# Emission Control of Two-and Three-Wheel Vehicles

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## EXECUTIVE SUMMARY

Two-wheel and three-wheel (hereafter referred to as “two-wheel”) vehicle production has been expanding rapidly over the past several years, especially in the urbanized areas of Asia. The world two-wheel vehicle fleet has been growing at a rate of about 7 million units per year due to sales of about 20 million per year less those scrapped. New vehicle sales are expected to continue to rise.

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

To address the serious pollution problems posed by two-wheel vehicles, a growing number of countries worldwide have implemented, or are in the process of implementing, motor vehicle pollution control programs aimed at substantially reducing harmful emissions from spark ignited two-wheel vehicles. Taiwan, for example, has implemented three phases of emission standards since 1992 with increasing strictness. The first two phases targeted primarily emissions from 2-stroke engines. The third phase targets emissions from all two-wheel vehicles including 2-stroke and 4-stroke engines. Catalytic exhaust controls have been developed as a result of these regulations and are generally recognized to be the most cost-effective way to meet stringent emission standards. Thus, fully developed and proven emission control systems are readily available. Other countries are now adopting similar regulations and standards.

Catalytic exhaust control technology uses a precious metal catalyst to chemically convert the harmful components of the vehicle’s exhaust stream to harmless gases. The catalytic material causes the desired chemical reactions to occur without being consumed. For 2-stroke engines, the catalytic control system installed in the exhaust stream promotes the reaction of hydrocarbons (HC) and carbon monoxide (CO) with oxygen to form carbon dioxide and water, and destroys white smoke (particulate matter) as well. Catalyst technology applied to two-wheel vehicles are capable of reducing HC and CO emissions in the range of 60 to 80 percent respectively and particulate matter greater than 50 percent. The 4-stroke engine catalyst technology can be designed similarly or as a three-way conversion catalyst (TWC) to bring about the simultaneous chemical reduction of oxides of nitrogen (NOx) as well by reaction with CO to form nitrogen. However, NOx emissions from two-wheel vehicles are relatively small compared to other mobile sources.

Catalyst technology offers a proven and cost-effective approach for reducing HC and CO emissions from two-wheel vehicles, while maintaining the desired engine performance characteristics. An excellent example of the application of catalyst technology to two-wheel vehicles is Taiwan where, since 1992, over 4.6 million catalyst-equipped 2-stroke motor vehicles have been manufactured to meet rigorous emissions requirements. As a result of the proven success of catalyst technology, manufacturers in Taiwan now use it for both 2-stroke and 4-stroke vehicles to meet the stringent emission standards that became effective for all two-wheel vehicles produced after January 1, 1998.

The critical elements of a successful pollution control program for two-wheel vehicles have emerged from the growing experience gained by countries which have implemented effective programs. These elements include:

1. Establish firm regulations with specific emission control performance requirements or “standards” and a duration period during which the vehicle must meet these standards (e.g., 15,000 km);

2. Establish a specific test procedure representative of actual two-wheel vehicle driving conditions in actual operation under which two-wheel manufacturers must demonstrate compliance with the emission standards;

3. Require a certification compliance process to demonstrate that the vehicle will meet the applicable standards for the required duration and/or time period;

4. Implement a vehicle inspection program to insure that vehicle emissions in use are meeting the required standards; and

5. Develop a public education program to gain public support and to assure public understanding of the health benefits of low polluting two-wheel vehicles, the importance of good vehicle maintenance, and of using proper fuels and lubricating oils.

## 1.0 INTRODUCTION & BACKGROUND

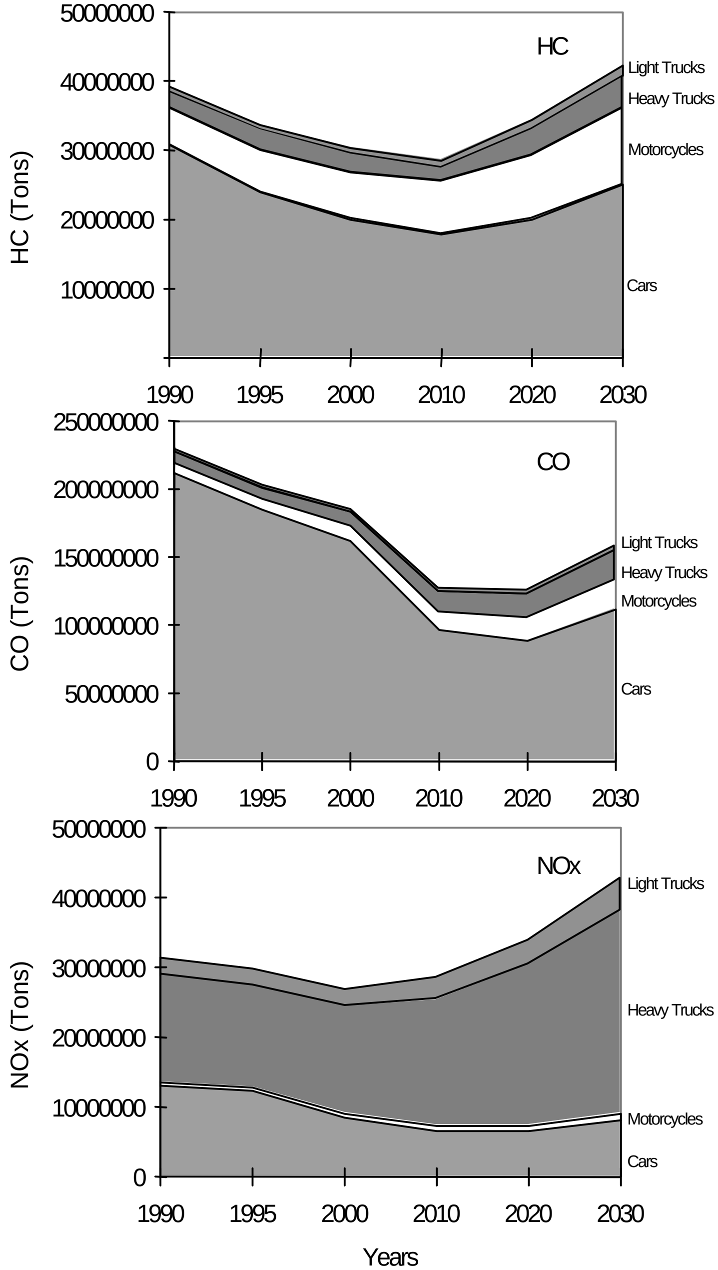
Worldwide, two-wheel vehicle usage is increasing at a rapid pace, especially in the urbanized areas of Asia. Well over 100 million two-wheel vehicles are currently in use and this number is growing at a rate of around 7 million vehicles per year (the net of ~ 20 million vehicle sales less vehicles scrapped). The majority of these vehicles are powered by 2-stroke engines. 2-stroke engines have very high exhaust emissions. This paper examines the growth of two-wheel vehicles and the need to control their emissions with an emphasis on vehicles powered by small, air cooled, single cylinder power plants with displacements from 50 to 150 cc. Catalytic control technologies will be examined and regulations and standards are discussed.

The large population of two-wheel vehicles accounts for a significant portion of global mobile source hydrocarbon (HC) and carbon monoxide (CO) as illustrated in Figure 1. NOx emissions from 2-stroke engine vehicles are relatively small compared to other mobile sources. Confronted with the need to address deteriorating air quality, a growing number of countries worldwide have implemented, or are in the process of implementing, programs to substantially reduce gaseous emissions from spark-ignition (SI) two-wheel vehicles. In making pollution control decisions, countries in Asia and Europe, where ~20 million two-wheel vehicles are sold each year, are considering a number of issues. These issues include the levels of the emission standards to implement, the types of control strategies that will be implemented, and, in some cases, even whether the 2-stroke engine should be abandoned and replaced with the lower-polluting 4-stroke engine.

In controlling emissions from two-wheel vehicles, legislative authorities have tended to implement increasingly stringent emission standards in stages. Strict standards normally result in the use of catalytic exhaust technology. As emission standards are tightened even further, a systems approach using more developed engine designs and advanced catalyst technology will be needed. The use of improved engines and operating systems in combination with catalytic technology makes possible very significant emission reductions from two-wheel vehicles. The staged implementation of increasingly stringent emission standards provides the opportunity to achieve a smooth transition toward very low emitting two-wheel vehicles.

Catalyst technology is a proven and cost-effective approach for reducing hydrocarbon, carbon monoxide and particulate emissions from both 2- and 4-stroke powered two-wheel vehicles while maintaining the desired engine performance characteristics. Worldwide, over 5 million catalyst-equipped two-wheel vehicles have been sold. An excellent example of catalyst technology application on two-wheel vehicles is in Taiwan where catalyst technology has enabled over 4 million 2-stroke engine powered motor vehicles to meet rigorous emissions requirements since 1992. The result is a proven success of catalyst technology and Taiwan manufacturers have expanded its use to both 2-stroke and 4-stroke vehicles to meet the more stringent emission standards effective for all two-wheel vehicles produced after January 1, 1998.

**Figure 1**
**Global Emission Trends Emitted per Year**




M.P. Walsh, "Motorcycle Vehicle Pollution Control The Global Market", MECA Report, 1993

## 2.0 SOURCES OF EMISSIONS

### 2.1 2-stroke Engines

The primary emissions from two-wheel vehicles powered by a 2-stroke engine are HCs, CO, and particulate matter (PM) emissions in the form of white smoke. NOx emissions are typically very low for 2-stroke engines because of the effect of high residual combustion gas retained in the combustion chamber (internal EGR) and, therefore, NOx emissions are not regarded as a significant issue.

High amounts of unburned gasoline and partially combusted HCs, as well as CO emissions, are the result of inefficient combustion during idle and part-load operating conditions. A large fraction of the air/fuel mixture passes through the engine and into the exhaust system without being combusted – this is due to the inefficient scavenging process of the convention 2-stroke engine. These ‘scavenging losses’ can amount to 15 to 40 percent of the unburned fresh charge escaping through the exhaust port. These ‘scavenging losses’ account for the high hydrocarbon and particulate emissions and higher specific fuel consumption typically associated with 2-stroke engines (1).

White smoke emissions from 2-stroke engines are actually small, unburned lubrication oil droplets that are emitted with the exhaust gases. In order to lubricate the moving parts of a 2-stroke engine, oil is mixed with the fuel either manually or by a metering pump. During the cylinder scavenging process a portion of the unburned mixture of gasoline and oil escape through the exhaust port. In addition, incomplete combustion and partial engine misfire account for additional losses of oil droplets to the atmosphere.

### 2.2 4-stroke Engines

4-stroke engine emissions are more the traditional mix of HC, CO, and NOx. HC and CO emissions are the result of inefficient combustion of the air/fuel mixture within the cylinder. Since the combustion of fuel within the cylinder of a 4-stroke engine is more efficient than that of a 2-stroke engine, NOx emissions are higher, HC emissions are considerably lower, and CO emissions about the same.

## 3.0 REDUCING ENGINE-OUT EMISSIONS

### 3.1 2-stroke Engines

Base emissions from 2-stroke engines result from a number of design features that can be modified to reduce engine-out emissions. HC and CO emissions from 2-stroke power plants can be reduced somewhat by using relatively simple, low cost solutions such as improved ignition systems and fuel delivery carburetors, or by using leaner air/fuel calibrations, and with the use of higher grade engine components. More sophisticated engine design changes; for example, port design and timing, combustion chamber design and spark plug location; can be made to reduce 'scavenging' fuel losses and improve combustion efficiency. Further engine-out emission reductions require the use of advanced engine control systems such as exhaust port control valves and in-cylinder fuel injection. While advanced engine control systems hold the potential for improving fuel economy and reducing pollutants, they add to vehicle cost and complexity.

White smoke emissions are very sensitive to 2-stroke oil selection/composition and fuel/oil ratios. Reductions in white smoke emissions are possible by the use of synthetic lubrication oils rather than mineral-based oils (2,3). The use of leaner fuel/oil ratios will also reduce white smoke production (2,3).

### 3.2 4-stroke Engines

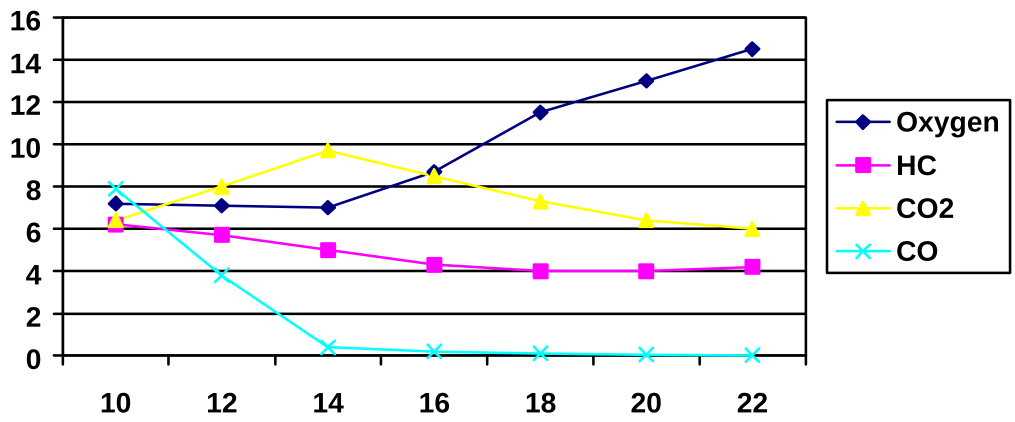
Reduction of base engine-out emissions from 4-stroke engines is similar to that for 2-stroke engines. HC and CO emissions from 4-stroke engines are primarily the result of poor in-cylinder combustion. Higher levels of NOx emissions are the result of leaner air/fuel ratios and the resulting higher combustion temperatures. Using improved ignition systems and carburetors, as well as leaner air/fuel ratios can lower HC and CO emissions. The addition of air to the hot exhaust gases at the engine exhaust port can initiate high temperature homogeneous gas phase oxidation reactions resulting in the elimination of some HC and CO emissions. Further emission reductions require the use of advanced engine control systems such as fuel injection. As with 2-stroke engines, the application of any advanced engine control system will add to vehicle cost and complexity.

### 3.3 Air/Fuel Calibration

Air/fuel calibration of both 2-stroke and 4-stroke engines directly affects the release of undesirable pollutants to the environment. In order to achieve good driveability, the engines are typically calibrated to run fuel rich. As the air/fuel mixture becomes more fuel rich, less oxygen is available in the cylinder for complete combustion of the fuel mixture and, consequently, more HC and CO are released to the atmosphere. The formation of NOx is also dependent on engine air/fuel ratios. Fuel rich mixtures have lower combustion temperatures and, therefore, form less NOx. This is the case for both 2-stroke and 4-stroke engines. However, 4-stroke engines tend to be calibrated more fuel lean and, as a result, cylinder combustion temperatures are higher resulting in more NOx than that from a 2-stroke engine**.** Typical exhaust gas concentrations for small, 2- and 4-stroke engines are shown in Figure 2.

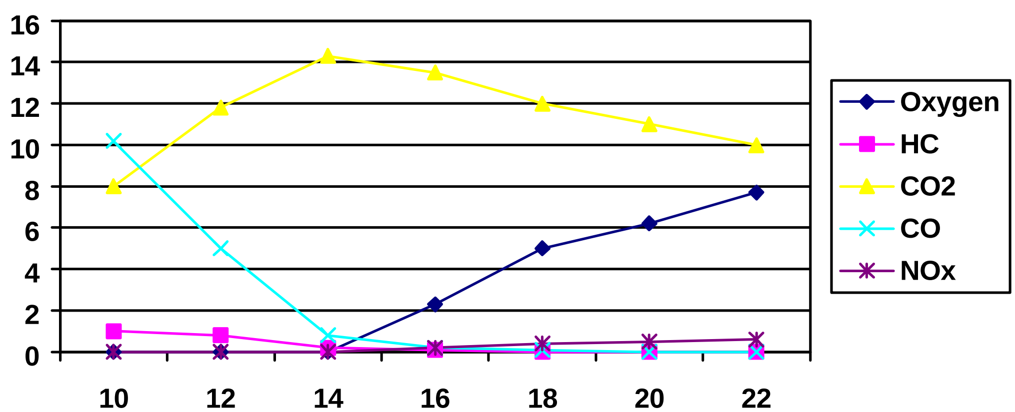
**Figure 2:**
**Typical Exhaust Gas Concentrations**

Concentration (%)




Air Fuel Ratio
a) 2-Stroke

Concentration (%)




Air Fuel Ratio
b) 4-Stroke

Source: T. Gotoh, "Two Wheelers with Catalytic Converters," Presented in Bangladore, India, February 1995

### 3.4 2-Stroke versus 4-Stroke Engine Comparison

2-stroke and 4-stroke engines each have their own specific advantages and disadvantages. The simplicity of design, size to power ratio (space envelope), light weight, low number of moving parts, ease of maintenance, and excellent power and torque characteristics make 2-stroke engines attractive power plants where the cost of transportation and high specific power output are important. For example, with the same displacement, a 2-stroke engine can produce up to 1.4 times as much power as a 4-stroke engine (4). The 2-stroke engine has two primary disadvantages: 1) poor fuel utilization because of the valveless design which results in higher specific fuel consumption due to large fuel losses during the cylinder scavenging process and 2) high HC and PM emission rates. A common considered strategy to reduce the emissions from two-wheel vehicles is to change from 2-stroke to 4-stroke engines. Table 1 compares the relative differences in HC, CO and NOx emissions from 2-stroke and 4-stroke, two-wheel vehicles.

4-stroke engines have significantly lower HC emissions, but, as Table 2 illustrates, there are tradeoffs to this approach in terms of increased vehicle complexity, cost, and weight. The 4-stroke engine requires up to 50 percent more physical space within the vehicle frame for an equivalent power output, and maintenance costs are higher. Consequently, while it is possible to substantially reduce base engine HC emissions from two-wheel vehicle fleets by converting to 4-stroke power plants, this may not be the most cost-effective solution for all markets.

**Table 1. Comparison of Engine-Out Emissions**

| ENGINE | HC | CO | NOx |
|---|---|---|---|
| 2-stroke | 1.00 | 0.80 - 1.00 | 0.10 – 0.25 |
| 4-stroke | 0.15 - 0.20 | 1.00 | 1.00 |

Source: Japan Automobile Manufacturers Association, Inc.

**Table 2. Comparison of Cost, Weight and Number of Parts**

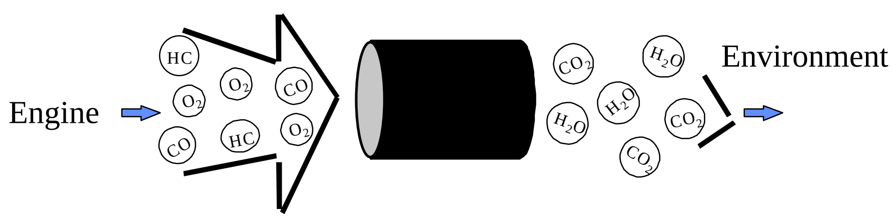
| ENGINE | NO. of PARTS | COST | WEIGHT |
|---|---|---|---|
| 2-stroke | 100 | $100 | 100 lbs. |
| 4-stroke | 128 – 139 | $120 - $136 | 120 – 130 lbs. |

Source: Japan Automobile Manufacturers Association, Inc.

## 4.0 TAILPIPE EMISSIONS REDUCTIONS USING CATALYTIC EXHAUST CONTROL

Catalytic technology uses a catalyst to assist in chemical reactions to convert the harmful components of the vehicle's exhaust stream to harmless gases. The catalyst performs this function without being changed or consumed by the reactions that take place. In particular, the catalyst, when installed in the exhaust stream, promotes the reaction of HC and CO with oxygen to form carbon dioxide and water. The chemical reduction of NOx to nitrogen is caused by reaction with CO. The role of the catalyst in promoting these beneficial reactions is depicted in Figure 3.

**Figure 3:**
**Principle of Catalytic Reactions**




### 4.1 Catalysts - Formulation

Catalysts used to treat exhaust gases from two-wheel vehicles generally are composed of a thin coating of platinum group metals and a composite of inorganic materials, mainly oxides, applied to the surface of a catalytically inactive metallic or ceramic honeycomb-like support, referred to as the substrate. The substrate design provides the large surface on which the thin catalytic layer is applied. Platinum, palladium, and rhodium, either individually or in combination, are the active catalytic metals located within the thin catalytic layer where the catalytic reactions take place. In order to achieve a maximum exposure of the catalytically active metals to the exhaust gases, the metals are finely dispersed over a very high surface area made up of refractory ceramic oxides. The thin structure is commonly referred to as the active catalytic layer or "washcoat."

Alumina is usually the primary washcoat component. Other common washcoat components are ceria, zirconia, and lanthanum oxide. Thermal stabilizers and activity promoters can be added to the washcoat formulation to improve thermal stability of the various catalyst components and to modify catalytic activity to achieve specific performance characteristics. The selection of platinum group metals and washcoat composition is a function of the desired emissions reductions, catalyst operating temperatures, and other application specific considerations.

### 4.2 Catalysts - Substrate

The catalytic layer consisting of platinum group metals and washcoat components are attached firmly to a substrate. The role of the substrate is to provide a chemically inert, thermally stable, high geometric surface area upon which the catalytic layer, with its active components, can be effectively attached to and exposed to the exhaust gases. Substrates are composed of either metallic or ceramic materials. Currently, most catalyst designs for two-wheel vehicle applications employ metallic substrates.

The selection of an appropriate substrate form is a function of the required emissions reduction and application specific parameters including size and location restrictions. The small dimensional envelope of most two-wheel vehicles applies restrictions to both the size and locations available for the application of catalyst technology to these vehicles. The catalytic unit may be in a form that is incorporated into the existing exhaust system or alternatively, an existing part of the exhaust system can be used as the substrate upon which the catalyst layer is applied. For example, a section of the exhaust pipe leading from the engine to the muffler expansion chamber, or one or more of the baffles or structures typically present in the muffler, can be used to apply an effective catalytic layer. The advantage of the latter approach is that the application of catalyst technology has minimal impact on the existing exhaust system design, noise suppression and gas dynamics. However, the limited geometric surface areas available for coating may be insufficient for achieving the required emissions reductions.

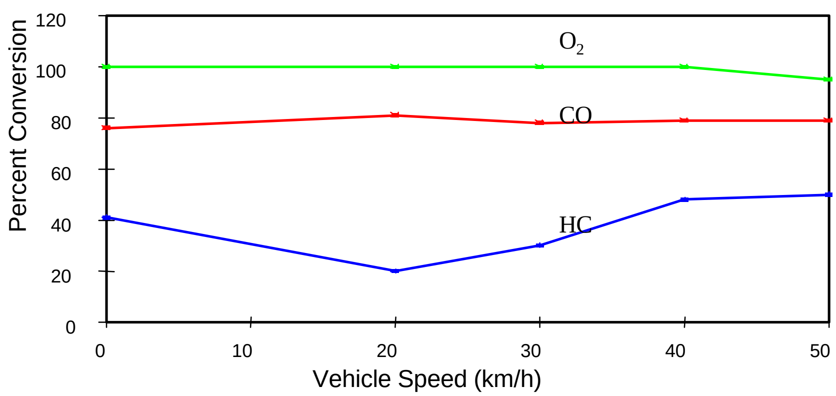
Conventional monolithic honeycomb catalytic units, such as those used in the automotive industry, are often incorporated into the existing exhaust system. This adds a new component to the exhaust system and attention must be given to avoid any possible negative impact on the vehicle’s performance characteristics. Design modifications may be necessary to minimize or eliminate power losses, minimize localized areas of high temperature, and for other exhaust system considerations. Nevertheless, monolithic honeycomb catalytic units, with their high geometric surface area, allow for maximum quantities of catalytically active materials that can be used and also improves the exposure of exhaust gases to the catalytic surface thereby increasing mass transfer and improving overall efficiency.

The catalytic reactions applicable here are exothermic and the released energy causes an increase in exhaust gas temperature. Therefore, regardless of the type of catalytic unit employed and the mounting location selected, specific consideration must be given to protect riders from coming into contact with high temperature surfaces. Generally, if needed, insulation and heat shielding are applied to external surfaces of the exhaust system to prevent potential harm to the riders.

### 4.3 Exhaust Gas Chemistry

The net oxygen available for combustion is governed by the air/fuel calibration used for a given engine family. However 'scavanging' losses and misfire conditions typical of 2-stroke engine operation cause oxygen and gasoline mixtures to enter the exhaust system and to be easily combusted within the catalyst. This situation is similar, but to a lesser extent, in some small 4-stroke engines. That is, when inefficient combustion takes place, the exhaust stream has higher products of incomplete combustion associated with unconsumed oxygen. These conditions are ideal for catalyst technology to complete the combustion process.

**Figure 4:**
**Conversion Efficiency as a Function of Vehicle Speed for a 50 cm$^3$ 2-Stroke Motorcycle**



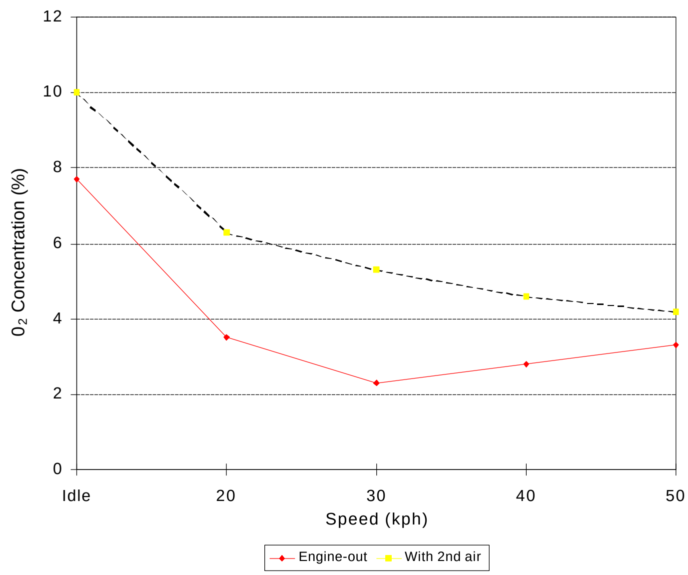

D. Dou, D.R. Palke, and M.A. Tyo, "Catalyst Technology for Motorcycle Emission Control", CATEC 1997, Beijing, China, May 1997

To achieve good driveability, the engines of two-wheel vehicles are usually calibrated to operate rich of stoichiometry. This overall fuel rich operation limits the degree to which HC and CO can be destroyed by a catalyst. Figure 4 shows the percent reduction of oxygen, hydrocarbons, and carbon monoxide in the exhaust gas stream of a 50 cc, 2-stroke motorcycle as a function of vehicle steady state operating speed. This vehicle is representative of small motorcycles calibrated for rich air/fuel operation. Complete conversion of oxygen occurs at all vehicle operating speeds except at 50 km/h.

This clearly demonstrates the efficiency of the catalyst for the oxidation of hydrocarbons and carbon monoxide and as well the need for oxygen as a critical element in achieving high levels of emission control.

If needed to meet applicable standards, HC and CO conversion efficiencies can be increased by the use of a supplemental air delivery system. Reed valve secondary air injection systems, because of their low cost and simplicity, are commonly used to increase exhaust stream oxygen availability. Figure 5 gives an example of the increase in exhaust gas oxygen concentration that is possible from a reed valve secondary air system.

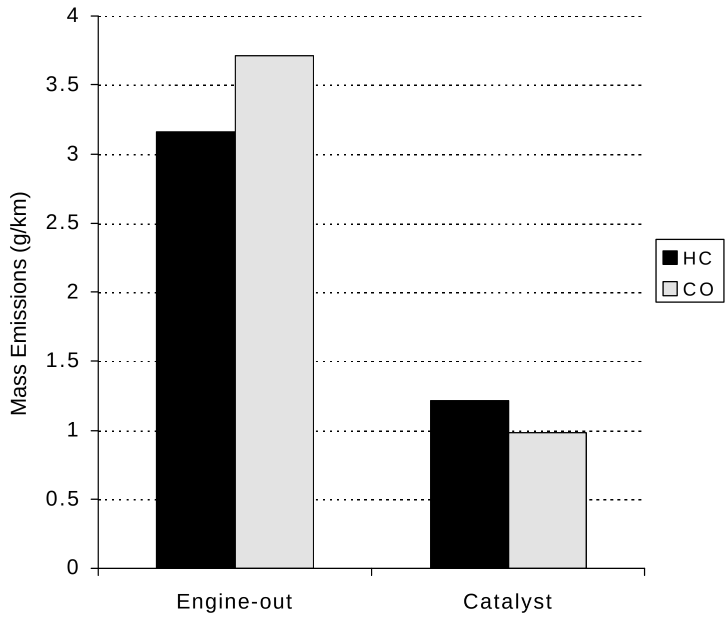
**Figure 5:**
**Tailpipe Oxygen Content (%vol) as a Function of Vehicle Speed**




### 4.4 Catalyst Technology Control Efficiency

The efficiency of catalyst technology is a function of many parameters, including substrate form, catalyst formulation, the location of the catalytic device, its operating temperature environment, and exhaust gas compositions (5-10). With appropriate system engineering, catalyst technology is very effective for the removal of harmful gases from two-wheel vehicles. Conversion efficiencies in the range of 60 to 80 percent have been achieved on two-wheel vehicles for HC and CO respectively. Figure 6 shows the reduction of HC and CO emissions from a 50cc, 2-stroke motorcycle with a 115 cc catalytic unit mounted in the vehicle's muffler. The presence of a catalyst reduces the hydrocarbon mass emissions from 3.16 g/km to 1.21 g/km and the carbon monoxide mass emissions from 3.71 g/km to 0.98 g/km, when tested over the ECE-R40 test cycle. This represents HC and CO reductions of 62 percent and 74 percent, respectively. These results are indicative of the reductions in exhaust emissions that are readily attainable by the use of catalytic technology.

**Figure 6:**
**Catalyst Performance**




Another beneficial use of catalyst technology is the reduction of white smoke (particulate) emissions. In an examination of the impact of retrofitting a fleet of 125 cc, 2-stroke motorcycles with catalysts, Hsien et al. reported reductions in exhaust stream opacity of 50 percent or greater due to the introduction of catalysts (11). The elimination of visible white smoke and the reduced build up of oil based deposits in the muffler of catalyzed two-wheel vehicles is reported in SAE Paper 750910 (12).

Catalysts used on 4-stroke motorcycles typically contain platinum and rhodium for the simulatneous control of CO, HC, and NOx. Emissions reductions of 60 percent, 75 percent, and 50 percent respectively have been found after catalysts have been aged for 30,000 km. 4-stroke motorcycle catalysts are used in Europe and to some extent in the U.S.

### 4.5 Catalyst Durability

Catalyst technology has demonstrated excellent durability in two-wheel vehicle applications. In Taiwan, where catalyst technology has been employed for a number of years, two-wheel vehicles now must meet stringent emissions requirements after 15,000 km of use. To demonstrate compliance with the required standards, two-wheel vehicles equipped with catalysts have been tested well beyond the 15,000 km requirement and have shown excellent emission control performance. The two major contributors to gradual decline in catalyst performance over time are; 1) extended operation at elevated temperatures, and 2) accumulation of catalyst poisons or masking agents on or within the catalytic layer. These two mechanisms are commonly referred to as 'thermal deactivation' and 'catalyst poisoning'. The use of rugged high temperature resistant catalyst designs that are integrated into overall engine system design is one way to minimize performance declines. Another is to conduct proper engine and vehicle maintenance. Good gasoline and lubricant oil quality are also essential.

**4.5.1** ***Thermal Deactivation* --** In the case of 2-stroke powered vehicles, the simultaneous presence of significant quantities of HC, CO, and oxygen creates the potential for a substantial temperature rise within the catalyst bed. This occurrence is caused by the energy from the exothermic oxidation of the HC and CO. While there is generally less temperature rise across the catalyst bed of 4-stroke engines, the temperatures of the inlet gases are usually higher. Therefore, 4-stroke engine catalysts can also be exposed to very high operating temperatures.

Mechanisms of thermal deactivation include; 1) sintering of the precious metal resulting in reduced dispersion within the catalyst layer, 2) alloy formation involving two or more platinum group metals, and 3) sintering of the catalyst's open porous structure resulting in narrowing or collapse of the channels needed for gas passage to and from the active catalytic sites.

Precious metal sintering is a function of the precious metal used. Pt sinters more than Pd and Rh. Alloy formation is avoided by keeping the precious metals separated. Vast improvements have been achieved in the thermal resistance of the porous structure of the catalyst layer. In fact, catalyst structures are now designed to resist exposure to temperatures of 1050 $^oC$ and higher compared to a former limit of 900 $^oC$. Careful selection of catalyst formulation, proper sizing, and location of the catalytic device are used to minimize exposure to high temperatures.

**4.5.2** ***Catalyst Poisoning* --** Catalyst poisons are classified as "physical" or "chemical". Chemical poisons, such as lead, cause loss of catalyst performance by combining with the catalytic components and rendering them inactive or by substantially changing their performance characteristics. Physical masking agents deactivate catalytic performance by forming a barrier between the catalytically active components and the exhaust gas. The sources of poisons can be the motor oil, fuel, or wear of engine components. Even the air brought through the engine can be a source of catalyst contamination if inadequate filters are used.

Fuels represent a potential source of chemical poisons. Leaded gasoline is a major and permanent poison of catalytic technology. One or two tank fills of leaded gasoline is all that is needed to destroy the catalyst's pollution control capabilities. Even residual lead in unleaded gasoline at levels as low as a few milligrams/ liter (or gallon) will very slowly accumulate on the catalyst and cause performance degradation. While many regions of the world have switched to unleaded fuel, in other areas leaded gasoline continues to be used. Unleaded fuel must be widely available before catalyst technology is introduced. In those areas where leaded and unleaded fuels are available, care must be taken to avoid mis-fueling.

It is essential that countries initiating emission control regulations and standards also address the quality of their gasoline. The maximum lead content specification should be 0.013 g Pb/liter (0.05 g/gallon) with zero lead addition permitted.

Sulfur, present at some level in all gasoline, is known to inhibit the performance of catalytic technology. The impact of sulfur on catalyst performance is a function of many parameters including engine calibration, fuel sulfur level, temperature, and catalyst formulation. Sulfur content ideally should be as low as possible in order to maximize the performance of emission control catalysts. The gasoline sulfur specification should not exceed 300 ppm. For North America and Europe, MECA recommends a maximum sulfur specification of 30 ppm.

Lubricating oil is a potential source of physical poisons. 2-stroke lubrication oil is formulated with low ash content. During normal use a certain amount of lube oil ash will accumulate on catalyst surfaces, however, too much accumulation will cause a decline in catalyst performance. 2-stroke engine catalyst technology designs have been developed with open porous surfaces that maintain performance even with some ash accumulation. 4-stroke engine oils contain higher amounts of lube oil ash – including compounds of phosphorous, zinc and calcium. If 4-stroke oils are used in 2-stroke engines then the resistance to ash accumulation is overwhelmed and the catalyst will likely suffer significant performance deterioration.

Proper maintenance of 4-stroke engines is necessary for long life. Lube oil changes at recommended intervals is very important. Poor maintenance resulting in high oil consumption will result in higher accumulation of oil ash masking poisons on the surface of the catalyst and result in lower catalyst performance.

The combination of advanced catalyst designs and the development of modern 2-stroke and 4-stroke lubricating oil formulations along with SAE specifications for lubricating oils have reduced the concern for gross negative impacts of oil on catalyst performance. However, the improper use of 4-stroke oils in 2-stroke engines or use of low grade 2-stroke oils can expose the catalyst to high levels of catalyst poisons and negatively impact catalyst performance.

### 4.6 Field Experience with Catalyst Technology

Currently, the use of catalyst technology to reduce the emission of harmful exhaust gases from two-wheel vehicles is widely used in Taiwan, Austria and Switzerland. Other countries where catalysts are used on two-wheel vehicles include Thailand, India, Japan, the United States, and Germany. Control requirements being established in India and the European Union will necessitate the widespread use of catalysts on two-wheel vehicles within the next two years.

Worldwide, over 5 million catalyst-equipped two-wheel vehicles have been sold. In 1995 approximately 6 percent (1 million vehicles) of all motorcycles produced were equipped with catalysts. In 2000 it is estimated that about 26 percent (6 million vehicles) of the total worldwide production will be catalyst equipped.

Taiwan is unique in that it is currently the only country that has a durability requirement for motorcycle emissions. Starting with Phase II emission standards that became effective from 1991, two-wheel vehicles were required to meet tailpipe standards for 6,000 km of use. With the introduction of Phase III emission standards effective in 1998, the durability requirement has been increased to 15,000 km. Taiwan has an active inspection and maintenance system (IM Program). The purpose of this system is to encourage drivers to undertake periodical inspections and maintenance in order to correct emissions caused by improper vehicle operation and to monitor compliance of two-wheel vehicles to the appropriate emission standards. Through the IM program Taiwan inspects about 1.5 million vehicles annually.

# 5.0 GLOBAL EMISSIONS STANDARDS FOR TWO-WHEELVEHICLES

## 5.1 Standards

Two-wheel emission control regulations were first introduced in the U.S. in 1978. Two-wheel vehicles are now regulated in many countries and the allowable emissions limits vary widely. Table 3 summarizes motorcycle emission control regulations throughout the world. The stringency of the standards depends on several factors including the extent of the existing pollution problem, as well as various political and economic factors. As would be expected, the more demanding control requirements tend to be found in areas with the highest concentration of two-wheel vehicles.

With the notable exception of the United States and Singapore, the emission control requirements in all countries regulating two-wheel vehicles contain a mass emission regulation, an idle emission regulation, and a prescribed test method (idle emissions are not regulated in the United States or Singapore). In a growing number of countries some durability requirements are being established which specify that the emission regulation must be met for some minimum accumulated mileage.

Mass emissions are expressed in a unit mass per unit distance such as gram/km or gram/mile. Idle emission standards are normally expressed as parts per million in the case of HCs and volume percent in the case of CO. However, in Austria and Switzerland idle standards are specified in a unit mass per unit time standard of gram/minute. Since the test procedures used by different countries vary, a straightforward comparison of mass emission standards and the corresponding vehicular emissions between different countries is not possible. In order to conduct such a comparison, the test procedures would need to be identical.

## 5.2 Test Methods

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

The ECE R40 is the most widely used test method. This test procedure, or slight modifications of it, is used extensively in Europe and in many parts of Asia. India has adopted a test method that is unique to their own driving conditions, known as the India Driving Cycle or the IDC. Another European cycle, the ECE R47 test method is used primarily for vehicles having engine displacements less than 50 cc and maximum speeds less than 50 km/hour. These various test methods are presented in Figure 7.

**Table 3**

# Worldwide 2-Wheel Emission Legislation

| Country | Vehicle | Mass Emissions [g/km] | | | | Idle Test | | Durability Requirement | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | HC | CO | $NO_x$ | Test Cycle | HC | CO | | |
| **Austria** | Moped | 1.0 | 1.2 | 0.2 | ECE R47 | 0.2g/min | 0.2g/min | | Current |
| | 2-stroke | 7.5 | 8.0 | 0.1 | ECE R40 | | | | |
| | 4-stroke | 3.0 | 13.0 | 0.3 | ECE R40 | | | | |
| **Switzerland** | Moped | 0.5 | 0.5 | 0.1 | ECE R47 | 0.1g/min | 0.1g/min | | Current |
| | 2-stroke | 3.0 | 8.0 | 0.1 | ECE R40 | | | | |
| | 4-stroke | 3.0 | 13.0 | 0.3 | ECE R40 | | | | |
| **European Union (EU)** | Moped | 3.0[1)] | 6.0 | | ECE R47 | | | | Current |
| | 2-stroke | 4.0 | 8.0 | 0.1 | ECE R40 | | 4.5% | | |
| | 4-stroke | 3.0 | 13.0 | 0.3 | ECE R40 | | 4.5% | | |
| | Moped | 1.2[1)] | 1.0 | | ECE R47 | | 4.5% | | 10/2001 |
| **Japan** | 2-stroke | 5.26 | 14.4 | 0.14 | ISO 6460 | 7,800ppm | 4.5% | | 10/98 - 4 year |
| | 4-stroke | 2.93 | 20.0 | 0.51 | ISO 6460 | 2,000ppm | 4.5% | | phase-in |
| **Singapore** | All MCs | 5.0[1)] | 12.0 | | CVS-78 | | | | Current |

# Table 3 Continued

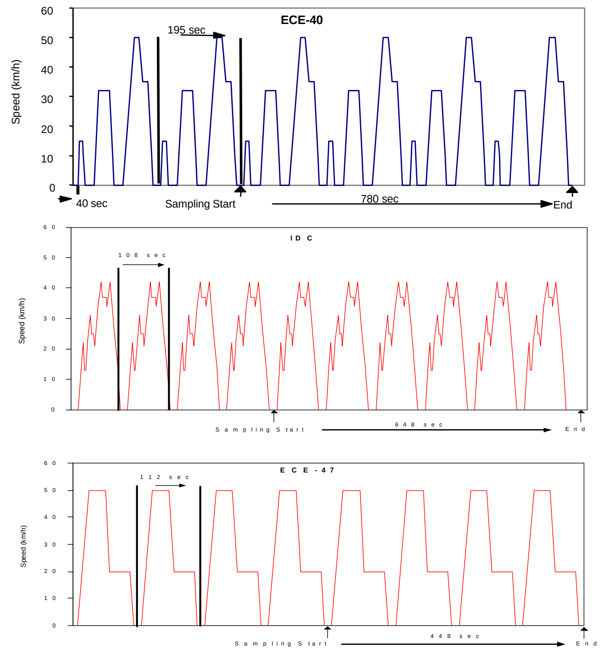
## Worldwide 2-Wheel Emission Legislation

**Table 3 continued**

| Country | Vehicle | Mass Emissions [g/km] | | | | Idle Test | | Durability Requirement | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | HC | CO | $NO_x$ | Test Cycle | HC | CO | | |
| **USA** | All MCs | 5.0[1)] | 12.0 | | CVS-78 | | | | Current |
| **Taiwan** | All MCs | 2.0[1)] | 3.5 | | CNS | 6,000ppm | 4.0% | 15,000 km | Current |
| | 2-stroke<br>4-stroke | 1.0[1)]<br>2.0[1)] | 7.0<br>7.0 | | CNS<br>"cold start" | 3,000ppm | 1.5% | 15,000 km | 12/03 **(proposed)** |
| **Thailand** | All MCs | 5.0[1)] | 13.0 | | ECE R40 | 10,000ppm | 4.5% | | Current |
| | All MCs | 3.0[1)] | 4.5 | | ECE R40 | TBD | TBD | 12,000 km | 7/99 - 3 year phase-in |
| **China** | 2-stroke | 13 / 21 | 20 - 50 | | GB/T 14622 | 7,000ppm | 4.5% | | Current |
| | 4-stroke | 10 / 14 | 30 - 60 | | GB/T 5466 (Idle) | 1,200ppm | 4.5% | | |
| **India** | All MCs | 3.6[1)] | 4.5 | | IDC | | 4.5% | | Current |
| | All MCs | 2.0[1)] | 2.0 | | IDC | | 4.5% | | 4/00 |

1) HC + $NO_X$

**Figure 7:**
**Common Two-Wheel Mass Emission Test Cycles**




## 5.3 Inspection and Maintenance (I/M)

Vehicle inspection is a tool employed to ensure that vehicles meet applicable exhaust emission standards under normal operating conditions. These inspections most commonly use gas concentration analysis test methods where gas samples are taken and analyzed with a direct reading instrument at vehicle idling conditions. Two different types of inspections are commonly performed; 1) periodic inspections in which the vehicle is inspected at an approved testing station at regular fixed time intervals (i. e. annual), and 2) spot inspections performed on a random basis by pulling vehicles off the road for on-site inspection (generally referred to as “roadside inspections”). If testing determines the vehicle is exceeding the emission requirements, the vehicle owner is required to perform the necessary corrective actions within a prescribed time period. Fines or withholding registration tags are normally employed to ensure that the vehicle owner carries out the necessary corrective action.

## 5.4 Education

Education is an essential element of any successful emission reduction program. The public must be educated and understand the health benefits of the use of emission controls in order to obtain their full cooperation. To achieve program goals, they must understand the importance of proper maintenance of the vehicle and, where catalyst technology is employed, the importance of using unleaded fuel and the correct lubrication oil. In particular, the public must appreciate the health benefits of using unleaded gasoline and the health hazards of leaded gasoline, along with the understanding that unleaded fuel is needed to ensure proper catalyst performance and reduced vehicle pollution.

## 6.0 CONCLUSIONS

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

- A typical approach taken by countries was to phase-in the regulations and emission standards. Now that two-wheel emissions control programs have proven successful and the technology needed is readily available these first tentative steps are not necessary. Countries can now go directly to strict emission control regulations and standards. Such regulations and standards require the use of catalytic emission control technology. Beyond this, further reductions are possible with the combination of advanced catalyst technology and advanced engine improvements.

- Catalyst technology has clearly demonstrated the ability to achieve significant emissions reductions from both 2-stroke and 4-stroke powered two-wheel vehicles. Countries that have adopted emission standards that result in the use of catalytic technology include Austria, Switzerland, Taiwan, and Thailand. Worldwide, over 5.0 million catalyst-equipped two-wheel vehicles have been sold.

- Two-wheel vehicles equipped with 2-stroke power plants can comply with stringent hydrocarbon and carbon monoxide emissions standards by using catalyst technology – which in addition removes a high percentage of particulate emissions. Therefore, in markets where the cost of basic transportation and higher specific power output are important, these preferred power plants will continue to find widespread use.

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

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

- Public education is an essential element of a successful emission control program for two-wheel vehicles. The public must be educated to understand the health benefits of reducing the harmful pollution from two-wheel vehicles in order to build support for the program. Two-wheel vehicle users should be advised of the importance of proper vehicle maintenance to ensure good performance, optimum fuel economy, and continued effective emission control. In situations where catalyst technology is utilized, users must be educated on the importance of fueling two-wheel vehicles with unleaded gasoline only.

**REFERENCES**

1) M. Saxena, “Analysis of Dual-Charging Two Stroke Engine”, SAE Paper 972117, (1997)

2) M. Kagaya, and M. Ishimaru, “A New Challenge for High Performance Two-Cycle Engine Oils”, SAE Paper 881619, (1988)

3) K. Sugiura and M. Kagaya, “A Study of Visible Smoke Reduction form a Small 2-stroke Engine Using Various Engine Lubricants”, SAE Paper 770623, (1977).

4) “Recommendations for Improvement of air pollution in India, for two-wheeled vehicles”, JAMA, (1993).

5) D.R. Palke, M.A. Tyo, J.E. Dillon, and H.J. Robota, “Catalytic Aftertreatment of Vehicle Exhausts from 2-stroke Engines”, SAE Paper 960235, (1996).

6) D.R. Palke, M.A. Tyo, M.X. Hopmann, and H.J. Robota, “Durable Catalytic Aftertreatment of Motorcycle Exhaust”, SAE Paper 962473, (1996).

7) D.R. Palke, and M.A. Tyo, “Catalytic Aftertreatment and Small 2-stroke Powered Motorcycles”, SAE Paper 970800, (1997)

8) H.S. Hwang, J.C. Dettling, and J.J. Mooney, “Catalytic Converter Development for Motorycle Emission Control”, JSAE Paper 9734764 (SAE Paper 972143), (1997).

9) F. Castagna, B. Martin, D. Duran, J. Favennec, and M. Dubus, “Influence of Various Parameters on the Performance of Catalysis for 2-stroke Engines”, JSAE Paper 9734773 (SAE Paper 972144), (1997).

10) D.R. Palke, and M.A. Tyo, “The Catalytic Reduction of Hydrocarbon and Carbon Monoxide in Small 2-stroke Engine Powered Vehicle Exhaust Stream”, JSAE Paper 9734755 (SAE Paper 972142), (1997).

11) P.H. Hsien, L.K. Hwang, and J.H. Wang, “Emission Reduction by Retrofitting a 125 c.c. 2-stroke Motorcycle with Catalytic Converter”, SAE Paper 922175, (1992)

12) J.J. Mooney, J.G. Hansel, and R.D. Hoyer, “Catalytic Control of 2-stroke Motorcycle Exhaust Emissions”, SAE Paper 750910, (1975)