Journal of the Air & Waste Management Association

ISSN: 1096-2247 (Print) 2162-2906 (Online) Journal homepage: http://www.tandfonline.com/loi/uawm20

Comparison of Tail-Pipe Emissions from Motorcycles and Passenger Cars

Chang-Chuan Chan , Chiu-Kuei Nien , Cheng-Yuan Tsai & Guor-Rong Her

To cite this article: Chang-Chuan Chan , Chiu-Kuei Nien , Cheng-Yuan Tsai & Guor-Rong Her (1995) Comparison of Tail-Pipe Emissions from Motorcycles and Passenger Cars, Journal of the Air & Waste Management Association, 45:2, 116-124, DOI: 10.1080/10473289.1995.10467347

To link to this article: https://doi.org/10.1080/10473289.1995.10467347

Published online: 05 Mar 2012.

TECHNICAL PAPER

ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **45**: 116-124

Comparison of Tail-Pipe Emissions from Motorcycles and Passenger Cars

Chang-Chuan Chan and Chiu-Kuei Nien
Institute of Occupational Medicine and Industrial Hygiene, College of Public Health, National Taiwan University, Taipei, Taiwan

Cheng-Yuan Tsai and Guor-Rong Her
Department of Chemistry, National Taiwan University, Taipei, Taiwan

ABSTRACT

The tail-pipe emissions of carbon monoxide (CO), nitrogen oxides (NO_x), total hydrocarbons (THC), and speciated volatile organic compounds (VOCs) from the exhausts of cars and motorcycles with and without catalysts in the Federal Test Procedures (FTP) and European Community Emission (ECE) driving cycles were measured and compared. Compared with catalyst cars, motorcycles were found to emit 12 times as much THC and CO for every kilometer driven. Cars and four-stroke motorcycles emitted much higher levels of NO_x than two-stroke motorcycles. Motorcycle emission rates of benzene were lower than those from noncatalyst cars but higher than those from catalyst cars. The catalyst's reduction efficiency in motorcycles was only one-half that in cars. Among the exhaust components, the reduction efficiencies of aromatics were lower than those of THC and CO by the catalysts. For most pollutants, the greatest reduction of emissions by the catalysts occurred in Phase 2 of the FTP driving cycle. In this study, the VOC profiles in the emissions were found to be relatively rich in benzene.

INTRODUCTION

To control and regulate mobile sources of air pollution, many studies have characterized the emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HCs) from motor vehicles in several developed countries. The successful identification of emissions from various vehicles in different driving cycles has also been very helpful in developing various control technologies and in setting standards for automobile emissions, such as the innovation of catalytic converters by the auto industry and the requirement of unleaded gasoline and alternative fuels in the U.S. Clean Air Act Amendments (CAAA) of 1977 and 1990.[1,2] Although air pollution associated with mobile sources is growing increasingly worse in Taiwan, the government has not yet developed a successful control strategy. The results of recent studies have shown that commuters in the Taipei metropolitan area are exposed to very high concentrations of CO and benzene.[3-5] The 10.4 million two-stroke and four-stroke motorcycles and 3.3 million motor vehicles in Taiwan are thought to be the main source of commuters' CO and benzene exposures. This assertion is even more evident because most of the motorcycles and about 80% of the motor vehicles in Taiwan are not equipped with catalytic converters. To develop a practical policy to control exhaust-related air pollution problems, it is essential to improve the understanding of factors affecting tail-pipe emissions from motorcycles and cars in Taiwan. Therefore, this study compared motorcycle and passenger car tail-pipe emissions, thus providing a better emission inventory of mobile sources in Taiwan. The measured emissions include CO, NO_x, total hydrocarbon (THC), eight speciated hydrocarbons, and carbon dioxide (CO_2). The factors of catalysts, driving cycles, and fuel components in reducing emissions between motorcycles and cars are also compared in order to evaluate the catalysts' function in motorcycles.

IMPLICATIONS

The problem of air pollution in cities of newly developed and developing countries is mainly created by a rapid growth in the use of motorcycles and passenger cars as traffic tools. In comparison to passenger cars, information about motorcycles' hardware controls on emissions, including catalyst, engine design, and fuel composition, is scarcely available. The results of this study provide us with a better understanding of how motorcycle tail-pipe emissions are affected by fuel type, engine type, and catalyst. The measured vehicle-specific emission profiles can be applied to receptor modeling in estimating contributions of the two-stroke motorcycle to various air pollutants in Taipei. The findings should also help regulatory agencies, motorcycle industries, and fuel industries explore optimal control strategies to reduce motorcycle-related air pollution in various countries.

MATERIALS AND METHODS

An experiment was designed to assess tail-pipe emissions from vehicles with different types of engines, catalytic converters, driving cycles, and fuel components (Figure 1). Because the factors of engine type, converter, driving cycle, and fuel were arranged in a hierarchical way in the study design, the influence of these factors on emissions can be determined statistically by matched pair-tests.

Car 1	Noncatalyst	FTP	standard fuel commercial unleaded gasoline standard fuel +(3% benzene, 5% toluene, 3% ethylbenzene)
	Catalyst	FTP	standard fuel commercial unleaded gasoline standard fuel +(3% benzene, 5% toluene, 3% ethylbenzene)
Car 2	Catalyst	FTP	standard fuel standard fuel +(3% benzene, 5% toluene, 3% ethylbenzene)
Car 3	Catalyst	ECE-Cold Start	standard fuel standard fuel +(3% benzene, 5% toluene, 3% ethylbenzene)
	Catalyst	ECE-Hot Start	standard fuel standard fuel +(3% benzene, 5% toluene, 3% ethylbenzene)
2-Stroke Motorcycle	Noncatalyst	ECE	standard fuel commercial unleaded gasoline standard fuel +(3% benzene, 5% benzene, 5% toluene, 10% toluene, 3% ethylbenzene, 5% ethylbenzene)
	Catalyst	ECE	standard fuel commercial unleaded gasoline standard fuel +(3% benzene, 5% benzene, 5% toluene, 10% toluene, 3% ethylbenzene, 5% ethylbenzene)
4-Stroke Motorcycle	Noncatalyst	ECE	standard fuel commercial unleaded gasoline standard fuel +(3% benzene, 5% benzene, 5% toluene, 10% toluene, 3% ethylbenzene, 5% ethylbenzene)

Figure 1. The experimental design.

Test Motorcycles and Passenger Cars

The characteristics of five vehicles—two motorcycles and three passenger cars—used in the study are shown in Table 1. They were all company-owned test vehicles, which either were normally used as QA/QC vehicles in routine emission tests or were experimental vehicles for the purpose of improving emission control technology. The engine size was 125 cc for the four-stroke motorcycle, which was not equipped with catalytic converters. The engine size was 50 cc for the two-stroke motorcycle, which was operated with and without catalytic converters in the study. An oxidation catalyst was used in the motorcycle. All three passenger cars were

Table 1. Characteristics of test vehicles.

Vehicle	*Emission System*	*Year*	*Make and Model*	*Engine Size*	*Engine Type*	*Fuel System*	*A/F Ratio*	*km/l of Fuel*	*Mileage (km)*
Car 1	Noncatalyst	1991	Toyota	1,600 cc	I4	EFI[a]	≈14.5	11.7~12.5	3,000
Car 1	3-way catalyst	1991	Toyota	1,600 cc	I4	EFI	≈14.5	11.7~12.5	3,000
Car 2	3-way catalyst	1991	Ford	1,800 cc	I4	EFI	≈14.5	11.2~14.1	20,000
Car 3	3-way catalyst	1993	CM6505H	1,000 cc	FR L4	FBC[b]	≈14.5	8.4~9.0	New
2-stroke motorcycle	Noncatalyst	1992	Sanyang	50 cc	Single cylinder	Carburetor	17.0~18.7	38.8~40.5	New
2-stroke motorcycle	Oxidation catalyst	1992	Sanyang	50 cc	Single cylinder	Carburetor	18.8~12.4	38.8~42.1	New
4-stroke motorcycle	Noncatalyst	1992	Sanyang	125 cc	Single cylinder	Carburetor	15.7~17.6	36.3~37.6	New

[a]EFI: Electronic fuel injection

[b]FBC: Feedback carburetor

equipped with three-way catalysts. In the experiment, Car 1 (Toyota) was operated both with and without its catalyst.

Test Fuels

The properties of the gasoline used in the experiment are listed in Table 2. The standard fuel, obtained from the Chinese Petroleum Company, was specified by the Taiwan Environmental Protection Agency (EPA) as a reference fuel for auto emission tests. The commercial fuel, purchased from a gas station in Taipei, was the most widely used unleaded gasoline in Taiwan. To test the effects of fuel components on benzene emissions, the standard fuels were blended with 3–10% by volume of benzene, toluene, and ethylbenzene individually in the experiments.

Table 2. Properties of test fuels.

Test Fuel	*Standard Fuel*	*Commercial Fuel*
API gravity	0.742	0.74
Octane number, (R+M)/2	90.1	90
RVP, kpa	56.5	69
Sulfur, ppm	0.004	0.10
Lead, g pb/l	<0.02	0.013
Aromatics, % vol	32.7	42
Benzene, % vol	3.0	4.8
Distillation, °C, % evaporated		
10%	52.6	74
50%	90.4	127
90%	150.4	190
F.B.P.	196.1	225
Residue, % vol	0.5	2

Driving Cycles

All emission tests were performed using dynamometers from three automobile companies and one motorcycle company. Motorcycle emissions were tested in the European Community Emission (ECE) driving cycle only. Passenger car emissions were tested in both the ECE and the Federal Test Procedures (FTP) driving cycles.

Collection and Analysis of Emissions

Three currently regulated emissions—THC, CO, and NO_x—were measured using the standard methods. To be consistent with normal FTP practice, separate emission samples for speciated measurements of volatile organic compounds (VOCs) were collected from the cold start, stabilized, and hot start portions of the FTP test (bags 1, 2, and 3, respectively). The dilution air of each bag was also sampled in order to correct the background VOC concentrations (bags 4, 5, and 6, respectively). The sampling was more straightforward for the ECE driving cycle, because there was only one emission bag and one dilution air bag. The sampling points were all located at the tubing immediately prior to the analyzers of the regulated criteria pollutants.

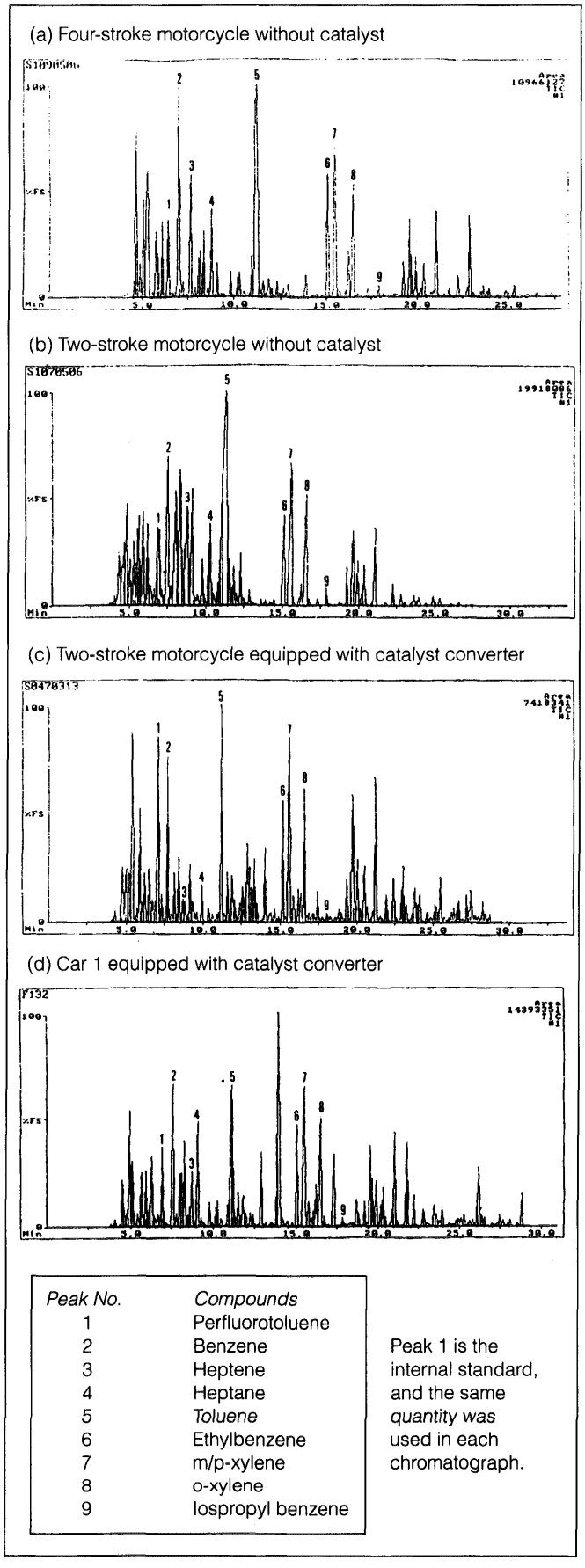

Figure 2. Total ion chromatograms (TIC) of tail-pipe VOC emissions from motorcycles and passenger cars.

The U.S. EPA TO-1 method was modified to collect and analyze the VOCs.[6] The sampling system consisted of a stainless steel tube (178 mm x 5.2 mm ID) with 0.4 g Tenax-GC, and a low-flow sampling pump (Gilian, Model LFS 113D). The emissions, collected in the dilute exhaust bags, were drawn into the Tenax-GC adsorbent at a sampling rate of 50 ml/min for one min. Major components of the analytical system included a thermal desorption system (Tekmar, Model 6000), a capillary gas chromatographic system (50 m x 0.2 mm HP-1 fused silica capillary column), and a quadruple mass spectrometer (VG, MD800). The detailed conditions of analytical instruments and QA/QC results have been reported in a previous study.[7] In brief, the recovery efficiencies were greater than 85%, the relative mean deviation of duplicate samples were within 10%, and the limits of detection (LODs) were about 0.02–0.04 mg/km for most VOCs.

Statistical Analysis

The general linear regression models from the statistical package SAS® were applied to analyze the emission data.[8] The fuel-type effect on emissions was first tested by these models. In this experiment, the emissions were not significantly different among various fuel types. Therefore, only the effects of car type, driving cycle, and catalyst on the emissions are discussed further in this paper.

RESULTS AND DISCUSSION

Species of VOC Emissions

The detailed species of hydrocarbons in motorcycle and car tail-pipe emissions are shown in the total ion chromatograms (TICs) of Figure 2. Approximately 30 VOCs range from C_6–C_{11} in these chromatograms, which can be identified by the library search of the mass spectrometry. Because of the limitations of the sampling and analytical methods in this study, no VOCs of C_1–C_5 in the emissions were detected. Among the detected hydrocarbons, only eight VOCs (benzene, heptene, heptane, toluene, ethylbenzene, m/p-xylenes, o-xylene, and isopropyl benzene) were directly quantified by using their respective standards. On average, the TIC peak areas of these eight VOCs accounted for 34–59% of total TIC peak areas of all identified C_6–C_{11} VOCs in the emissions. Comparison of TICs indicated that noncatalyst vehicle emissions contained more VOCs than the catalyst vehicle emissions. Apparently some hydrocarbons in the emissions were converted by the catalysts. Comparison of different motorcycles' TICs indicated that two-stroke engines contained more VOCs in their emissions than four-stroke engines. The results indicated that two-stroke motorcycle emissions were more likely to contain some VOCs as a result of the incomplete combustion of gasoline and engine oil.

Vehicular Difference in Tail-Pipe Emissions

The emission rates of motorcycles and passenger cars for CO, NO_x, THC, CO_2, and eight VOCs are summarized in Table 3. Significant differences in these emissions were found among noncatalyst cars, catalyst cars, two-stroke motorcycles, and four-stroke motorcycles. For THC and CO emissions, noncatalyst cars and two-stroke motorcycles were significantly higher than other vehicles. The mean emission rates of THC were 1.3637 g/km for noncatalyst cars

Table 3. Motorcycle's and passenger car's tail-pipe emission rates of VOCs, THC, CO, NO_x, and CO_2 (g/km).

	Car 1				*Car 2*		*Car 3*				*2-Stroke Motorcycle*				*4-Stroke Motorcycle*	
	Noncatalyst FTP		*Catalyst FTP*		*Catalyst FTP*		*Catalyst ECE-Cold*		*Catalyst ECE-Hot*		*Noncatalyst ECE*		*Catalyst ECE*		*Noncatalyst ECE*	
N	*14*		*14*		*12*		*12*		*14*		*21*		*23*		*26*	
Compounds	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Benzene	0.0786	(0.0228)	0.0183	(0.0080)	0.0184	(0.0103)	0.0369	(0.0236)	0.0123	(0.0084)	0.0333	(0.0255)	0.0191	(0.0069)	0.0260	(0.0104)
Heptene	0.0089	(0.0118)	0.0021	(0.0023)	0.0016	(0.0126)	0.0047	(0.0093)	0.0014	(0.0025)	0.0071	(0.0075)	0.0023	(0.0019)	0.0020	(0.0011)
Heptane	0.0469	(0.0523)	0.0125	(0.0117)	0.0058	(0.0170)	0.0234	(0.0304)	0.0077	(0.0109)	0.0299	(0.0264)	0.0059	(0.0044)	0.0107	(0.0115)
Toluene	0.1358	(0.0309)	0.0301	(0.0124)	0.0289	(0.0182)	0.0753	(0.0504)	0.0178	(0.0101)	0.0524	(0.0407)	0.0319	(0.0118)	0.0461	(0.0192)
Ethylbenzene	0.0374	(0.0152)	0.0066	(0.0029)	0.0075	(0.0070)	0.0125	(0.0145)	0.0027	(0.0014)	0.0179	(0.0139)	0.0090	(0.0033)	0.0134	(0.0071)
m/p-xylene	0.0868	(0.0130)	0.0130	(0.0032)	0.0140	(0.0059)	0.0270	(0.0146)	0.0054	(0.0014)	0.0366	(0.0130)	0.0278	(0.0050)	0.0276	(0.0061)
o-xylene	0.0330	(0.0107)	0.0054	(0.0028)	0.0042	(0.0039)	0.0110	(0.0107)	0.0023	(0.0012)	0.0161	(0.0107)	0.0100	(0.0034)	0.0113	(0.0053)
Isopropyl benzene	0.0020	(0.0006)	0.0003	(0.0002)	0.0004	(0.0008)	0.0009	(0.0008)	0.0002	(0.0001)	0.0056	(0.0070)	0.0007	(0.0003)	0.0010	(0.0010)
Sum of 8 VOCs	0.4294		0.0883		0.0737		0.1917		0.0209		0.1989		0.1066		0.1381	
THC	1.3637	(0.0360)	0.1295	(0.0222)	0.1214	(0.0156)	0.2997	(0.0446)	0.0343	(0.0188)	3.7700	(0.6893)	2.0597	(0.3490)	0.6419	(0.1275)
CO	7.2782	(0.8561)	0.8698	(0.0822)	1.2902	(0.1964)	2.3106	(0.5291)	0.5644	(0.4435)	7.4680	(1.8954)	2.8989	(0.5953)	3.9913	(0.8277)
NO_x	1.8763	(0.0469)	0.1096	(0.0164)	0.1441	(0.0145)	0.4218	(0.0400)	0.0826	(0.0299)	0.0071	(0.0127)	0.0000	(0.0000)	0.1948	(0.0622)
CO_2	187.4143	(2.8857)	203.3500	(5.6848)	172.9583	(8.7883)	275.8122	(2.9642)	258.0344	(3.8201)	35.7057	(2.6739)	47.7060	(0.7030)	55.5189	(1.1295)
Sum of 8 VOCs/THC	31.5%		68.2%		56.4%		64.0%		51.0%		5.3%		5.2%		21.5%	

and 3.7700 g/km for two-stroke motorcycles. The mean emission rates of CO were 7.2782 g/km for noncatalyst cars and 7.4680 g/km for two-stroke motorcycles. Compared with catalyst cars, noncatalyst cars and two-stroke motorcycles were found to emit 12 times as much THC and CO for every kilometer driven. For NO_x, noncatalyst cars had the highest emissions, while the two-stroke motorcycles had the lowest emissions. In several emission tests of two-stroke motorcycles, the NO_x level was actually below the analyzer's detection limit. The exceptionally low NO_x emissions of two-stroke motorcycles can be explained by the two-stroke engine's specific compression and air/fuel ratios. In this study, the air/fuel ratios were 17–18.7 for two-stroke motorcycles without catalysts and 11.8–12.4 for two-stroke motorcycles with catalysts. Such air/fuel ratios were in the low NO_x emissions regions for a typical gasoline engine.[9]

Significant differences were detected in emissions between two-stroke and four-stroke motorcycles. The four-stroke motorcycles had higher NO_x emissions but lower THC and CO emissions than the two-stroke motorcycles. The mean emission factors (g/km) of the four-stroke motorcycles were 0.6419 for THC, 3.9913 for CO, and 0.1948 for NO_x. For THC emissions, four-stroke motorcycles had only 1/6 to 1/3 the emissions of two-stroke motorcycles. The two-stroke motorcycles were expected to have greater THC emissions because of more emissions from the engine's wall quenching, incomplete combustion, and cylinder scavenging.[10]

The proportions of the sum of eight VOCs in THC emissions were significantly different among various vehicles. The proportions were 32% for noncatalyst cars, 51–68% for catalyst cars, 5% for two-stroke motorcycles, and 22% for four-stroke motorcycles. Catalyst cars had the highest proportions because aromatics in eight VOCs were less easily catalytically converted. Two-stroke motorcycles had the lowest proportions because of their high THC emissions. Benzene emissions were also significantly different among vehicles and driving cycles. The emission rates (g/km) were in the following order: noncatalyst car in FTP mode (0.0786) > catalyst car in ECE-cold mode (0.0369) > noncatalyst two-stroke motorcycle (0.0333) > noncatalyst four-stroke motorcycle (0.0260) > catalyst two-stroke motorcycle (0.0191) > catalyst car in FTP mode (0.0184) > catalyst car in ECE-hot mode (0.0081). Apparently, noncatalyst motorcycle benzene emissions were lower than those from the noncatalyst cars but higher than those from the catalyst cars.

The emission rates of CO_2 were 172–276 g/km for passenger cars and 36–56 g/km for motorcycles. Passenger car emission rates were three to eight times as high as the motorcycle emission rates. By comparison, the fuel economies were 36–42 km/l for motorcycles and 11–14 km/l for cars. Motorcycle fuel economy was three to four times that of passenger cars. The difference in CO_2 emissions between cars and motorcycles simply reflected the difference in fuel economy. A similar result was found for the passenger cars in three phases of the FTP cycle. The cars' CO_2 emissions were as follows: Phase 1 > Phase 2 > Phase 3. By comparison, their fuel economies were Phase 1 < Phase 2 < Phase 3. The catalyst passenger cars in the FTP cycle were found to have 50–100 g/km lower CO_2 emissions than in the ECE cycle. Therefore, the variation of CO_2 emissions in different vehicles and driving cycles should be considered when calculating the relative contributions of different mobile sources to total CO_2 emissions.

VOC Emission Profiles

The VOC emission profiles based on benzene : toluene : ethylbenzene : xylenes ratios (B : T : E : X) are shown in Table 4. Generally, these profiles can be divided into three groups. The first group included noncatalyst motorcycles and noncatalyst cars, and the B : T : E : X ratios were 1 : (1.4–

Table 4. Tail-pipe VOC emission profiles for different vehicles and fuels.

Vehicle			Fuel Type	
Engine Type	*Catalyst Converter*	*Driving Cycle*	*Standard Test Fuel B : T : E : X*[a]	*Commercial 95 Unleaded B : T : E : X*
2-stroke motorcycle	Noncatalyst	ECE	1 : 1.6 : 0.4 : 1.4	1 : 1.4 : 0.3 : 1.4
2-stroke motorcycle	Catalyst	ECE	1 : 1.6 : 0.6 : 2.5	1 : 1.9 : 0.5 : 2.0
4-stroke motorcycle	Noncatalyst	ECE	1 : 1.7 : 0.5 : 1.6	1 : 1.5 : 0.3 : 1.5
Car 1	Noncatalyst	FTP	1 : 1.7 : 0.5 : 1.6	1 : 1.9 : 0.7 : 2.2
Car 1	Catalyst	FTP	1 : 1.1 : 0.3 : 1.1	1 : 1.8 : 0.4 : 0.9
Car 2	Catalyst	FTP	1 : 2.4 : 0.3 : 0.8	NA
Car 3	Catalyst	ECE-cold	1 : 2.3 : 0.3 : 0.8	NA
Car 3	Catalyst	ECE-hot	1 : 2.7 : 0.3 : 0.9	NA

[a] B : T : E : X Benzene : toluene : ethylbenzene : xylenes
NA Not applicable

1.9) : (0.3–0.6) : (1.4–2.2). The second group included all catalyst cars except Car 1, and the B : T : E : X ratios were 1: (2.3–2.7) : 0.3 : (0.8–0.9). The second group had relatively higher toluene emissions than the first group. Car 1's toluene/benzene ratio was lower than the other car's because its toluene emissions were exceptionally low in the experiment without apparent explanation. The two-stroke motorcycles with catalysts composed the third group, and their B : T : E : X ratios were 1 : (1.6–1.9) : (0.5–0.6) : (2.0–2.5). This group had relatively high emissions of xylenes. Compared to other studies conducted in the United States and the United Kingdom, emission profiles were very similar for noncatalyst cars but slightly different for catalyst cars among various studies. For example, the B : T : E : X ratios were 1.0 : 1.6 : 0.3 : 1.6 for noncatalyst passenger cars in the study by Cohu et al.[11]; 1.0 : 2.4 : 0.4 : 1.3 for catalyst passenger cars in the FTP cycle in the study by Sigsby et al.[12]; and 1.0 : 2.2 : 0.6 : 2.6 in the ECE driving cycle in the study by Bailey et al.[13] The higher benzene and aromatics contents in the test fuel were thought to result in lower xylene/benzene ratios in the emissions of our studies. The test fuels contained 3–5% benzene and 33–42% aromatics in Taiwan. By comparison, the test fuels contained less than 2% benzene and 33% aromatics in other studies.

The tail-pipe emission profiles were also different from the profiles of the ambient measurements on Taipei roads. The B : T : E : X ratios were found to be 1.0 : 2.6 : 0.8 : 3.9 for commuters' exposures in Taipei.[14,15] The alkyl benzene concentrations were apparently much more abundant in ambient air than in our test vehicles' emissions. The difference in VOC profiles between tail-pipe emissions and ambient measurements was most likely caused by more diverse sources of emissions on the roads, such as evaporation from vehicles and exhausts from old vehicles, diesel trucks, and diesel buses. Variation in these VOC emission profiles indicated that the B : T : E : X ratios can be used as the emission source's fingerprints in the chemical mass balance-based (CMB) receptor modeling. Therefore, ambient benzene concentrations in Taipei can be apportioned to various emission sources, such as motorcycles and passenger cars, through these modeling procedures.

Catalyst Effects on Emission

The catalysts' efficiencies in reducing various tail-pipe emissions are illustrated in Figure 3. The average converting efficiencies of the passenger cars with three-way catalysts were 90.5% for THC, 88.0% for CO, 94.2% for NO_x, and 73.3–85.0% for eight VOCs. In contrast, the average converting efficiencies of the two-stroke motorcycles with oxidation catalysts were 45.4% for THC, 61.2% for CO, and 24.3–80.1% for eight VOCs. The motorcycles' catalysts had significantly lower efficiencies in reducing emissions than those of the passenger cars. For the motorcycles, the catalysts' efficiencies of reducing aromatic hydrocarbons and carbon monoxide in the emissions were particularly low. The lower converting efficiency in motorcycles is believed to be caused by worse air/fuel (A/F) controls, lower exhaust temperatures, and different compositions of converters in motorcycles. The two-stroke motorcycle without catalyst was operated in lean-burn condition with averaging A/F ratios of 17.8 and exhaust temperatures of 320 °C during emissions testing. In contrast, the two-stroke motorcycle with catalyst was operated in rich-fuel condition with averaging A/F ratios of 12.1 and exhaust temperatures of 250–300 °C. Theoretically, such a difference in A/F ratios may have already resulted in a 20–30% increase in emissions of various air pollutants for the motorcycles with catalysts. The compositional effects on tail-pipe emissions, however, cannot be evaluated in the current study because the catalyst's detailed components were not fully provided by the companies.

The box plots in Figure 3 also indicate that C_6–C_9 aromatic hydrocarbons had lower converting efficiencies than

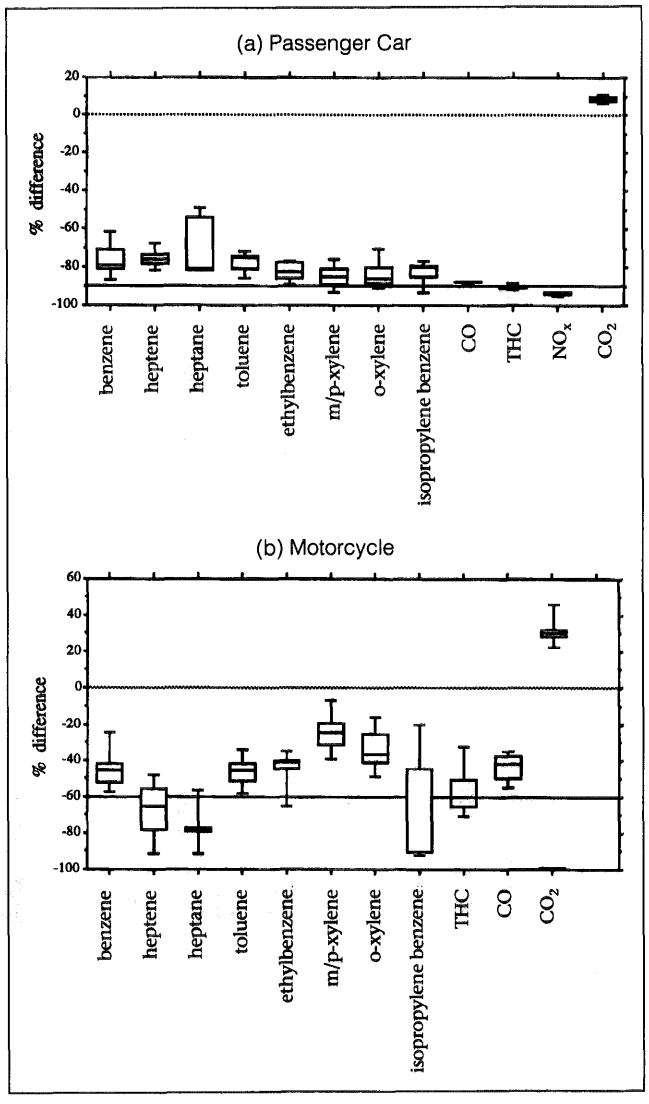

Figure 3. Catalyst reduction efficiencies in passenger cars and motorcycles.

CO and THC. This can be explained by the variation of catalysts in oxidizing and de-alkylating various hydrocarbons in the emissions. Kuo et al. suggested that the oxidation efficiencies of catalysts were 20–80% for saturated HC and 85% for olefins and aromatics.[16] The study by McCabe et al. indicated that the reactivities of hydrocarbons in the catalysts were: unsaturated HC > aromatics > saturated HC > methane.[17] Apparently, a significant proportion of THC in the exhaust was probably C_2–C_5 olefins. These highly reactive olefins therefore contributed to a greater proportion of the catalyst's THC reduction. Unfortunately, these olefins cannot be determined by our sampling and analytical method. A lower converting efficiency for benzene can also be caused by the catalyst's de-alkylation reactions for aromatics. Pelz et al. and Summer et al. suggested that benzene can be formed in the exhausts through alkyl-benzene's hydrodealkylation reactions during a vehicle's high-speed acceleration.[18,19] However, the magnitude of forming benzene through such reactions in exhausts cannot be estimated by the current study because our sampling and analytical methods were limited. Such effects can be evaluated by using on-line monitoring systems for measuring real-time VOCs in the exhaust as suggested by Dearth et al.[20]

CATALYST'S EMISSION REDUCTION AT DIFFERENT PERIODS OF THE FTP AND ECE CYCLES

The emission rates during three phases of the FTP cycle are shown in Figure 4. As expected, the noncatalyst cars' emission rates of THC, CO, and NO_x were all significantly different across three phases of the FTP cycle. For THC and CO, the greatest emission rates always occurred during the engine's low start-up temperatures in Phase 1. For benzene, ethylbenzene, and xylenes, the highest emission rates also occurred during Phase 1. For toluene, the highest emission rates, however, occurred in Phase 2. Such a discrepancy in the emissions of aromatics can be partially explained by the speed difference during three phases of the FTP cycle. Bailey et al. indicated that toluene had the greatest emission reduction among aromatics when the driving speeds changed from 20 km/hr to more than 60 km/hr.[21] Coincidentally, the averaging speeds in our study were about 60–90 km/hr in Phase 1 and 25–45 km/hr in Phase 2.

The magnitude of emission reduction during different phases of driving cycles are illustrated in Table 5. The reduction efficiencies of VOCs during the FTP cycle were 19–65% for Phase 1, 85–95% for Phase 2, and 75–85% for Phase 3. The reduction was the greatest at Phase 2 but the smallest at

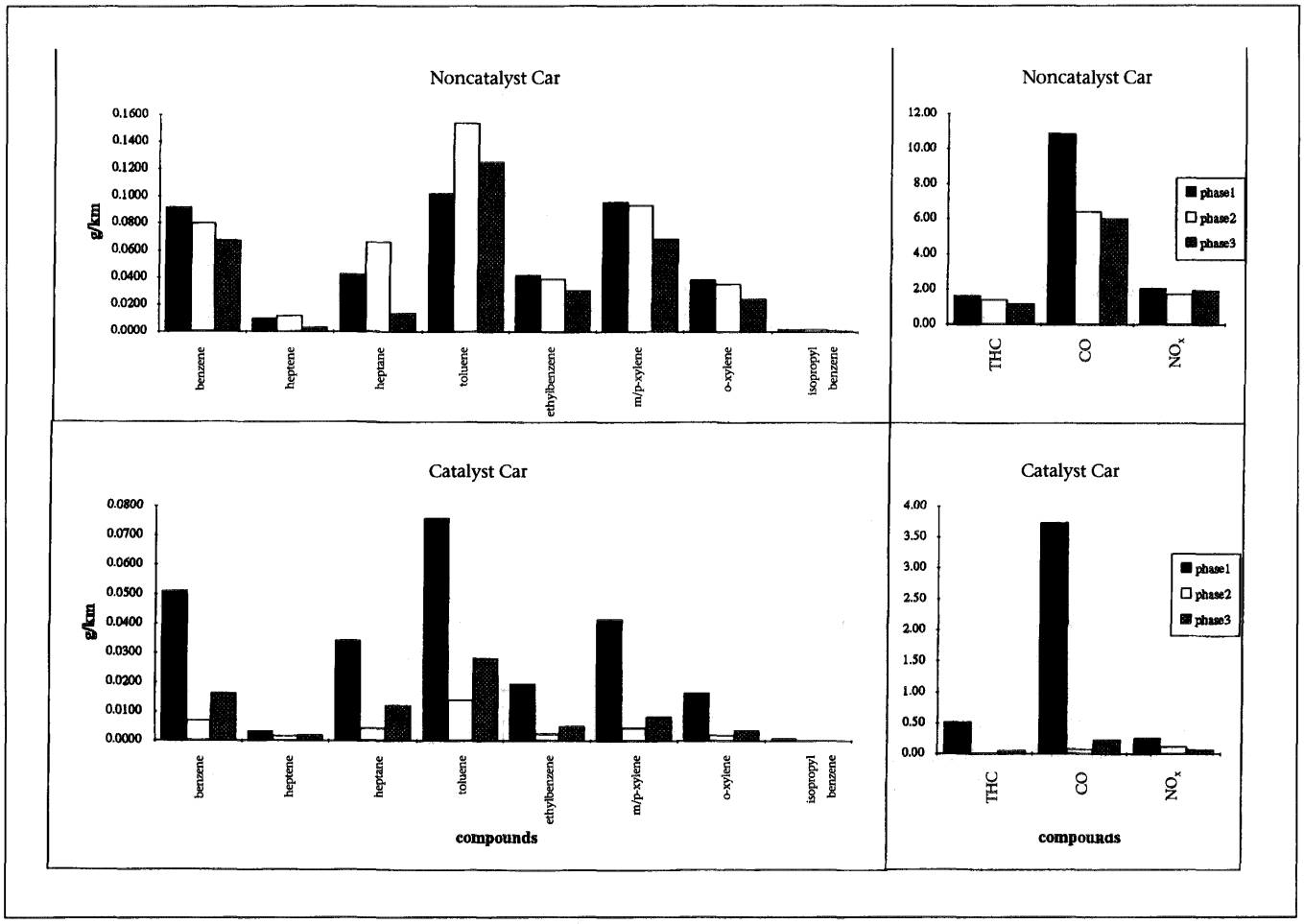

Figure 4. Tail-pipe emission rates during the FTP cycle's three phases.

Table 5. Catalyst reduction efficiencies (%) during different phases of FTP and ECE driving cycles.

Compounds	*Phase 1*	*Phase 2*	*Phase 3*	*Hot vs. Cold*
Benzene	-44.3	-91.3	-76.0	-76.7
Heptene	-65.4	-84.8	-42.6	-76.4
Heptane	-19.5	-93.3	-12.7	-73.3
Toluene	-25.8	-90.9	-77.7	-77.8
Ethylbenzene	-53.8	-93.8	-83.5	-82.4
m/p-xylene	-56.7	-95.1	-87.7	-85.0
o-xylene	-57.1	-94.3	-84.7	-83.6
Isopropyl benzene	-57.4	-91.7	-83.4	-85.0
THC	-68.1	-99.3	-94.8	-90.5
CO	-65.9	-98.7	-96.2	-88.0
NO_x	-87.6	-93.2	-96.4	-94.2
CO_2	7.3	9.0	8.4	8.5

Phase 1 in the FTP cycle. The catalyst's efficiency differences between Phase 2 and Phase 1 were about 40% for eight VOCs, 30% for THC and CO, and 5–10% for NO_x. For the ECE cycle, the catalyst's efficiency differences between hot-start and cold-start were 73–85% for eight VOCs, 91% for THC, 88% for CO, and 94% for NO_x. These differences were understandable because the catalyst's performances depended on exhaust temperatures. Hillard and Springer have previously noted that the catalyst is cold at the start of the driving cycles (about 16–30 °C) and then warms to 200–300 °C later when oxidation of CO and HC occurs.[22]

CONCLUSION

The significance of motorcycles in the emission inventory of mobile sources in Taiwan has been identified in this study. From the viewpoint of the emission rates (g/km) for individual vehicles, one motorcycle's THC and CO emissions were equivalent to the emissions from 12 catalyst cars. In contrast, NO_x emissions occurred mainly from the exhausts of four-stroke engines of cars and motorcycles. For the emissions of CO_2, one of the greenhouse gases, one car's emissions were equivalent to those of about three to eight motorcycles' emissions. Such information is fundamental to valid mobile source emission modeling for tail-pipe emissions, such as the U.S. EPA's MOBILE models. By incorporating motorcycle emission rates, vehicular number, model year, and traveling distance into the emission model, the motorcycle's contribution to the total tail-pipe emission inventory of THC, CO, NO_x, and VOCs can be calculated. First, the results imply that a significant amount of tail-pipe emissions of THC and CO can be reduced by replacing all motorcycles with cars. Second, catalysts should be required in all vehicles to further reduce the emissions of THC, CO, NO_x, and VOCs. This study also demonstrated that the two-stroke motorcycle's catalyst was far less efficient than the car's catalyst. On average, the two-stroke motorcycle's catalyst was only half efficient in reducing emissions compared to the car's. The two-stroke motorcycle's poor control over A/F ratios was thought to be a key factor affecting its emissions and its catalyst's function.

Several limitations exist in this study. First, the factors of fuel component, catalyst, and driving speed that affect the two-stroke motorcycle's emissions of speciated VOCs cannot be fully evaluated because the sampling systems cannot measure emissions continuously. A reliable on-line system for measuring VOCs in emissions should be developed to improve understanding of the formation and removal mechanisms of two-stroke motorcycle exhausts. Second, some important VOCs, such as 1,3-butadiene and ozone precursors, were not measured because our sampling and analytical method cannot trap light-chain hydrocarbons. Applying whole air sampling instruments, such as canisters and Tedlar bags, to emission tests is recommended to collect these compounds. Third, the measured emission rates are lower than averaged emission rates among all vehicles in Taiwan because test vehicles used in this study are relatively new. Additional measurements covering more vehicles and a wider range of model years are essential to verify the study's tail-pipe emission rates in Taiwan.

ACKNOWLEDGMENTS

We would like to thank the Taiwan Environmental Protection Agency (Contract No. EPA-82-E4F1-08-23) for funding this study. We would also like to thank all of the technicians in the emission test facilities for their resourceful help in conducting the study.

REFERENCES

1. Clean Air Act 42; U.S.C. Sections 7401–7671, 1977.
2. Clean Air Act 42; U.S.C. Sections 7401–7671, 1990.
3. Chan, C.C.; Lin, S.H.; Her, G.R. "Student's exposure to volatile organic compounds while commuting by motorcycle and bus in Taipei City," *J. Air & Waste Manage. Assoc.* **1993**, *43*, 1231.
4. Chan, C.C.; Lin, S.H.; Her, G.R. "Office worker's exposure to volatile organic compounds while commuting and working in Taipei City," *Atmos. Environ.* **1994**, *28A*, 2351.
5. Liu, J.J.; Chan, C.C.; Jeng, F.T. "Predicting personal exposure levels to carbon monoxide (CO) in Taipei, based on actual CO measurements in microenvironments and a Monte Carlo simulation method," *Atmos. Environ.* **1994**, in press.
6. Winberry, W.T.; Murphy, N.T.; Riggin, R.M. "Compendium of methods for determination of toxic organic compounds in ambient air,," U.S. Environmental Protection Agency: Research Triangle Park, NC, 1988; EPA-600/4-89/017.
7. Chan, C.C.; Lin, S.H.; Her, G.R. "Student's exposure to volatile organic compounds while commuting by motorcycle and bus in Taipei City," *J. Air & Waste Manage. Assoc.* **1993**, *43*, 1231.
8. SAS® Proprietary Software Release 6.04, ©1987 SAS Institute Inc.: Cary, NC.
9. Heinen, C.M. "We Have Done the Job—What's It Worth?" Paper 801357, The Society of Automotive Engineers, 1980.
10. Patterson, D.J.; Henein, N.A. *Emissions from Combustion Engines and Their Control*, 3rd ed., 1974.

11. Cohu, L.K.; Rapp, L.A.; Segal, J.S. *EC-1 Emission Control Gasoline*; ARCO Products: Anaheim, CA, 1989.
12. Sigsby, J.E.; Tejada, S.; Ray, W.; Lang, J.M.; Duncan, J.W. "Volatile organic compound emissions from 46 in-use passenger cars," *Environ. Sci. Technol.* **1987**, *21*, 466.
13. Bailey, J.C.; Schmidl, B.; Williams, M.L. "Speciated hydrocarbon emissions from vehicles operated over the normal speed range on the road," *Atmos. Environ.* **1990**, *24A*, 43.
14. Chan, C.C.; Lin, S.H.; Her, G.R. "Student's exposure to volatile organic compounds while commuting by motorcycle and bus in Taipei City," *J. Air & Waste Manage. Assoc.* **1993**, *43*, 1231.
15. Chan, C.C.; Lin, S.H.; Her, G.R. "Office worker's exposure to volatile organic compounds while commuting and working in Taipei City," *Atmos. Environ.* **1994**, *28A*, 2351.
16. Kuo, J.C.; Morgan, C.R.; Lassen, H.G. "Mathematical modeling of converter systems," Paper No. 910289, The Society of Automotive Engineers, 1971.
17. McCabe, R.W.; Siegl, W.O.; Chun, W.; Perry, J.J. "Speciated hydrocarbon emissions from the combustion of single component fuels," *J. Air & Waste Manage. Assoc.* **1991**, *42*, 1071.
18. Pelz, N.; Dempster, N.M.; Hundleby, G.E.; Shore, P.R. "The composition of gasoline engine hydrocarbon emissions—An evaluation of catalyst and fuel effects," Paper No. 902074, The Society of Automotive Engineers, 1990.
19. Summers, J.C.; Silver, R.G. "Catalytic control issues associated with the use of reformulated gasolines," Paper No. 902072, The Society of Automotive Engineers, 1990.
20. Dearth, M.A.; Glerczak, C.A.; Slegl, W.O. "On-line measurement of benzene and toluene in diluted vehicle exhaust by mass spectrometry," *Environ. Sci. Technol.* **1992**, *26*, 1573.
21. Bailey, J.C.; Schmidl, B.; Williams, M.L. "Speciated hydrocarbon emissions from vehicles operated over the normal speed range on the road," *Atmos. Environ.* **1990**, *24A*, 43.
22. Hilliard, J.C.; Springer, G.S. *Fuel Economy in Road Vehicles Powered by Spark Ignition Engines*; Plenum Press: London, 1984.

About the Authors

Chang-Chuan Chan and Chiu-Kuei Nien are with the Institute of Occupational Medicine and Industrial Hygiene, College of Public Health, National Taiwan University, Room 1447, No. 1 Jen-Ai Road, 1st Sec., Taipei, Taiwan. Cheng-Yuan Tsai and Guor-Rong Her are with the Department of Chemistry, National Taiwan University, No. 1 Roosevelt Road, 4th Sec., Taipei, Taiwan.