Air pollutant emission factors from new and in-use motorcycles

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Abstract

The emissions of carbon monoxide (CO), nitrogen oxides (NO_x) and total hydrocarbon (THC) from 7 new and 12 in-use motorcycles with or without the catalyst were evaluated by testing these vehicles on a dynamometer. Also the concentrations of volatile organic compounds (VOCs) in five driving patterns, including idle, acceleration, 30 km h⁻¹ cruise, 50 km h⁻¹ cruise, and deceleration, were monitored. Experimental results indicate that the emissions of CO and THC from in-use motorcycles are significantly higher than new ones, but not for NO_x, and the emissions of THC from 2-stroke motorcycles are much higher than 4-stroke ones. The emissions of VOCs from in-use motorcycles are higher than new motorcycles for all five driving patterns, and those from 2-stroke engines are higher than 4-stroke motorcycles. Emission of VOCs in the modes of deceleration and idle accounts for the most mass emitted during the test driving cycle. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Motorcycle; Dynamometer; Volatile organic compound; Driving pattern; Emission factor

1. Introduction

Taiwan has had significant air pollution problems accompanied with the rapid economic development since 1970s. A great number of motor vehicles, including passenger cars, buses, and motorcycles, route around the island and exhibit serious air pollution problems both in urban areas and suburban regions. There are about 16 million motor vehicles in Taiwan, with about 66% motorcycles, 32% gasoline passenger cars, and 1% of diesel trucks and buses (MOT, 1998). These vehicles contribute a greater portion of air pollutant emissions. For example, in 1995 the emissions of carbon monoxide (CO), nitrogen oxide (NO_x), non-methane hydrocarbon (NMHC), and particulate matters (PM) were estimated to be 1720, 420, 840, and 530 thousand metric tons, respectively, in Taiwan (TEPA, 1997). Meanwhile, the mobile emissions accounted for 83% of CO, 49% of

NO_x, 33% of NMHC, and 9% of PM in the inventory. The detailed source profiles of various mobile emissions further indicated that 38% of CO, 3% of NO_x, 64% of NMHC, and 30% of PM were released from motorcycles (TEPA, 1998). Because of their mobility and convenience, motorcycles are extremely popular in both urban and rural areas in Taiwan and some other countries in South-east Asian, and the quantity of motorcycles is expected to increase in the future. The main type of motorcycles in Taiwan is 2-stroke engine with 61%, and the other is 4-stroke engine.

In order to improve the air quality, the Taiwan Environment Protection Administration has declared a policy to minimize the emissions from major sources. However, a more accurate emission inventory is necessary for successful strategy and implementation. For instance, when considering whether to give priority to phase-out of the 2-stroke engine motorcycles, is it definitely needed to understand the source profile, emission rate, and source inventory? Although some researches about control programs for motorcycle emissions have been reported, only few studies focus on motorcycle emissions (Chan et al.,

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1995; Tsai et al., 1997). Consequently, this study was undertaken to assess the engine exhaust of CO, THC and NO_x, from both new and in-use motorcycles. Emission tests were conducted on a dynamometer following the designated test procedure similar to that of the Economic Commission for Europe (ECE). The effects of engine types (2- and 4-stroke), mileage, and installation of the catalyst on the emission were evaluated.

2. Methods and materials

2.1. Selection of motorcycles

Test motorcycles were selected according to the engine type, installation of the catalyst or not, and mileage of in-use motorcycles in southern Taiwan. There were 19 motorcycles tested in this study, including 7 new and 12 in-use motorcycles. The later consisted of eight 2-stroke and four 4-stroke engines, while the former of four 2-stroke and three 4-stroke engines.

The new motorcycles were supplied by a manufacture plant and were ready for sell. All these new motorcycles must comply with EPA’s emission standard. The in-use motorcycles tested in this study were selected from a service center of in-use motorcycles. These in-use motorcycles were chosen mainly considering theirs accumulated running mileage. Unlike new motorcycles, tested in-use motorcycles did not necessarily comply with the emission standard, though the in-use motorcycle emission standard is quite loose.

According to the engine types (2- and 4-stroke), running mileage (new, in-use) and the condition of catalyst (with and without), the tested motorcycles were divided into five groups (as shown in Table 1): 2-stroke-new-w-catalyst, 4-stroke-new-w/o-catalyst, 2-stroke-in-use-w-catalyst, 2-stroke-in-use-w/o-catalyst, and 4-stroke-in-use-no-catalyst. The oldest motorcycle tested in this study was produced in 1982.

2.2. Selection of testing cycle

The driving patterns of vehicles in the metropolitan areas in Taiwan are similar to those of ECE cycle, which is adopted as the test standard consequently (TEPA, 1996). One complete test cycle (780 s) includes idle (240 s), acceleration (168s), cruising (228s), and deceleration (144s), and four different cruising speeds are applied in the tests: 15, 32, 35, and 50 km h⁻¹. Fig. 1 shows the driving pattern of testing cycle.

2.3. Dynamometer testing

The dynamometer used in this study is located in a certified laboratory of a motorcycle manufacture plant.

Table 1
Conditions of tested motorcycle

Classification		Number	Mileage (10 ³ km)
2-stroke	New-w-catalyst	4	
	In-use-w-catalyst	5	3.1–34.1
	In-use-w/o-catalyst	3	43.4–210
4-stroke	New-w/o-catalyst	3	
	In-use-w/o-catalyst	4	10.8–41.4

Tested motorcycles were examined first for safety and replaced fuel to make sure that no additives in the fuel. Overnight, after preliminary examination, tested motorcycles were warmed up before running the driving cycles on the dynamometer. Each motorcycle was tested once for whole cycles. Fig. 2 indicates the flow scheme of dynamometer testing and gas sampling.

2.4. Gas sampling and analysis

Two types of samples were collected in each test. One was for the entire cycle with an automated instrument for CO, NO_x, and THC measurements, and the other was for stage emissions under different driving patterns for hydrocarbon speciation. The tailpipe of motorcycles was directly connected to a sampling system under testing conditions of the entire cycle. Exhaust gas was emitted to a constant volume system (chamber) and diluted using indoor air, then was leaded into sampling bags and analyzed for CO, THC, and NO_x by monitors (HORIBA, MEXA-8320). The background concentrations of indoor air were also analyzed routinely and deducted from the test results. Background concentrations for CO, THC, and NO_x were about 2, 6 ppm C, and 0.1 ppm, respectively, and were much lower than sampled gases.

For different driving pattern sampling, five vacuum boxes were applied to contain various gas samples, and each vacuum box contained a 3-l Tedlar bag. Exhaust gas was diluted using room ambient air pumped with a controlled flowrate. Several control valves were used to guide samples of different driving patterns into various designated Tedlar bags. Due to the limitation of available facility, the sampling work was conducted manually. After samples were taken, the bags were placed into a black container and carried to the analysis laboratory for hydrocarbon species analysis within 4 h. Background samples from the room air in the dynamometer laboratory were also recorded.

In the analysis laboratory, hydrocarbon species in the sample bags were preconcentrated by a purge and trap system (AERO Trap Desorber, Tekmar 6000) and then analyzed by a GC/MS (Hewlett Packard 5890II &

Fig. 1. ECE driving cycle of vehicle testing procedure.

Hewlett Packard 5972). The thermal desorber was preheated at 200°C and the injection temperature was 225°C; the samples were standby at 35°C and the trap was cooled down to -170°C . Cryo was standby at 200°C, the focus temperature was -170°C , and the MS line temperature was 200°C. GC was equipped with a fused silica capillary column (60 m at 0.32 mm ID with 1 μm DB-1).

Calibration standard gases of hydrocarbon species were prepared by diluting the certified standard gas (56 Environ-Mat Ozone Precursor, 16183, Matheson) with ultra-high-purity nitrogen in dilution bottles. The performance of GC/MS was evaluated with perfluorotributylamine for quality control. The sum of those non-methane hydrocarbon species was determined afterwards.

2.5. Data analysis

The emission factors of various pollutants were assessed with the exhaust concentrations, the volume of the exhaust, and the total running mileage in one test cycle. Because the actual exhaust volumes in various driving patterns were not available, the mean rotating speed of

engine, volume of the cylinder, and the running time in that driving period were applied to derive the emission factors. The equations are listed as follows:

$$E = M \times V^* \times 10^{-3}, \quad (1)$$

$$EF = E/L, \quad (2)$$

where E is the exhaust amount of the pollutant (g) in a specific driving mode, M is the concentration of the pollutant (mg N m^{-3}), V^* is the normalized value of the exhaust gas volume given by the dynamometer laboratory of the motorcycle manufacture plant after temperature and pressure correction (N m^3), L is the traveled mileage during the test procedure (km), and finally EF is the emission factor of that pollutant (g km^{-1}).

3. Results and discussion

3.1. Emission factors

The emission factors for various pollutants are listed in Table 2. Except for NO_x , the emission factors of CO ,

Fig. 2. Schematic diagram of gas sampling system.

Table 2
Emission factors of different type motorcycles

Motorcycle type		Emission factors (g km ⁻¹)			
		CO	NO _x	THC	VOCs
2-stroke	New-w-catalyst	2.63 ± 1.96	0.035 ± 0.035	3.28 ± 2.01	2.59 ± 2.43
	In-use-w-catalyst	21.72 ± 13.86	0.016 ± 0.006	15.16 ± 12.36	5.17 ± 3.70
	In-use-w/o-catalyst	39.92 ± 27.18	0.015 ± 0.003	20.04 ± 10.29	7.89 ± 6.37
4-stroke	New-w/o-catalyst	5.66 ± 0.76	0.46 ± 0.040	1.50 ± 1.49	0.15 ± 0.065
	In-use-w/o-catalyst	36.10 ± 13.58	0.25 ± 0.13	3.20 ± 0.56	2.22 ± 0.81

THC, and VOCs from in-use motorcycles are all higher than those from new ones. The most substantial differences occur in CO: the emission factor of in-use motorcycles is approximately 8–15 times higher than the new ones of 2-stroke engine and 6 times than that of 4-stroke engine. In-use motorcycles also contribute more THC per kilometer than the new ones, especially for 2-stroke ones (4–6 times more). In addition, 2-stroke engines emitted more THC per kilometer traveled than 4-stroke ones, especially for the used motorcycles. The results obtained in this study are comparable to those of others

(Chan et al., 1995). These data indicate that the motorcycles equipped with catalyst significantly reduce CO and THC emissions. Summary from above results and statistics of Ministry of Transportation (1998), 2-stroke motorcycles are the dominant emission source of THCs in Taiwan.

In contrast, the NO_x emission factors of 4-stroke motorcycles are much higher than 2-stroke ones. However, the emission standard of NO_x for in-use motorcycle is not yet regulated in Taiwan. High combustion efficiency of fuel, may reduce emissions of hydrocarbon and CO,

but increase emission of NO_x . These effects may explain the difference between 2- and 4-stroke engine emissions.

3.2. Emission vs. engine mileage and catalyst converter installation

The relationship between accumulated running mileage of the in-use motorcycles and various pollutant emissions show a slight correlation but great variation. For in-use 2-stroke motorcycles, the emission factors of CO and THC for those without catalyst are 1.84 and 1.32 times of those with catalyst, respectively. Installation of catalyst could effectively reduce emissions of CO and THC, but not for NO_x . However, the emissions of CO and THC from in-use 2-stroke motorcycles without catalyst are 15.2 and 6.1 times of those from brand new 2-stroke motorcycles. The effective lifetime of catalyst is typically only 1–2 years, thus two-year or longer used motorcycles may perform as those without catalyst installation, unless those catalysts are replaced by new ones. Therefore, the status of catalyst can be very important to the emission degradation of THC and CO from 2-stroke motorcycles. In general, the emissions of CO and THC increase with the engine age. This trend is consistent with the study of Winebrake and Deaton (1997) in investigating the positive relationship between HC emissions and the age of the vehicle. Interesting enough, the NO_x emissions of in-use 2-stroke engines are not correlated with the installation of catalyst. In fact, new 2-stroke motorcycles with catalyst have higher NO_x emission than in-use 2-stroke motorcycles regardless of installation of catalyst or not. New motorcycles may perform better combustion efficiency and lead higher NO_x emissions.

3.3. VOC groups in the tailpipe exhaust

The concentrations of individual volatile organic compounds in the tailpipe exhaust were listed in Table 3. There are totally 48 species of volatile organic compounds identified and quantified. Some species carried in the standard gas could not be found in the exhaust gas.

For new 2-stroke motorcycles, the dominant VOC species in the tailpipe exhaust include isopentane, *n*-pentane, toluene, 2-methylpentane, and 3-methylpentane. For in-use 2-stroke motorcycles, the dominant species are isopentane, toluene, 2-methylpentane, *n*-pentane and *m,p*-xylene, which are similar to new 2-stroke motorcycle exhaust.

The dominant species of VOCs in the exhaust from new 4-stroke motorcycle are toluene, isopentane, propylene, *n*-pentane, and *m,p*-xylene. The concentrations of the other species are usually lower than 20 mg N m^{-3} . The dominant species of VOCs in the exhaust from

in-use 4-stroke motorcycle are toluene, isopentane, *m,p*-xylene, *n*-pentane, and *o*-xylene, with concentrations beyond 200 mg N m^{-3} .

The prevalently dominant VOCs species in the exhaust from various types of motorcycles include isopentane, *n*-pentane, and toluene, while *m,p*-xylene is also a dominant component among VOC speciation in the engine exhaust. The data shown in Table 3 also indicate that the VOCs profiles in the motorcycle exhaust from are very complicated. However, the profile of VOCs in the engine exhausts is anticipated to be affected by fuel composition, engine combustion condition, and pollution control device equipped.

Totally 47 species of volatile organic compounds in the tailpipe exhaust were identified and grouped into three categories: alkane (24 species), alkene (13 species), and aromatics (10 species), while 9 remaining components of standard gas were not detected in the exhausts. The molecule weight of these species are in the range between ethylene ($\text{MW} = 28.05$) and *n*-nonane ($\text{MW} = 128.26$), which include benzene, toluene, xylene, and trimethylbenzene. The mass fractions of various VOC species from 2- and 4-stroke engines were not consistent. The concentrations of various species from new and in-use motorcycles were also varied a little. Table 4 indicates the mass fractions of three VOC groups based upon values of the emission factors.

Aromatic VOCs is the dominant group both for new and in-use 4-stroke engines. Alkane VOCs is the dominant group for 2-stroke engines. The mass fraction of aromatic VOCs in new and in-use 4-stroke motorcycles did not change significantly, but the mass fraction varied in 2-stroke motorcycle emissions. The changes of alkane and alkene between in-use and new motorcycles were obvious. The mass fraction of alkane reduced for in-use 2-stroke motorcycles while those of alkene and aromatic species increased significantly as compared to new ones. On the contrary, the mass fraction of alkane slightly increased for in-use 4-stroke engines while those of alkene decreased in the engine exhaust.

3.4. VOCs emission from various driving pattern

The emission factors of total 47 VOCs at various driving modes on the dynamometer are listed in Table 5. For 2-stroke motorcycles, the emission during the deceleration mode is the highest among all driving modes both for the in-use and the new motorcycles. The installation of the catalyst significantly reduces VOC emission. For used 4-stroke motorcycles, the emission during the deceleration mode is also the highest. In all cases the emission factors of VOCs in the 50 km h^{-1} cruising mode is higher than those in 30 km h^{-1} mode. These results are different from that reported by Sigsby et al. (1987), who suggested a less hydrocarbon emissions with a higher cruising speed.

Table 3
Mass concentrations (mg Nm^{−3}) of VOCs from motorcycle exhaust^a

		2-stroke New (N = 4)	In-use (N = 8)	4-stroke New (N = 4)	In-use (N = 6)
Alkane	<i>n</i> -Butane	26.5	48.0	0.3	17.3
	Isobutane	12.4	11.7	0.1	4.6
	<i>n</i> -Pentane	455.5	484.1	7.0	205.4
	Isopentane	513.1	1128.0	14.0	408.8
	Cyclopentane	34.9	90.5	1.0	28.2
	Methylcyclopentane	96.4	121.5	0.4	41.2
	Cyclohexane	5.8	16.7	0.0	4.8
	<i>n</i> -Hexane	40.2	128.3	0.3	32.6
	2-Methylpentane	182.9	526.9	3.1	109.0
	3-Methylpentane	139.2	274.1	1.9	76.7
	2,2-Dimethylbutane	68.1	141.5	1.1	29.8
	2,3-Dimethylbutane	72.4	141.9	1.5	36.3
	Methylcyclohexane	24.5	22.7	0.2	12.9
	2-Methylhexane	106.7	253.2	1.4	88.4
	2,3-Dimethylpentane	47.1	64.0	0.4	23.1
	2,4-Dimethylpentane	27.3	281.7	0.2	14.0
	3-Methylhexane	94.1	204.5	1.1	63.6
	<i>n</i> -Heptane	77.5	167.1	0.9	63.9
	2,2,4-Trimethylpentane	97.4	70.9	1.0	35.9
	2,3,4-Trimethylpentane	47.9	36.3	0.3	15.8
	2-Methylheptane	69.7	110.7	0.6	46.8
	3-Methylheptane	74.0	113.8	0.8	47.4
	<i>n</i> -Octane	40.0	54.1	0.5	31.6
	<i>n</i> -Nonane	28.5	29.7	0.3	21.2
Alkene	Propylene	0.0	33.9	8.4	114.7
	1-Butene	48.8	218.4	1.7	59.0
	<i>trans</i> -2-Butene	11.3	21.7	0.4	7.1
	<i>cis</i> -2-Butene	5.1	54.0	0.4	9.0
	3-Methyl-1-butene	4.1	13.2	0.1	2.5
	1-Pentene	6.8	21.6	0.3	9.6
	<i>trans</i> -2-Pentene	13.2	46.8	0.5	21.6
	<i>cis</i> 2-Pentene	7.4	27.0	0.4	15.2
	2-Methyl-2-butene	23.4	92.9	0.7	35.1
	Cyclopentene	4.4	26.1	0.4	12.4
	2-Methyl-1-pentene	7.9	15.6	0.3	6.7
	<i>trans</i> -2-hexene	3.1	7.8	0.1	3.4
Aromatic	<i>cis</i> -2-hexene	3.1	2.3	0.0	3.6
	Benzene	110.9	322.1	5.3	125.7
	Toluene	316.5	849.1	26.8	577.8
	Styrene	8.6	11.0	0.1	12.7
	Ethylbenzene	40.7	110.6	1.1	128.4
	<i>m, p</i> -Xylene	89.6	471.3	6.0	414.3
	<i>o</i> -Xylene	55.9	192.8	1.4	198.5
	Isopropylbenzene	16.3	22.7	0.2	17.5
	<i>n</i> -Propylbenzene	14.2	37.2	0.8	39.1
	1,3,5-Trimethylbenzene	47.9	76.9	2.5	154.8
	1,2,4-Trimethybenzene	66.2	39.6	3.8	92.3

^aN: Number of samples.

Table 4
Mass fractions (based upon emission factors) of three VOC groups

Motorcycle type		Number	VOC mass fraction (%)		
			Alkane	Alkene	Aromatic
2-stroke	New-w-catalyst	4	69 ± 4	5 ± 1	26 ± 3
	In-use-w-catalyst	5	57 ± 20	11 ± 7	32 ± 15
	In-use-w/o-catalyst	3	45 ± 6	16 ± 16	39 ± 22
4-stroke	New-w/o-catalyst	3	40 ± 11	13 ± 5	47 ± 6
	In-use-w/o-catalyst	4	44 ± 12	10 ± 5	46 ± 17

Table 5
Emissions of VOCs from motorcycle exhaust at different driving patterns

Motorcycle type		Emission factors (g km ⁻¹)				
		Idle	Acceleration	30 km h ⁻¹ cruise	50 km h ⁻¹ cruise	Deceleration
2-stroke	New-w-catalyst	0.98 ± 0.99	1.24 ± 0.47	1.60 ± 1.88	2.78 ± 2.52	4.13 ± 4.40
	In-use-w-catalyst	0.98 ± 0.82	2.27 ± 1.28	2.23 ± 1.32	3.11 ± 0.97	4.41 ± 3.52
	In-use-w/o-catalyst	2.11 ± 1.42	2.81 ± 2.23	5.20 ± 6.15	6.54 ± 6.94	13.39 ± 11.21
4-stroke	New-w/o-catalyst	0.01 ± 0.01	0.16 ± 0.14	0.07 ± 0.05	0.23 ± 0.21	0.16 ± 0.04
	In-use-w/o-catalyst	0.32 ± 0.28	0.47 ± 0.39	0.54 ± 0.46	0.83 ± 0.59	3.58 ± 1.69
		Mass emissions (g test-mode ⁻¹)				
2-stroke	New-w-catalyst	3.92 ± 4.00	1.18 ± 0.43	2.29 ± 2.53	1.85 ± 1.70	3.49 ± 3.79
	In-use-w-catalyst	3.92 ± 3.48	2.17 ± 1.26	3.21 ± 1.92	2.07 ± 0.62	3.73 ± 2.80
	In-use-w/o-catalyst	8.44 ± 5.72	2.68 ± 2.11	7.47 ± 8.50	4.36 ± 4.86	11.31 ± 9.42
4-stroke	New-w/o-catalyst	0.04 ± 0.04	0.15 ± 0.14	0.10 ± 0.07	0.15 ± 0.14	0.14 ± 0.04
	In-use-w/o-catalyst	1.28 ± 1.16	0.45 ± 0.38	0.78 ± 0.65	0.56 ± 0.39	3.02 ± 1.62

The total emissions of VOCs in a test cycle to simulate the on-road emission fraction for various driving modes are also shown in Table 5. For in-use 2-stroke motorcycles with catalyst, the emissions from idle and deceleration modes contribute about 50% of total emission of the test cycle, and 57% of those without catalyst. The data strongly support the policy to phase out the 2-stroke motorcycles in the near future for THC emission reduction in Taiwan. However, the type shift of motorcycles from 2- to 4-stroke will increase the emission of NO_x in the source category of motorcycles.

4. Conclusions

The emissions of CO, THC, and some species of VOCs from in-use motorcycles are higher than those from new ones as tested on a dynamometer. The emission factors of THC from 2-stroke motorcycles, either with or without catalyst installation, are higher than that from 4-stroke motorcycles without catalyst. The emissions of CO for in-use motorcycles are much higher than new engines, no matter whether installation of catalyst or not. It also shows a clear degradation of CO emissions for in-use motorcycles. However, installation of catalyst on

2-stroke motorcycles could significantly reduce the emission of CO and THC, but not the NO_x emission. The effect of accumulated running mileage and engine age on the emissions of CO and THC show a slight correlation but great variation. The results indicate that a number of factors, such as maintenance, may play an important role in engine emission from motorcycles.

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