent of motorcycles under 50cc must be zero emission vehicles. In conjunction with this requirement, the government offers a subsidy of about $650 for an electric motorcycle purchase to offset the difference in cost relative to a gasoline motorcycle. [99] By 2001, this had resulted in the purchase of approximately 25,000 electric motorcycles, but sales were well below mandated levels due to consumer dissatisfaction with operating range, recharge time, motorcycle weight, and cost. [101] The government continues to support research aimed at boosting performance to gasoline-equivalent levels for a cost that is on par with gasoline (after the subsidy). At this time, it is clear that electric motorcycles offer substantial environmental benefits, but that current economics are such that significant subsidies are required to promote widespread market introduction. This situation could change with continued electrical component developments, but the timing and significance of such development are unknown.

5.10 *Inspection and Maintenance*

Periodic emissions inspection and maintenance (I/M) requirements are almost assuredly a critical element of a comprehensive motorcycle emissions reduction strategy. Such programs have been widely implemented in the automotive sector and are responsible for ensuring that in-use emissions remain within specified limits. I/M programs involve measuring motorcycle emissions and requiring consumer repairs when those emissions exceed specified levels. For this reason, they are generally unpopular with, but begrudgingly accepted by, consumers. I/M programs can require significant investments in labor and equipment, as well as trained personnel to conduct the emissions tests, but investments can be recouped through inspection fees.

Prior to the implementation of an I/M program, it is essential that effective research be conducted to establish reliable emissions testing procedures and pass/fail criteria that are fair to both consumers and manufacturers. Typically, it is not possible to administer a certification-type emissions test in the field. As a result, 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. For example, I/M testing is often conducted at idle, while certification testing involves emissions testing at various engine speeds and loads (including idle). Therefore, it is usually not possible to compare I/M emissions measurements to certification test standards. Instead, separate I/M standards must be established that either correlate with the certification test standards (which is seldom possible in practice) *or* are capable of preferentially identifying vehicles that would either exceed certification standards or which have emissions equipment malperformances.

Establishing I/M standards is not a trivial matter. If in-use motorcycles are misidentified as not meeting I/M requirements, yet have no emissions malperformance, the consumer is asked to spend repair dollars to fix a problem that does not exist. Often, such repairs actually end up increasing emissions. It is critical that false failures (or errors of commission) be minimized to ensure both program integrity and consumer confidence. Conversely, identifying a motorcycle with malperforming emissions control equipment as meeting I/M requirements results in excess in-use emissions. Such false passes (or errors of omission) should be kept as low as practical to ensure maximum emission reductions. For obvious reasons there is usually a tradeoff between the two types of errors and sound design practice dictates accepting higher than desired errors of omission to minimize errors of commission.

It is not clear from the literature that adequate research has been conducted on the design of effective motorcycle I/M requirements. As described in Section 5, many countries do administer in-use idle test standards for CO and, in some cases, HC. However, as is also described in that section, it is not clear that those idle test standards are capable of detecting any but the most egregious emissions failures. And while there is nothing inherently wrong with an I/M program that detects only a fraction of high emitters, such a program is likely to be cost inefficient relative to a more aggressive design. Nevertheless, in the absence of specific in-use emissions research aimed at designing an effective I/M test, the use of certification idle emissions requirements probably represents a reasonable compromise between design and implementation requirements. It should be recognized, however, that as motorcycle engine controls become more sophisticated it will not be possible to evaluate onroad emissions performance through idle testing alone. Electronic control systems in combination with fuel injection technology will allow engine operation to be set independently for different operating modes and low idle emissions will not necessarily translate into low emissions under differing speed and load conditions. Loaded emissions testing or onboard diagnostic systems will be required.

Equally important to the success of an I/M program, is the presence of a trained repair industry capable of repairing malperforming motorcycles. Excess emissions identification without repair results in no air quality benefits. As motorcycle emissions control becomes more sophisticated, the associated repair industry will also have to evolve and adapt. Potential problems in this area have been identified in all types of I/M programs and will certainly affect motorcycle I/M program effectiveness as well.

Despite the potential pitfalls, Taiwan province of China has administered an effective motorcycle I/M program since 1996. [8] The program now tests over 4 million motorcycles annually, failing between 10 and 40 percent depending on age. A review of annual failure rates shows a decrease of about five percentage points in age-specific failure rates over time, so the program appears to have been successful in removing higher emitting vehicles from the road or inducing durable repairs. The program is certainly worthy of an in-depth review by any regulatory agency contemplating I/M program implementation and would serve as a good starting point for researchers evaluating actual motorcycle I/M program effectiveness. Other existing I/M programs, such as the periodic decentralized program in operation in India would be equally interesting targets of detailed review. While such a review is beyond the scope of this report, the results would also be of special interest in assessing the durability of the latest emissions control technology and evaluating consumer acceptance and feedback.

5.11 *Usage Restrictions*

In addition to technology-based measures such as those described in the preceding sections, control measures targeting behavioral changes can also effect significant emission reductions. For this report, measures targeting behavioral changes signify any control strategy that attempts to reduce motorcycle usage rates either through direct restrictions or indirect mechanisms such as usage charges. The level of reductions achieved through such measures depends on both the design and scope of the implemented control, as well as the alternative transportation option(s) utilized in place of displaced motorcycles. Both the absolute effectiveness and cost efficiency of such measures are quite sensitive to local conditions, precluding the development of generalized estimates. Moreover, the potential universe of design options is essentially unlimited, ranging from outright usage bans to an infinite number of incentive-type program designs intended to encourage alternative transportation modes. In recognition of the locality-specific nature and unlimited design potential of such measures, this report is limited to a brief review of basic control options -- leaving in-depth analysis to subsequent dedicated research.

The most obvious control program targeting a reduction in motorcycle emissions is an outright ban. Bans have been implemented in as many as 70 Chinese cities. [110] Other similar, but less severe mechanisms, such as restricting the issuance of new motorcycle licenses, have also been implemented in mainland China to limit growth in motorcycle usage. [111] Selective bans that target only higher emitting motorcycles have also been implemented, such as a ban of two-stroke motorcycles in Kathmandu. [112] It is not clear that any focused studies have been performed on the air quality benefits that have resulted from such measures, but there is no reason to suspect that they are not significant.

However, in considering such measures, it should be recognized that they are also likely to disproportionately affect the lower income segments of society, who depend on comparatively inexpensive motorcycles for their transportation needs. Even if alternative transportation options are available, including cleaner motorcycles in the case of selective bans, it is likely that only a small segment of the affected population would have the financial capacity to undertake a new vehicle purchase. Therefore, it is essential that the implications of such measures be thoroughly evaluated prior to implementation and that, if implemented, they be supported with a viable and affordable alternative transportation market, as well as a system of subsidies, credits, or low-income financing options to ensure that options are available to all affected segments of the population. As described in the preceding sections, there are a number of motorcycle technology options that provide for relatively short consumer payback periods and selective bans combined with subsidies and a financing package that offers a payment schedule consistent with the payback savings schedule could be viable.

Rather than outright bans, usage restrictions could take the form of financial disincentives to motorcycle use. For example, a system of usage fees that is biased toward higher fees for motorcycles or higher fees for high-emitting motorcycles, will force motorcycle operators to weigh the cost-benefit of motorcycle use against the usage fee. Depending on the size of the usage change, some fraction of operators will curtail usage. As discussed above, the cost-effectiveness of such measures is highly dependent on local conditions and available transportation alternatives, but in general behavioral-type controls tend to be less cost-effective than technology-based controls. At the same time, behavioral controls have the benefit of being able to affect emissions from all in-use motorcycles. As was the case with outright bans on motorcycle use, the impacts of behavioral controls are likely to disproportionately affect the lower income segments of society, who depend on comparatively inexpensive motorcycles for their transportation needs. This does not mean that such controls should not be considered, but rather that they should be fully evaluated in the context of local conditions -- including in comparison to the cost of other control options such as more stringent emission standards for new motorcycles -- and implemented only in cases where they are justified from both socioeconomic and environmental viewpoints.

6. Summary of Issues and Options

Emissions from motorcycles can be significant contributors to air quality problems, especially in urban areas where they can serve as a primary transportation option due to both their relative affordability and their ability to maneuver in heavy traffic. As a result, control of motorcycle emissions is becoming an important element of an effective air quality control plan. Due to a continuing evolution in the knowledge database related to motorcycle emissions, there are a number of issues that merit further research and potential regulatory attention. At the same time, there are a number of currently recognized control options that can be implemented to control motorcycle emissions. While these options will also undoubtedly continue to expand and evolve, there is ample evidence that adoption of currently available control options would lead to dramatic and cost-effective emission reductions, while simultaneously promoting the continued development of next-generation controls.

Among the areas where additional research or support activity would be advantageous to the effective development of motorcycle emissions control programs are:

- Continuing efforts to recruit and test existing in-use motorcycles. Such efforts facilitate a better understanding of the current emissions burden associated with motorcycles, as well as allow for comparison of in-use performance to certification emission standards. As indicated by the emission factors used in this report, it is strongly suspected that in-use emissions are substantially greater than certification emissions and while the reasons for this are somewhat obvious, it is important that reliable estimates be established.

- Further confirmation that existing particulate matter emissions measurement techniques are (or are not) adequate for two-stroke motorcycle particulate that is dominated by lubricating oil emissions. Some existing research implies that the standard dilution tunnel methods associated with automotive emissions testing are adequate -- indicating that while there may be measurement differences between analytical methods, it does not appear that the differences are due to liquid sample loss (condensation on sample lines, etc.). [21] Emission measurements across methods appear to vary linearly with particulate mass so that correction factors could be developed if appropriate. Although this is encouraging, other research has reached differing conclusions and it is important that any issues be resolved and a reliable test method established.

- Further work on globally harmonized emission standards and associated emission testing protocols. While most countries currently rely on EU test methods and standards, there are several that have developed and implemented alternative protocols. In addition, the current EU protocols are evolving. The WMTC effort to derive a global test cycle is an important first step, but it is critical that it adequately allow for effective emission testing in all major motorcycle markets. Given that only a handful of manufacturers control the bulk of global motorcycle production (either through direct manufacturing or partnerships with smaller local manufacturers), it seems reasonable to institute one global standard of acceptability. Ideally this standard will be technology neutral to allow manufacturers to implement least cost solutions, but this requires a robust protocol to ensure that differing technologies are equally effective throughout the full useful life of a motorcycle.

- Expansion of emissions testing protocols to include evaporative emissions. As exhaust emissions continue to decline, evaporative emissions will gain in importance. Cost-effective control options are available, so effective emission reduction standards can be established.

- Expansion of emissions testing protocols to include standards for HC, CO, NO_x, and PM. Current standards apply either to HC and CO or HC+NO_x and CO. While research related to a definitive PM test regimen remains to be conducted, existing motorcycle PM emissions testing programs have demonstrated emission rates that are substantially greater than gasoline-powered automobile emissions.

- Consideration of the need for GHG emission standards. Several of the control options investigated in this report have the potential to cost-effectively reduce overall GHG emissions from motorcycles.

- Expansion of emissions testing protocols to include real-world durability requirements. Although many countries have established durability criteria, those criteria are far less stringent than actual useful life would dictate. The net effect is that this allows nondurable emissions control strategies to meet certification requirements while providing only limited in-use emission reductions. It is critical that certification durability requirements be expanded to ensure that compliance strategies actually produce expected in-use benefits.

- Where necessary, expansion of efforts to ensure that fuel quality is adequate to allow emission control catalysts to function effectively in-use. In-use fuel should approach certification fuel quality to ensure effective in-use emissions control.

- Development of effective in-use enforcement protocols. Current certification programs rely too heavily on initial certifications and production line testing. To ensure adequate in-use durability, regulators should conduct random in-use testing programs and require manufacturer recall when emission control equipment is not performing in accordance with certification requirements. While such programs are resource intensive, it is possible for global cooperation and efficiencies if globally consistent certification requirements are established.

- Development of effective I/M test protocols and standards, with appropriate demonstration that those protocols and standards accurately detect high-emitting motorcycles without erroneously flagging normal emitters.

- Development of comprehensive educational and instructional programs for both citizens and repair personnel. An adequate understanding of emissions issues could help to reduce detrimental in-use behavior (such as the use of incorrect lubricating oil), and there is no question that controlling in-use emissions requires an informed and effective repair industry.

Although there are obviously a number of issues where existing research is important to the efficient evolution of motorcycle emissions control, there are currently available control options that are effective on both a mass emissions reduction and cost basis. Moreover, many of these control options would substantially improve emissions durability and contribute to a much improved in-use motorcycle fleet. Table 9 provides a summary of the cost and emission reduction effectiveness of various emission control options evaluated in this report, while Table 10 presents corresponding cost-effectiveness estimates. As indicated, there are a number of technology options that provide consumer savings and could therefore be used to set stringent global emission standards for the near term. Such an approach will ensure that effective emission reduction technology is introduced into the existing fleet while the various issues highlighted above are evaluated and resolved.

Table 9. Summary of Control Option Effectiveness and Cost (1)

Technology	Base Technology	Percent Reduction (2)					Cost (4)	Durability
		HC	CO	NO_x	PM	FC (3)		
2-Stroke Oxy Cat	Uncontrolled 2-Stroke	55 (5)	50	0	45	0	$34	30,000 km (18,600 mi)
2-Stroke Oxy Cat + SAI		80 (5)	75	0	70	0	$46	
2-Stroke DI		80 (5)	80	-50	50	40	$42	Full Useful Life 85,200 km (52,950 mi)
2-Stroke DI + Oxy Cat		90 (5)	90	-50	70	40	$76	
2-Stroke to 4-Stroke		95 (5)	30	-200	80	35	$36	
4-Stroke SAI	Uncontrolled 4-Stroke	20 (5)	40	0	(6)	0	$26	
4-Stroke SAI + Oxy Cat		80 (5)	90	0	(6)	0	$61	
4-Stroke TWC		55 (5)	50	25	(6)	0	$39	
4-Stroke FI		40 (5)	80	-50	(6)	20	$111	
4-Stroke FI + TWC		85 (5)	90	25	(6)	20	$166	
Permeation Controls	Uncontrolled	60 (7)	0	0	0	<1	$2	

(1) All data are applicable to a 100cc motorcycle. Effectiveness and cost may differ for larger motorcycles, but generally small motorcycles represent worst case control targets since emissions control technology costs represent a larger fractional impact on motorcycle retail price.

(2) Negative values represent percent increases.

(3) FC indicates fuel consumption.

(4) 2005 U.S. dollars.

(5) Impact is on exhaust HC only.

(6) Modest reductions are likely, at a minimum due to reductions in the soluble organic fraction of PM. However, since both total 4-stroke PM and the soluble organic fraction of 4-stroke PM are low, this report does not quantify 4-stroke PM reductions.

(7) Impact is on evaporative HC only.

Table 10. Summary of Control Option Cost-Effectiveness ($/metric ton)

Technology	Calculation Base	Calculation Basis (1)	Technology Cost Only			Technology Cost with Fuel Savings (2)			
			HC Only	HC+NO_x	HC+CO+ NO_x+PM	HC Only	HC+NO_x	HC+CO+ NO_x+PM	Payback Period
2-Stroke Oxy Cat	Uncontrolled 2-Stroke	Individual	$136	$136	$65	$136	$136	$65	Never
2-Stroke Oxy Cat + SAI		Combined	$124	$124	$59	$124	$124	$59	Never
2-Stroke DI		Individual	$39	$39	$18	-$1,074	-$1,077	-$493	0.5 yrs
2-Stroke DI + Oxy Cat		Combined	$63	$63	$29	-$916	-$917	-$422	0.8 yrs
2-Stroke DI + Oxy Cat		Marginal Cat	$678	$678	$320	$678	$678	$320	Never
2-Stroke to 4-Stroke		Individual	$29	$29	$21	-$792	-$797	-$571	0.5 yrs
4-Stroke SAI	Uncontrolled 4-Stroke	Individual	$1,522	$1,522	$59	$1,522	$1,522	$59	Never
4-Stroke SAI + Oxy Cat		Combined	$891	$891	$59	$891	$891	$59	Never
4-Stroke TWC		Individual	$832	$779	$67	$832	$779	$67	Never
4-Stroke FI		Individual	$3,266	$4,019	$127	-$8,180	-$10,067	-$317	4.1 yrs
4-Stroke FI + TWC		Combined	$2,289	$2,192	$160	-$3,097	-$2,967	-$217	6.5 yrs
4-Stroke FI + TWC		Marginal Cat	$1,420	$1,136	$353	$1,420	$1,136	$353	Never
Permeation Controls	Uncontrolled	Individual	$81	$81	$81	-$1,342	-$1,342	-$1,342	<1 yr
Lubricating Oil Controls	Requires locality-specific analysis								
Alternative Fuels									
I/M Testing									
Usage Restrictions									

(1) Individual indicates that only a single technology is included in the cost-effectiveness calculation. Combined indicates that the combined cost of multiple technologies are included in a single cost-effectiveness calculation. Marginal indicates that the marginal cost of the indicated single technology is evaluated relative to the cost of the other technologies included in the package.

(2) Negative cost-effectiveness estimates signify control options that result in fuel savings that exceed the cost of the control technology (i.e., the overall cost is negative and emissions benefits effectively accrue for free).

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Appendix

Derivation of Motorcycle Emission Factors
for
Estimating Emissions Significance
and
First-Cut Analysis of Emissions Control
Cost-Effectiveness

Reliable global emission factors for motorcycles are not readily available for several reasons. Such reasons include:

- Variations in the design of motorcycles and motorcycle engines across geographic regions,
- Variations in the design of motorcycles and motorcycle engines over time,
- Variations in the regulatory requirements for motorcycles both across geography and over time,
- The omission of cold start, aggressive driving behavior, and extended durability testing from most existing motorcycle certification emissions testing, and most importantly,
- A general lack of detailed emissions test data from in-use motorcycles, which can exhibit emissions substantially different that new motorcycles tested over emissions certification cycles.

Despite such limitations, there is a body of research on motorcycle emissions from which generalized emission rate estimates can be developed for first-cut purposes. Nevertheless, such emission rates should not be confused with the robust emissions database that will ultimately be required to support and evaluate both the benefits and cost effectiveness of aggressive motorcycle emissions control programs. Any regulatory program should be based on detailed local emissions test data that better reflect local climatic, regulatory, fleet characterization, and fleet activity conditions. The generalized emission rates should be considered as appropriate only for initial first-cut assessments, subject to appropriate and necessary local refinement. While they are useful for determining general significance estimates, they are not sufficiently robust to capture all important local nuances.

It is also important to recognize that although this report presents both emissions rate data and background information on existing and emerging emission standards, the presented emission rates should not be taken as an indication of the stringency (or attainability) of any specific emission standards. The primary focus of the report is to estimate *in use* motorcycle emissions. Thus, to the extent possible, the presented emission rates are indicative of the performance of motorcycles that have accumulated significant in service life under real world usage and maintenance conditions. The emission rates are derived through the aggregation of data presented in a number of technical references, but they generally reflect the results of emissions tests performed on a small number of in use Asian and European motorcycles. In contrast, the emission rates of new motorcycles subjected to emissions standard certification testing under certification usage and maintenance conditions will be considerably lower than those presented in this report. As a result, the presented emission rate data does not reflect the attainability of current or emerging emission standards.

For the purpose of developing emission rate estimates for this report, the following references were utilized.

1. The European Union's COPERT III Emission Factor Model [i].

The COPERT III emission factor model is used by the European Union to estimate emissions from motor vehicles, including motorcycles. For purposes of this report, the COPERT III model was executed for an average travel speed of 32 km/hr (20 mph), generally consistent with both driving conditions in urban areas and the average speed of the ECE R40 driving cycle used for motorcycle emissions certification in many countries. Table A1 presents the generated emission rates for mopeds (less than 50 cc engine size) and motorcycles.

COPERT III and the U.S. MOBILE6.2 emission factor model, reflect the only generalized source of evaporative emissions estimates for motorcycles. However, since the U.S. motorcycle fleet is dominated by large fuel injected motorcycles that are required to demonstrate compliance with an existing evaporative emissions standard, MOBILE6.2 emission rates are unlikely to be representative of the evaporative emission rates of the smaller carbureted motorcycles that dominate the global motorcycle fleet. Conversely, COPERT III provides emission rates separately for carbureted and fuel injected motorcycles as well as for various levels of emissions control. For this reason, the COPERT III model was used as the sole source of evaporative emissions rate data for this report.

COPERT III evaporative emissions data is expressed in grams per day for diurnal emissions, grams per event for soak emissions, and grams per kilometer for running loss emissions. These data were converted to equivalent grams per kilometer data (as necessary) using the methodology described in Section 5.7 in the body of the main report and summed to derive the aggregate evaporative emission rates presented in Table A1.

Table A1. COPERT III Motorcycle Emission Rate Data (g/km)

Size/Type	Technology	Exh VOC	Evap VOC	NO_x	CO	CO_2	PM	N_2O	CH_4
<50 cm³	Conventional	9.00	0.64	0.03	15.00	26.5		0.001	0.22
<50 cm³	97/24/EC-I	4.05	0.64	0.03	7.50	54.0		0.001	0.10
<50 cm³	97/24/EC-II	1.98	0.64	0.01	1.50	70.0		0.001	0.05
2-stroke >50 cm³	Conventional	10.60	1.27	0.03	22.58	30.1		0.002	0.15
2-stroke >50 cm³	97/24/EC	5.98	1.27	0.02	9.53	38.7		0.002	0.15
4-stroke <250 cm³	Conventional	2.14	1.27	0.11	26.62	37.2		0.002	0.20
4-stroke <250 cm³	97/24/EC	0.93	1.27	0.17	7.92	82.7		0.002	0.20
4-stroke 250-750 cm³	Conventional	1.80	1.27	0.11	23.79	69.1		0.002	0.20
4-stroke 250-750 cm³	97/24/EC	0.93	1.27	0.17	7.92	82.7		0.002	0.20
4-stroke >750 cm³	Conventional	3.31	1.27	0.13	17.32	106.4		0.002	0.20
4-stroke >750 cm³	97/24/EC	0.93	1.27	0.17	7.92	82.7		0.002	0.20

2. SAE Technical Paper 2005-32-0114 [ii].

In SAE 2005-32-0114, McDonald et al. present exhaust emissions test data for three in-use motorcycles from Thailand. Motorcycle A is a single cylinder, crankcase-scavenged, 100cc, 2001 model year, two-stroke, air cooled, six-speed manual transmission model. Motorcycle B is a single cylinder, crankcase-scavenged, 148cc, 1995 model year, two-stroke, water cooled, six-speed manual transmission model. Motorcycle C is a single cylinder, crankcase-scavenged, 123cc, 1993 model year, two-stroke, air cooled, five-speed manual transmission model. The test data from SAE 2005-32-0114 are presented in Table A2.

Motorcycles A and B were tested over both the U.S. motorcycle federal test procedure (MC FTP) and the U.S. New York City (NYCC) driving cycles. Motorcycle C experienced mechanical difficulties during the MC FTP cycle testing and was, therefore, not subjected to replicate MC FTP testing or any testing over the NYCC. For this reason, only the data for motorcycles A and B were used to develop the generalized emission factors used in this report.

The MC FTP cycle is a transient driving cycle with a maximum speed of about 60 km/hr and an average speed that is generally higher than allowed by travel conditions in most urban areas. The NYCC is also a transient driving cycle, but with lower maximum and average speeds reflective of conditions in the highly congested areas of downtown New York City.

Table A2. Motorcycle Emission Rate Data from SAE 2005-32-0114 (g/km)

Motorcycle ID	Test Cycle	Exh VOC	Evap VOC	NO_x	CO	CO_2	PM	N_2O	CH_4
A	MC FTP	19		0.12	22	29	0.6		
B	MC FTP	12		0.02	13	39	0.3		
C	MC FTP	13		0.14	7	46	0.24		
A	NYCC	27		0.07	21	56	0.6		
B	NYCC	24		0.05	24	59	0.4		
C	NYCC								
Average	MC FTP	14.67		0.09	14.00	38.0	0.38		
Average	NYCC	25.50		0.06	22.50	57.5	0.50		
Average	Average	20.08		0.07	18.25	47.8	0.44		
A&B Average	MC FTP	15.50		0.07	17.50	34.0	0.45		
A&B Average	NYCC	25.50		0.06	22.50	57.5	0.50		
A&B Average	Average	20.50		0.07	20.00	45.8	0.48		

3. Supat/World Bank Data [iii].

Supat Wangwongwatana, Director of the Air Quality and Noise Management Division of the Thailand Pollution Control Department provided a spreadsheet summary of data for a series of 13 emissions tests conducted on three two-stroke motorcycles. Detailed specifications for the motorcycles or information on the test regimen were not provided, but it appears that the motorcycles were tested over the U.S. motorcycle federal test procedure (MC FTP) as the provided data are presented individually for three testing phases with aggregate weighting factors consistent with those used for the three phase MC FTP cycle. The aggregate cycle data are summarized in Table A3.

Table A3. Motorcycle Emission Rate Data from Supat/World Bank Data.xls (g/km)

Motorcycle ID	Test ID	Exh VOC	Evap VOC	NO_x	CO	CO_2	PM	N_2O	CH_4
SKA220979	2002-020-3002	20.39		0.15	22.63	28.8	0.61		
SKA220979	2002-020-3003	17.57		0.15	20.40	28.4	0.50		
SKA220979	2002-020-3004	17.73		0.07	22.06	29.8	0.67		
SKA220979	2002-020-3005	26.54		0.07	20.22	55.3	0.59		
KAXA54786	2002-025-5002	20.74		0.13	21.74	72.0	0.92		
KAXA54786	2002-025-5003	12.05		0.03	11.00	41.9	0.41		
KAXA54786	2002-025-5004	22.67		0.00	20.27	55.3	0.04		
KAXA54786	2002-025-5006	11.41		0.02	13.55	38.8	0.36		
KAXA54786	2002-025-5007	10.87		0.03	14.12	37.6	0.21		
KAXA54786	2002-025-5008	23.48		0.05	24.01	58.6	0.47		
KAXA54786	2002-025-5009	11.80		0.02	12.89	36.2	0.14		
HNX0014787	2002-025-4001	12.85		0.13	8.88	43.2	0.22		
HNX0014787	2002-025-4002	12.89		0.15	6.57	49.2	0.25		
SKA220979	Average	20.56		0.11	21.33	35.6	0.59		
KAXA54786	Average	16.15		0.04	16.80	48.6	0.36		
HNX0014787	Average	12.87		0.14	7.72	46.2	0.24		
Three MC Average	Average	16.52		0.10	15.28	43.5	0.40		

4. SAE Technical Paper 982711 [iv].

In SAE 982711, Bovonsombat et al. present exhaust emissions test data for three new 150cc two-stroke motorcycles. The motorcycles were tested periodically over the ECE R40 driving cycle (every 1,000 km through 5,000 km and every 5,000 km thereafter) through a total distance accumulation of 20,000 km. Since the focus of the technical paper was to investigate the potential impact of an oxidation catalyst retrofits on two-stroke motorcycle emissions, all testing was performed both with and without an oxidation catalyst. The resulting test data are summarized in Table A4. Only the "without catalyst" data were used in the estimation of a generalized emission rate.

5. SAE Technical Paper 2002-01-1681 [v].

In SAE 2002-01-1681, Kojima et al. present exhaust emissions test data for three Bajaj two-stroke three-wheelers, a 1995 model (vehicle 1), a 1996 model (vehicle 2), and a 1993 model (vehicle 3). Tests were conducted over the Indian Driving Cycle (IDC) and investigated emissions sensitivity to a number of parameters including:

- Test fuel, namely a blend of 80 RON (research octane number) gasolines from five filling stations in Dhaka and an 87 RON "reference" gasoline purchased in India. Gasoline sold in Dhaka is often mixed with kerosene.

- Lubricant type, namely straight mineral oil (SMO) as commonly used in Dhaka, JASO-FB 2T oil (2T), and JASO FC "low smoke" oil (JFC).

- Lubricant quantity, namely a 3% blending rate as recommended by Bajaj and an 8% blending rate commonly practiced in Dhaka.

- The state of maintenance, represented as "as received" (i.e., before maintenance) and after maintenance.

- The presence of an oxidation catalyst.

The resulting test data are summarized in Table A5.

6. SAE Technical Paper 2000-01-0862 [vi].

In SAE 2000-01-0862, Prati et al. present exhaust emissions test data for 16 in-use two-stroke mopeds and 6 in-use 125cc two-stroke motorcycles. All used carbureted fueling systems without emissions aftertreatment, and were reported to be about two years old. The mopeds were tested over the ECE R47 cycle and the motorcycles were tested over the ECE R40 cycle. The reported test data are summarized in Table A6. Only the 125cc motorcycle data were used in the estimation of a generalized emission rate

7. SAE Technical Paper 2003-01-1897 [vii].

In SAE 2003-01-1897, Etheridge et al. present exhaust emissions test data for 12 motorcycles reflecting a range of engine and emissions aftertreatment designs. Table A7a presents descriptive data for the 12 motorcycles. The motorcycles were tested over three driving cycles,

Table A4. Motorcycle Emission Rate Data from SAE 982711 (g/km)

Motorcycle ID	Odometer at Testing (km)	Without Catalyst			With Catalyst		
		Exh VOC	CO	CO_2	Exh VOC	CO	CO_2
MC 1	0	9.68	8.37	44.67	3.17	9.42	67.22
	1,000	12.07	8.00	46.82	5.22	12.85	70.50
	2,000	11.75	10.27	45.49	3.96	11.26	72.14
	3,000	11.06	4.87	47.78	3.16	5.80	73.99
	4,000	9.09	4.42	46.29	4.20	5.87	66.78
	5,000	9.66	9.27	45.53	4.38	11.00	65.61
	6,000	10.29	8.08	47.43	5.79	9.40	68.58
	8,000	10.67	8.45	44.36	10.11	9.00	42.38
	10,000	10.13	7.97	43.18	9.72	10.90	40.10
	15,000	8.13	3.22	42.32	5.02	4.74	66.17
	20,000	9.23	3.57	42.94	10.16	4.64	42.49
MC 1	Every 5,000 km Average	9.68	7.30	44.08	6.86	8.99	53.86
	Overall Average	10.16	6.95	45.16	5.90	8.63	61.45
MC 2	0	10.25	6.26	43.86	3.35	6.39	68.16
	1,000	10.38	7.15	44.04	4.54	8.32	67.06
	2,000	9.93	7.25	45.80	5.32	2.71	67.38
	3,000	10.32	7.39	49.32	3.69	8.37	72.27
	4,000	10.19	7.54	48.99	4.84	7.93	71.58
	5,000	10.08	8.48	43.74	5.00	8.96	67.09
	6,000	10.30	6.73	44.78	3.99	9.09	67.31
	8,000	10.05	8.05	44.14	5.58	9.05	64.71
	10,000	10.14	7.59	42.33	8.26	7.98	56.96
	15,000	8.27	2.56	35.77	9.22	3.12	38.77
	20,000	9.72	4.26	40.82	8.12	3.73	41.27
MC 2	Every 5,000 km Average	10.05	6.65	42.69	6.18	6.77	58.37
	Overall Average	9.97	6.66	43.96	5.63	6.88	62.05
MC 3	0	10.16	8.18	42.96	3.33	7.76	66.24
	1,000	10.61	7.92	40.32	5.04	8.34	63.15
	2,000	10.76	7.13	43.45	4.51	8.76	66.40
	3,000	9.48	8.18	42.34	4.06	9.09	63.31
	4,000	9.91	8.53	43.41	4.73	10.50	67.00
	5,000	9.83	7.71	42.05	4.58	9.63	64.31
	6,000	9.41	6.93	45.03	5.56	8.21	67.55
	8,000	10.24	7.36	42.13	5.26	8.44	64.00
	10,000	10.35	7.61	43.29	18.89	23.60	34.51
	15,000	9.43	5.41	45.25	9.53	5.80	44.02
	20,000	11.97	12.50	45.28	10.67	11.90	41.64
MC 3	Every 5,000 km Average	10.58	9.00	43.40	9.37	13.22	51.68
	Overall Average	10.20	7.95	43.23	6.92	10.18	58.38
Overall Average	Every 5,000 km Average	10.10	7.65	43.39	7.47	9.66	54.63
	Overall Average	10.11	7.19	44.12	6.15	8.56	60.63

Table A5. Motorcycle Emission Rate Data from SAE 2002-01-1681 (g/km)

MC Num	Fuel	Oil	Repair Status	Emission Control	Exh VOC	NO_x	CO	CO_2	PM
1	Dhaka	SMO 3%	Before	None	8	0.07	8.1	46	0.35
	Ref	2T 3%	Before	None	8.8	0.09	10	50	0.21
	Dhaka	2T 8%	Before	None	7.4	0.08	5	44	0.38
	Ref	SMO 8%	Before	None	9.2	0.08	7.6	50	0.6
MC 1 Average			Before	None	8.35	0.08	7.68	47.50	0.39
1	Dhaka	JFC 3%	After	None	7.8	0.11	3.6	50	0.33
	Ref	2T 8%	After	None	7.8	0.12	3.2	52	0.31
	Dhaka	SMO 8%	After	None	8.3	0.09	1.6	53	0.76
	Ref	JFC 8%	After	None	9	0.21	3.5	56	0.53
	Ref	SMO 3%	After	None	9.2	0.08	5.4	59	0.41
MC 1 Average			After	None	8.42	0.12	3.46	54.00	0.47
2	Dhaka	2T 3%	Before	None	7.3	0.27	7.4	50	0.27
	Ref	JFC 3%	Before	None	10	0.27	10	49	0.2
	Dhaka	JFC 8%	Before	None	8.2	0.16	6.8	45	0.56
	Ref	2T 8%	Before	None	8.2	0.19	6.9	48	0.4
	Ref	SMO 8%	Before	None	9.1	0.15	6.3	51	0.85
	Ref	2T 3%	Before	None	9	0.15	11	48	0.32
MC 2 Average			Before	None	8.63	0.20	8.07	48.50	0.43
2	Dhaka	2T 3%	After	None	7.2	0.06	11	53	0.24
	Ref	JFC 3%	After	None	10	0.05	16	49	0.19
	Dhaka	JFC 8%	After	None	7.2	0.04	12	49	0.29
	Ref	2T 8%	After	None	8	0.04	15	48	0.24
	Ref	SMO 8%	After	None	7.8	0.04	13	47	0.63
	Ref	2T 3%	After	None	9.4	0.04	18	44	0.16
	Dhaka	2T 8%	After	None	7.1	0.03	13	48	0.45
	Dhaka	SMO 3%	After	None	8	0.03	14	47	0.45
	Dhaka	JFC 3%	After	None	7.6	0.03	14	46	0.19
	Dhaka	SMO 3%	After	None	7	0.04	14	44	0.34
	Dhaka	SMO 3%	After	Catalyst	3.6	0.02	11	65	0.26
	Dhaka	SMO 8%	After	Catalyst	2.9	0.01	8.1	69	0.24
	Dhaka	SMO 3%	After	Catalyst	3.6	0.01	13	67	0.3
	Dhaka	SMO 3%	After	None	6.7	0.02	15	44	0.3
MC 2 Average			After	None	7.82	0.04	14.09	47.18	0.32
			After	Catalyst	3.37	0.01	10.70	67.00	0.27
3	Dhaka	JFC 3%	Before	None	23	0.07	25	43	1.15
	Dhaka	JFC 3%	Before	None	25	0.05	25	37	1.06
	Dhaka	SMO 8%	Before	None	23	0.03	25	43	2.67
	Ref	SMO 3%	Before	None	28	0.11	23	43	1.51
	Ref	JFC 8%	Before	None	25	0.12	22	42	1.67
	Ref	JFC 8%	Before	None	27	0.1	25	45	1.7
	Dhaka	SMO 8%	Before	None	22	0.08	25	44	2.5
MC 3 Average			Before	None	24.71	0.08	24.29	42.43	1.75

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Table A5. Motorcycle Emission Rate Data from SAE 2002-01-1681 (g/km)

MC Num	Fuel	Oil	Repair Status	Emission Control	Exh VOC	NO_x	CO	CO_2	PM
3	Ref	JFC 3%	After	None	18	0.1	17	48	0.79
	Dhaka	JFC 8%	After	None	14	0.06	16	49	1.17
	Dhaka	JFC 8%	After	None	15	0.05	16	54	1.3
	Dhaka	2T 3%	After	None	16	0.09	17	51	0.88
	Ref	2T 8%	After	None	18	0.1	16	50	1.02
	Ref	SMO 8%	After	None	17	0.12	15	52	1.39
	Ref	JFC 3%	After	None	19.9	0.14	15	51	0.74
MC 3 Average			After	None	16.84	0.09	16.00	50.71	1.04
Three MC Average			Before	None	13.90	0.12	13.34	46.14	0.86
			After	None	11.03	0.08	11.18	50.63	0.61

Table A6. Motorcycle Emission Rate Data from SAE 2000-01-0862 (g/km)

Test Vehicles	Test Cycle	Exh VOC	Evap VOC	NO_x	CO	CO_2	PM	N_2O	CH_4
16 In-Use Mopeds	ECE R47	9.21		0.03	17.60	30.52			
6 In-Use 125cc MCs	ECE R40	19.10		0.03	23.20	38.11			

Table A7a. Motorcycle Descriptive Data from SAE 2003-01-1897

Motorcycle Number	Engine Size (cc)	2-Stroke or 4-Stroke	Number of Cylinders	Fuel System Type	Secondary Air Injection?	Catalyst?
1	180	4S	1	Carbureted	No	No
2	150	4S	1	Carbureted	Yes	No
3	950	4S	3	EFI	No	Yes
4	800	4S	2	Carbureted	Yes	Yes
5	650	4S	1	EFI	No	Yes
6	500	4S	2	Carbureted	No	No
7	400	4S	1	Carbureted	Yes	No
8	50	2S	1	EFI	No	No
9	1300	4S	4	EFI	No	Yes
10	250	4S	2	Carbureted	Yes	No
11	50	2S	1	Carbureted	No	Yes
12	650	4S	2	Carbureted	Yes	No

the ECE R40 cycle, the ECE R40 cycle in combination with the EU EUDC (Extra Urban Driving Cycle), and version 7 of the World Motorcycle Test Cycle (WMTC). The reported test data are summarized in Table A7b. Only data for test motorcycle #1 (as described in Table A7a) were used in the estimation of a generalized emission rate as the other motorcycle designs were not considered to be representative of the majority of vehicles comprising the global motorcycle population.

Table A7b. Motorcycle Emission Rate Data from SAE 2003-01-1897

MC Num	Exh VOC	CO	NO_x	CO_2	MC Num	Exh VOC	CO	NO_x	CO_2
ECE R40 Test Cycle					*WMTC Version 7 Test Cycle*				
1	0.75	4.55	0.14	74.80	1	0.69	10.83	0.18	57.50
2	3.13	5.90	0.21	57.60	2	1.94	7.08	0.47	47.40
3	0.86	6.52	0.07	166.20	3	0.76	6.88	0.60	106.60
4	0.22	4.68	0.04	140.70	4	0.42	13.31	0.23	104.70
5	0.92	20.05	0.04	95.50	5				
6	1.56	20.32	0.10	85.70	6	0.88	20.73	0.28	76.80
7	1.83	5.48	0.12	81.40	7	1.07	11.57	0.46	66.90
8	0.92	0.44	0.41	37.90	8	0.90	0.71	0.40	39.60
9	0.30	1.84	0.03	192.30	9	0.40	2.72	0.20	125.90
10	0.75	8.76	0.16	62.60	10	0.67	22.66	0.31	53.00
11	3.37	3.24	0.04	38.90	11	4.90	11.67	0.05	37.70
12	0.63	7.95	0.19	125.30	12	0.65	19.65	0.43	88.50
ECE R40+EUDC Test Cycle					*Three Cycle Average Emission Rates*				
1	0.78	10.99	0.26	64.70	1	0.74	8.79	0.19	65.67
2	1.43	6.85	0.45	61.10	2	2.17	6.61	0.38	55.37
3	0.73	6.59	0.28	123.50	3	0.78	6.66	0.32	132.10
4	0.38	10.64	0.11	109.90	4	0.34	9.54	0.13	118.43
5					5				
6	0.99	15.13	0.20	77.40	6	1.14	18.73	0.19	79.97
7	1.03	7.04	0.27	67.10	7	1.31	8.03	0.28	71.80
8	0.84	0.67	0.56	40.70	8	0.89	0.61	0.46	39.40
9	0.44	2.55	0.23	137.60	9	0.38	2.37	0.15	151.93
10	0.64	12.94	0.24	54.70	10	0.69	14.79	0.24	56.77
11	3.76	4.05	0.03	40.50	11	4.01	6.32	0.04	39.03
12	0.82	11.70	0.35	97.80	12	0.70	13.10	0.32	103.87

8. Shah and Harshadeep Data [viii].

In 2001, Shah and Harshadeep of the World Bank presented motorcycle emission rate data at the Regional Workshop on Reduction of Emissions from 2-3 Wheelers in Hanoi, Vietnam (held from September 5-7, 2001). In their presentation entitled "Urban Pollution from Two Stroke Engine Vehicles in Asia: Technical and Policy Options," they presented the data summarized in Table A8. Unfortunately, the presentation includes no additional information on the derivation of these data.

Table A8. Motorcycle Emission Rate Data from Shah and Harshadeep (g/km)

Vehicle Type	Engine Type	Exh VOC	Evap VOC	NO_x	CO	CO_2	PM	N_2O	CH_4
Three Wheel MCs	2-Stroke	7.5					0.5		
Two Wheel MCs	2-Stroke	5					0.5		
Motorcycles	4-Stroke	1					0.1		

Estimation of Generalized Emission Rates.

Using the data sources presented above, generalized emission rates were developed for two-stroke and four-stroke motorcycles. Since the various data sources present emission rates for test fleets of differing sizes, an attempt was made to provide equal weighting to each data source by using only a single summary emission rate for each in the development of the generalized emission rate estimates. For example, if one data source presented emission rates for three motorcycles, the individual emission rates were averaged and the average emission rate was then treated as a single data point in the development of the generalized emission rates. In this way, references with smaller test fleets are treated with the same weight as references with larger test fleets.

The following data were used for two-stroke motorcycles:

- the Supat [iii] three motorcycle overall average emission rates,
- the SAE 2000-01-0862 [vi] emission rates for motorcycles,
- the SAE 2005-32-0114 [ii] average emission rates for motorcycles A and B,
- the COPERT III [i] emission rates for "conventional technology" two-strokes, and
- the SAE 982711 [iv] three motorcycle 5,000 km average emission rates.

The Shah and Harshadeep [viii] data for two-strokes were not used due to a limited focus (only VOC and PM rates were reported) and a lack of documentation for a VOC emission rate that differs significantly from that of the other references. The SAE 2003-01-1897 [vii] data for two-strokes were not used as only data for mopeds, one fuel injected and one with a catalyst, were reported and these are not considered to be generally reflective of the two-stroke motorcycles prevalent globally. The SAE 2002-01-1681 [v] data were not used as they were restricted to three-wheel vehicles and provided no significant additional data to that already available for two-wheel motorcycles. However, it should be noted that the data from SAE 2002-01-1681 [v] are generally consistent with the two-wheel motorcycle data.

Emission rate data for four-stroke motorcycles is much more sparsely reported due to the two-stroke focus of most emissions concerns. In fact, four-stroke emissions data were only reported in:

- SAE 2003-01-1897 [vii],
- the COPERT III [i], and
- Shah and Harshadeep [viii].

To develop the generalized emission rate for four-stroke motorcycles, data for test motorcycle #1 of SAE 2003-01-1897 [vii] was combined with average emission rate data for conventional and "97/24/EC" technology vehicles from COPERT III [i] and the four-stroke data reported by Shah and Harshadeep [viii]. While these latter data were not used for two-stroke emission rate development due to documentation concerns, they represent the only source that reports four-stroke PM data and the reported VOC emission rate for four-strokes does not exhibit the variation from the other VOC data sources that was observed with the two-stroke data.

To develop the generalized emission rates, the data from the individual sources are arithmetically averaged and then rounded (to avoid exhibiting undue precision). The maximum CO_2 emission rate (i.e., the CO_2 emission rate that would occur if all carbon emitted as VOC and CO were emitted as CO_2) is initially recalculated (based on mass balance constraints) from the rounded VOC, CO, and CO_2 emission rates and then rounded.

The only exception to this process is for the generalized CO_2 emission rate for four-stroke engines, which is adjusted to be consistent with the generalized CO_2 emission rate for two-stroke vehicles. This adjustment is necessary to ensure consistency between the two-stroke and four-stroke emission rates, given that there may be significant differences in the characteristics of the underlying motorcycle test fleets (other than the obvious two-stroke versus four-stroke differences). For example, four-stroke technology has historically been used on larger motorcycles (although the technology is now spreading across the entire motorcycle size range). This is especially true in the EU (and the U.S.) and is therefore likely to have influenced the database used to develop the emission rates represented in the COPERT III model, a prime resource for the generalized four-stroke emission rates. To correct for this influence, the generalized assumption that basic two-stroke engine technology sacrifices about 33 of its intake charge to exhaust scavenging was used to adjust the basic four-stroke CO_2 emission rate to be consistent with that of the derived two-stroke emission rate.[a] [ix,x,xi] This resulted in an

[a] It is perhaps also important to note that the generalized two-stroke CO_2 emission rate that is used as the basis for the estimation of the basic four-stroke CO_2 emission rate, when converted into equivalent fuel economy is almost exactly equal to the two-stroke fuel economy reported in reference xi (19.9 km/liter versus 20 km/liter), which serves as a primary basis for the generalized four-stroke to two-stroke CO_2 emission relationship. Thus, it is expected that this approach is quite consistent with existing research data.

approximate 15 percent reduction in the generalized CO_2 emission rate for four-stroke motorcycles (equal to an approximate 18 percent increase in the generalized fuel economy of such motorcycles).

It is important to note that advanced two-stroke designs have significantly reduced the quantity of fuel lost to exhaust scavenging. This, of course, can result in significant differences between the emissions characteristics of advanced two-stroke engines and the basic two-stroke engine designs assumed in this report, but such basic engine designs continue to dominate the global motorcycle fleet and the performance of the global fleet is the primary focus of this report. It is nevertheless important for readers to recognize that advanced two-stroke designs may continue to be marketed with significantly improved emissions characteristics.

Table A9 summarizes both the reference emission rates and the process used to estimate the generalized emission rates. Once again, it is important to recognize that significant variations in the emission rates of specific motorcycles can be expected due to differences in design technology, vehicle maintenance practices, and usage characteristics. Moreover, the tabulated rates are intended to be representative of in-use emission rates, not new vehicle certification emission rates. The former are generally much greater than the latter due to in service behavior and the fact that new engine certification testing is performed under "idealized" conditions.

Table A9. Aggregate Motorcycle Emission Rates Used for Impact Estimation (g/km)

2-Stroke Motorcycles	Exh VOC	Evap VOC	Total VOC	CO	NO_x	PM	CO_2	Max CO_2	N_2O	CH_4
Supat/World Bank	16.5			15.3	0.10	0.4	43.5	120.0		
SAE 2000-01-0862	19.1			23.2	0.03		38.1	135.2		
SAE 2005-32-0114	20.5			20.0	0.07	0.5	45.8	142.3		
COPERT III	10.6	1.27		22.6	0.03		30.1	99.3	0.002	0.15
SAE 982711	10.1			7.6			43.4	87.5		
Average	15.4	1.27		17.7	0.06	0.4	40.2	116.9	0.002	0.15
Rounded, excl. Max CO_2	15.5	1.25	16.75	18	0.05	0.5	40	117.5	0.002	0.15
Fully Rounded	**15.5**	**1.25**	**16.75**	**18**	**0.05**	**0.5**	**40**	**118**	**0.002**	**0.15**

4-Stroke Motorcycles	Exh VOC	Evap VOC	Total VOC	CO	NO_x	PM	CO_2	Max CO_2	N_2O	CH_4
COPERT III	1.5	1.27		16.6	0.14		67.9	98.5	0.002	0.20
SAE 2003-01-1897	0.7			8.8	0.19		65.7	81.8		
Shah and Harshadeep	1.0					0.1				
Average	1.1	1.27		12.7	0.17	0.1	66.8	90.1	0.002	0.20
CO_2 Adjusted Average	1.1	1.27		12.7	0.17	0.1	54.6	77.9	0.002	0.20
Rounded, excl. Max CO_2	1.0	1.25	2.25	12.5	0.15	0.1	55	77.8	0.002	0.20
Fully Rounded	**1.0**	**1.25**	**2.25**	**12.5**	**0.15**	**0.1**	**55**	**77**	**0.002**	**0.20**

While the use of the tabulated emission rates is expected to provide for a reasonable estimation of global emissions characteristics, the emission rates should not be confused with the robust emissions database that will ultimately be required to support and evaluate the benefits and cost effectiveness of aggressive motorcycle emissions control programs. Such programs should be based on detailed local emissions test data that better reflect local climatic, regulatory, fleet characterization, and fleet activity conditions.

References for Appendix.

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