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Criteria Pollutants and Volatile Organic Compounds Emitted from Motorcycle Exhaust under Various Regulation Phases

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ABSTRACT

Establishment of emission standards is an important measure for controlling vehicle exhaust. This study examined the emission factors of air pollutants from 40 four-stroke motorcycles of various emission standard phases, ages, and mileage. Based on the emission standards, the motorcycles were divided into three groups (Phases III, IV and V). Regulated air pollutants (CO, HC, and NO_x), CO_2, and 52 volatile organic compounds were evaluated on a chassis dynamometer using the Economic Commission for Europe (ECE) test cycle. The sequence of CO and HC emission factors was Phase III > Phase IV > Phase V, and their ratios of emission factor of Phase IV to Phase III and Phase V to Phase III were 0.66 and 0.42 for CO and 0.61 and 0.57 for HC, respectively. Exhaust from motorcycles deteriorates with age and mileage. For NO_x emission, the sequence of emission factor was Phase V > Phase IV > Phase III. However, the relationship was insignificant between CO_2 emission factor and motorcycle age. The total VOC emissions of Phase V motorcycles were the lowest (0.59 g km^{-1}) among all test motorcycles; however, the fraction of VOC groups was similar among all test motorcycles regardless of different regulation phases. For organic air toxics, the emissions of benzene, toluene, ethylbenzene, and xylene (BTEX) decreased by 37–58% and 44–62%, respectively, for Phases IV and V motorcycles compared to those of Phase III motorcycles. Results also indicated that the ozone formation potential (OFP) was high in older motorcycles with high mileage. In summary, emissions of CO, HC, total VOCs, BTEX, and OFP may decrease with the decrease of motorcycle age and mileage as well as the phase of emission standards. The results implied that tightening emission standards indeed encourages motorcycle manufacturers to improve engine technology and combustion efficiency, resulting in reduced emission of air pollutants, except NO_x emission in this study.

Keywords: Volatile organic compounds (VOCs); Organic air toxics; ozone formation potential (OFP); Motorcycle deterioration.

INTRODUCTION

In 2013, there were about 350 million motorcycles in the world, and that number was expected to increase to 500 million by 2015. Motorcycles are an important means of transportation in Asia (The Freedonia Group, 2013). Recently in Europe, the use of motorcycles has increased significantly in Italy (Rome, Milan), France (Paris), the United Kingdom (London), and Spain (Barcelona) (Dall'Osto and Querol, 2013; MECA, 2014). In Asia, motorcycles with small engine capacity (less than 150 cm^3) predominate. About 65–75% of on-road vehicles are motorcycles, most with displacements of 50–125 cm^3, which are by far more popular than heavy-duty motorcycles (displacement over 250 cm^3) in China, India, Indonesia, Taiwan, and Thailand (The Freedonia Group, 2013). A significant amount of air pollution, especially carbon monoxide (CO) and hydrocarbon (HC) emissions in urban areas (Xie *et al.*, 2004; Cheng, 2013; Yao and Tsai, 2013; Lin *et al.*, 2014, Wu *et al.*, 2015; Yao *et al.*, 2017), is contributed by motorcycles in Taiwan and other Asian counties. According to the Taiwan Environmental Protection Administration (TEPA) emission inventory, motorcycles contributed approximately 178,700 ton yr^{-1} (19.6%) for CO, 89,300 ton yr^{-1} (10.6%) for HC, and 13,500 ton yr^{-1} (2.6%) for oxides of nitrogen (NO_x) (TEPA, 2013). Continuous growth in the use of motorcycles has made their emissions a major source of air pollutants in urban areas in Taiwan (CTCI Corporation, 2007), and the pollution problem is also a concern in other Asian countries (Sahu *et al.*, 2014; Mishra and Goyal, 2015).

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To improve air quality, the TEPA began introducing emission standards for motorcycles in 1987 according to two main categories: (1) idle testing for in-use motorcycles and (2) idle testing and dynamometer driving cycle testing for new motorcycles. These tests are performed to curb CO, HC, and NO_x emissions by their emission factors. The detailed motorcycle emission standards of each standard phase are shown in Table 1. A primary change was made in the Phase IV standard (enforced in January 2004), which is that the testing driving cycle was changed from hot-start to cold-start. In Taiwan, the average travelling distance of a ride was less than 10 km for 75% of motorcycles, and the traveling time was less than 20 min (MOTC, 2012). The cold-start driving cycle reflects actual driving habits, as the subtropical weather in Taiwan requires no warm up for motorcycles. The motorcycle population in Taiwan comprises primarily four-stroke motorcycles. The exhaust standards were revised again in Phase V, with the current standard (enforced in July 2007) forcing motorcycle manufacturers to develop new engine technology, i.e., fuel injection, to replace carburetors. Phases VI and VII have also been established and will be enforced in 2017 and 2021, respectively.

Previous work showed a slight correlation but great variation in the relationship of accumulated running mileage and engine age on the emissions of CO and HC (Tsai *et al.*, 2000). A number of mechanical factors, such as motorcycle maintenance and inspection and deterioration, may play an important role in engine emissions from motorcycles. Few works have focused on mileage and age effects on the emission of motorcycle tailpipe exhaust (Chen and Jeng, 2009; Yang *et al.*, 2012) in the real world. Chen and Jeng (2009) determined the failure rate based on the regular pollutant emissions of motorcycles by the regular testing program during 1996–2005 and evaluated the effectiveness of the implemented government control measures. The work focused mainly on failure rate and motorcycle age, but it did not address the relationship of exhaust emission and motorcycle age and running mileage. Yang *et al.* (2012) selected nine motorcycles to determine their CO, hydrocarbon, NO_x, CO_2 and carbonyl species emission. The mileage of their test motorcycles was less than 16,000 km. In Taiwan, more than 50% of motorcycles are older than 6 years, and their running mileage is higher than 16,000 km, so the data of Yang *et al.* (2012) did not accurately reflect the high mileage and age of motorcycles in Taiwan. According to statistical data issued by the Ministry of Transport and Communications (MOTC), the mean age of motorcycles was 10.5 years in 2014. The mean cumulative running mileage of motorcycles was 30,972 km in 2014, and the yearly mean mileage was 4,772 ± 367 km for four-stroke motorcycles in 2010 (TEPA, 2013; MOTC, 2016). The lifetime of motorcycles can be up to 16 years (MOTC, 2016).

In this work, 40 four-stroke motorcycles reflecting the actual age distribution of motorcycles in Taiwan were selected. In addition, dynamometer testing was employed following the ECE test cycle to identify the detailed constituents of motorcycle exhaust. The regulated air pollutants (CO, HC and NO_x) and CO_2 from motorcycle

Table 1. Motorcycle Emission Standards in Taiwan.

Emission standard		Driving test (g km^{-1})					Idle			Mileage guarantee (km)
		CO	HC[3]	NO_x	PM	NO_x + HC (g km^{-1})	CO (%)	HC (ppm)	Opacity (%)	
Initial (1980/06/05)	New	-				-	4.5	7000		-
	In-use	-				-	4.5	9000		-
Phase I (1988/07/01)	New[1]	10.2				6.5	4.5	7000		-
	New[2]	8.8				5.5				
	In-use	-				-	4.5	9000		-
Phase II (1991/07/01)	New	4.5				3.0	4.5	7000		6000
	In-use						4.5	9000		
Phase III (1998/07/01)	New	3.5				2.0	4.0	6000		15000
	In-use						4.5	9000		
Phase IV (2003/12/31)	New 2-stroke	7.0				1.0	3.0	2000		15000
	4-stroke	7.0				2.0				
	In-use						3.5	2000		
	New 4-stroke	2.0	0.8	0.15		-	3.0	1600		15000
Phase V (2007/07/01)	In-use						3.5	1600		
Phase VI (Euro 4) (2017/01/01)	New	1.14	0.38	0.07			2.0	1000	15	20000
	In-use						2.0	1000	30	
Phase VII (Euro 5) (2021/01/01)	New	1.0	0.1/0.068 (HC/NMHC[4])	0.06	0.0045		2.0	1000	15	
	In-use						2.0	1000	30	20000

1. Motorcycles produced before December 31, 1987.
2. Motorcycles produced after January 1, 1988.
3. HC: Total hydrocarbon.
4. NMHC: non-methane hydrocarbon.

exhaust and fuel consumption were determined during the legislative test procedure. Volatile organic compound (VOC) constituents in exhaust for the entire driving cycle were also examined. Consequently, this study investigated the effects of mileage and age in motorcycles on engine exhaust emissions. The use of sufficient and representative data enables this study to make an important and novel contribution to the field of motorcycle emissions and air pollution control strategies in urban areas.

EXPERIMENTAL

Selected Motorcycles

Forty in-use four-stroke motorcycles were tested in this study, including those in compliance with Phase III, IV, and V emission standards. The engine displacement of all selected motorcycles was 125 cc. The age of motorcycles ranged from one to 14 years and the mileage from 90 to more than 50,000 kilometers. The mileage and age ranges of motorcycles were 28,083–50,512 km and 10–14 yrs., 18,490–43,633 km and 6–9 yrs., 90–28,083 km and 1–6 yrs. for Phases III, IV and V, respectively. The average age and mileage of selected motorcycles was 6.4 years and 22,000 km, respectively. The average yearly mileage of selected motorcycles was 3,450 km per vehicle. The correlation between age and mileage is illustrated in Fig. 1; a high correlation ($r^2 = 0.86$) is observed.

Dynamometer Testing

Exhaust emissions of target air pollutants were measured using selected motorcycles tested on a chassis dynamometer. A legislative test procedure, CNS 11386, was used for the motorcycle emission test. The test procedure is the same as the ECE test cycle. One complete test cycle (780 seconds) includes the following stages: idle (240 seconds), acceleration (168 seconds), cruising (228 seconds, 30 and 50 km hr^{-1}), and deceleration (144 seconds).

The exhaust emission tests were conducted on a chassis dynamometer in the certified laboratory of a local motorcycle manufacturer. The main dynamometer system consists of a dilution tunnel, a constant volume system (CVS) unit (HORIBA, CVS-51S) and an exhaust gas analyzer (HORIBA, MEXA-8320). The temperature in the test room ranges from 20 to 30°C. Exhaust samples were collected for the entire cycle; the exhaust gas was initially mixed with air, directed to the CVS unit, and then connected to the sampling bags and analyzer.

Test fuel was commercial unleaded gasoline with an octane number of 95 with 10.2% of methyl tert-butyl ether (MTBE) as the oxygenated additive. Oxygen content was 1.8 wt%; aromatics 30.0 wt%; olefins 10.8 wt%; paraffins 10.7 wt%; naphthenes 6.1 wt%; and benzene 0.52 wt%. The heating value was 44.2 MJ kg^{-1}; hydrogen content was 10.5 wt%; and carbon content was 88.2 wt%. The fuel was purchased from a gasoline station operated by the largest petroleum refinery in Taiwan, China Petroleum Corporation (CPC). Table 2 shows the gasoline properties in Taiwan, the United States and Europe; results indicated that the main property values are similar and in the same range of gasoline characteristics.

Test motorcycles were first examined for safety in the laboratory of a certified motorcycle manufacturer. Test fuel was replaced, and the engines were cooled down until the next day for the driving cycle testing.

Gas Sampling and Analysis

The sampling equipment for criteria and organic air pollutants was the same as in our previous work (Tsai *et al.*, 2003). Gas samples were collected for the entire cycle with an automated instrument, which took a constant sample volume (HORIBA, CVS-51S). The tailpipe of each motorcycle was connected directly to a sampling bag for the entire testing cycle. The CO, HC (including methane and non-methane hydrocarbons), NO_x and CO_2 contents in the exhaust sample were determined by an exhaust gas analyzer (ONO SOKKI). The background pollutant concentrations were also analyzed routinely and deduced from the test results. Results indicate that the background concentrations were approximately 2 ppm for CO, 6 ppm for HC, 0.1 ppm for NO_x, and 0.01% for CO_2, which were much lower than those of the exhaust gas.

A vacuum box containing a 10-L Tedlar bag was used to sample the volatile organic compounds (VOCs) from the exhaust of the entire ECE test cycle. VOCs were pre-concentrated in a purge-and-trap system (Entech 7100 instrument) and subsequently analyzed in a gas chromatography/mass spectrometer (HP-6890 GC plus with a HP 5973N MS). The GC was equipped with a fused silica

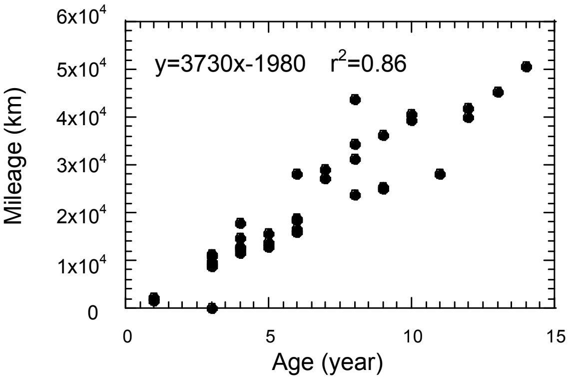

Fig. 1. Relationship of mileage and age of selected motorcycles.

Table 2. Gasoline properties of Taiwan, United States and Europe.

Gasoline	Taiwan	United State	European
Research octane number	95	91.2–96.7	98.4
MTBE (vol.%)	10.2	na	na
Oxygen content (wt.%)	1.8	< 0.1	0.01
Aromatics (vol.%)	30.0	14.1–35.8	36.3
Olefins (vol.%)	10.8	6.2–8.5	8.7
Paraffins (vol.%)	10.7	na	na
Naphthenes (vol.%)	6.1	na	na
Benzene (vol.%)	0.52	0.50–0.54	na
Heating value (MJ kg^{-1})	44.2	42.95–44.04	42.80
Carbon (wt.%)	88.2	85.12–87.03	87.48
Hydrogen (wt.%)	10.5	12.79–14.43	12.50
Remark	This work	DOE, 2014	European Commission, 2007

[1] na: not available.

[2] Ethanol < 0.1%.

capillary column (non-polar RTx-1, 105 m × 0.25 mm ID × 1.0 µm film thickness). Calibration standards were prepared by diluting the certified standard gas (56 Enviro-Mat Ozone Precursor, Matheson, USA) with ultra-high-purity nitrogen (99.995%) in dilution bottles. Perfluorotributylamine was applied to determine the performance and quality of the GC/MS. A total of 52 VOCs, including paraffins (27 species), olefins (9 species), and aromatics (16 species), were analyzed. The relative standard deviation for all VOCs was < 12%, the accuracy ranged from 86 ± 5% (propane) to 105 ± 9% (*p*-ethyltoluene), and the method detection limit varied from 0.04 (n-decane) to 0.10 (propene) ppb.

RESULTS AND DISCUSSION

Criteria Pollutants for Different Mileages and Ages

Fig. 2 shows the exhaust emission factors of CO, HC, NO_x, and CO_2 for various motorcycle mileages. CO emission factors increased with the increase of cumulative mileage (Fig. 2(a), $r^2 = 0.49$). HC emission factors increased slightly with the increase of mileage (Fig. 2(b), $r^2 = 0.20$). For NO_x (Fig. 2(c)), and the emission factor seemed to decrease with the increase of mileage, but their correlations were low. In addition, the relationship was insignificant between CO_2 emission factor and motorcycle mileage (Fig. 2(d)). According to Yang *et al.* (2012), a positive slope implies that the air pollutant emissions would increase after 15,000 km of driving; that is, the motorcycle could deteriorate with cumulative mileage, especially in terms of CO emissions. This finding could support the results of the current study.

The highest CO and HC emission factors, 10.3 and 1.84 g km^{-1} for CO and HC, respectively, were observed in the highest mileage motorcycle (14 years and 50,512 km), and low NO_x emission (0.09 g km^{-1}) was presented. High age and mileage could cause incomplete combustion and the release of pollutants in the tailpipe exhaust. Brand-new motorcycles had low CO and HC emissions but high NO_x emission. High combustion temperature in the engine could account for high NO_x emission in newer motorcycles.

The catalytic system of motorcycles can fail with high running mileage. In Taiwan, most motorcycle drivers do not change the tailpipe catalyst after failure of the exhaust gas control system, or they change the tailpipe without changing the catalyst, so in this study, the tailpipe and catalyst of the selected motorcycles was not changed. In Phase V motorcycles, a carburetor and a fuel injection system could be used. But the fuel injection system was employed for most motorcycles in Phase V groups. In Phase III and VI motorcycles, only carburetor technology was employed for the fuel supply. For NO_x emission, the average NO_x emission factor of Phase V motorcycles was higher than that of Phases III and IV motorcycles, as shown in Table 3 (the high engine combustion temperature could be an important reason for the high emission of NO_x in the exhaust of Phase V motorcycles).

Emission of Criteria Pollutants for Different Motorcycle Groups

Table 3 shows the emission factors of CO, HC, NO_x, and CO_2 for different emission standards (Phases III, IV, and V). For Phase III motorcycles, with the age ranging from 10–14 (11.7 ± 1.5) years and mileage from 28,083–50,512 (40,825 ± 6,850) km, the emission factors ranged from 3.4–10.3 (5.81 ± 2.45) g km^{-1} (CO), 1.1–1.8 (1.48 ± 0.27) g km^{-1} (HC), 0.14–0.29 (0.202 ± 0.051) g km^{-1} (NO_x), and 59–62 (61.0 ± 1.4) g km^{-1} (CO_2). For motorcycles in compliance with Phase IV standards, with age from 6–9 years and mileage from 16,490–43,633 km, the average emissions for CO, HC, NO_x, and CO_2 were 0.66, 0.61, 1.05, and 0.99 times, respectively, those of Phase III motorcycles. For the Phase V motorcycles, with age from 1–6 years and mileage less than 30,000 km, the average emissions for CO, HC, NO_x, and CO_2, were 0.42, 0.57, 1.11, and 0.99 times, respectively, those of Phase III motorcycles.

CO and HC emissions were high for Phase III motorcycles and low for Phase V motorcycles. The sequence of NO_x emission factor was Phase V > Phase IV > Phase III. High NO_x emission could result from the high combustion efficiency and high engine temperature of newer, low-mileage motorcycles. The sequence of fuel consumption was Phase III (0.033 L km^{-1}) > Phase IV (0.030 L km^{-1}) > Phase V (0.029 L km^{-1}). Motorcycles in compliance with Phase III standards, i.e., high age and mileage, presented

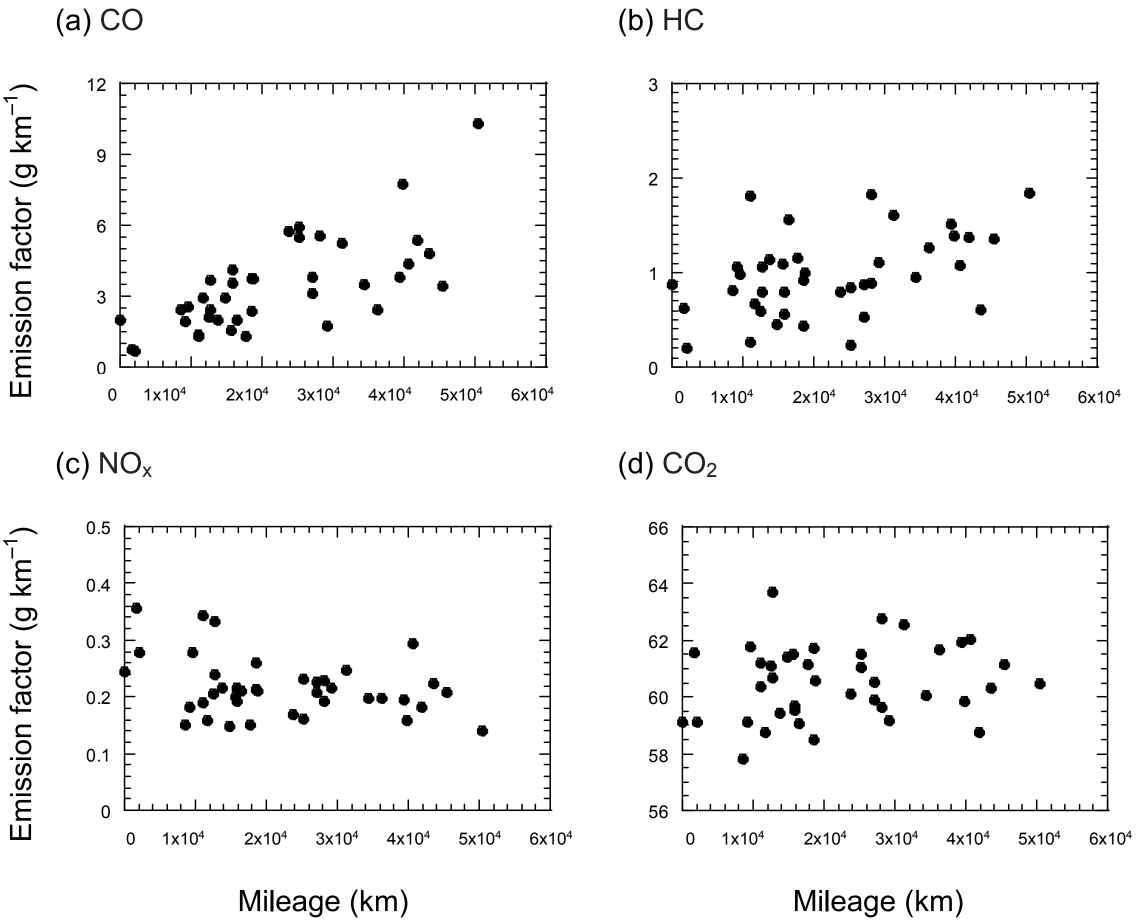

Fig. 2. Exhaust characteristics of motorcycles for various mileages.

Table 3. Age, mileage, exhaust emission (g km^{-1}) and fuel consumption for various motorcycles.

Regulation	Age (yrs)	Mileage (km)	CO	HC	NO$_x$	CO$_2$	Fuel consumption (L km^{-1})
Phase III (n = 7)[1]	11.7 ± 1.5[2]	40825 ± 6850	5.81 ± 2.45	1.48 ± 0.27	0.202 ± 0.051	61.0 ± 1.4	0.033 ± 0.002
Phase IV (n = 13)	7.5 ± 1.2	27423 ± 7934	3.85 ± 1.48	0.90 ± 0.36	0.213 ± 0.027	60.5 ± 1.1	0.030 ± 0.001
Phase V (n = 20)	4.0 ± 1.5	12179 ± 6372	2.45 ± 1.24	0.84 ± 0.36	0.225 ± 0.063	60.4 ± 1.4	0.029 ± 0.001

[1] n is motorcycle testing number.

[2] mean value ± standard deviation.

low engine combustion efficiency and may exhibit high emission in this study.

A three-way catalytic exhaust converter was employed for Phase V motorcycles, wherein the NO molecules are attracted to the Rh surface and then share the electron bond with Rh to desorb the N_2 gas. Oxygen atoms remain on the catalytic surface of Rh, CO molecules react with oxygen atoms to form CO_2, and then CO_2 desorbs from the clean Rh or Pt surface. Some catalysts include Ce_2O_3 to capture the excess O_2 to form CeO_2 for CO oxidation, and this mechanism can also enhance the NO reduction to form N_2 (Ramanathan and Sharma, 2011). The data seemed to indicate that NO_x emission was high for Phase V motorcycles, and their running mileages were within the guaranteed range; therefore, the catalytic converter should reduce the emission of pollutants. However, we did not address catalytic performance in this study because we did not test the exhaust pollutant concentration or determine the performance of catalyst convertors. We will address catalyst performance for motorcycle exhaust in a future study.

According to the Taiwan Emission Data System (TEPA, 2013), the emission factors (determined by the zero mile level and deterioration rate) could be lower than the results of these experiments, especially in CO and HC. Therefore, the emission of four-stroke motorcycles in TEDS could be underestimated. For a detailed comparison of the motorcycle emission factor and TEDS, further work and experimental design are necessary.

Emission Factors of Volatile Organic Compounds

The emission factors of a total of 52 VOCs were 1.38, 0.77, and 0.59 g km^{-1} for Phases III, IV, and V motorcycles, respectively. VOC emissions for Phase III motorcycles were 79 to 134% higher than those for Phases IV and V motorcycles. This implied that the older, high-mileage motorcycles emitted a significant amount of VOCs in exhaust and contributed more pollution in ambient air. The emissions of three VOC groups, i.e., paraffins, olefins, and aromatics, of Phases IV and V motorcycles were lower than those of Phase III motorcycles. The reduction values were 44/60% (paraffins), 41/62% (olefins), and 46/54% (aromatics) for Phases IV and V, respectively, compared with Phase III. The paraffins and aromatics made up more than 40% of mass fraction, and olefins were 11–14% in all test motorcycles regardless of emission standard phase. This implied that tightened emission standards indeed encourage motorcycle manufactures to improve engine technology and combustion efficiency, resulting in reduced emission of pollutants.

Our results indicated an insignificant relationship between 52 VOC species and mileage and also reflected the same low correlation between HC and mileage, as shown in Fig. 2(b). Fig. 3 shows the correlation between the main VOC species (isopentane, 1-butene, toluene and benzene) in exhaust and mileage (all of the linear regression, $r^2 < 0.15$). The abundance of gasoline constituents (isopentane, toluene and benzene) (Sigsby *et al.*, 1987; Chin and Batterman, 2012, Alves *et al.*, 2015) and combustion formation species (1-butene) (Sigsby *et al.*, 1987; Chin and Batterman, 2012) did not correlate with mileage. Motorcycle engine combustion is complex; therefore, the concentrations of VOC species are influenced not only by running mileage but also potentially by driver behavior, inspection and maintenance, engine type, and emission control system (catalysts).

Fig. 4 presents the main VOC species emission factors of the test motorcycles for different emission standards. Toluene, isopentane, m,p-xylene, 1,2,4-trimethylbenzene, and o-xylene were the dominant VOC species emitted from the tailpipe exhaust of the test motorcycles. The major VOC species were similar for the three phases of emission standard of motorcycles. Isopentane and toluene represent the highest emissions among the VOC species in all the test motorcycles for the three phase standards. For Phase III motorcycles, the emission factors of isopentane and toluene were > 0.1 g km^{-1}; for Phases IV and V, the values were 0.065/0.067 g km^{-1} and 0.043/0.045 g km^{-1}, respectively. Jia and coworkers (2005) indicated that the aromatic compounds (benzene, toluene, xylene isomers (*o*-xylene, *m*-xylene and

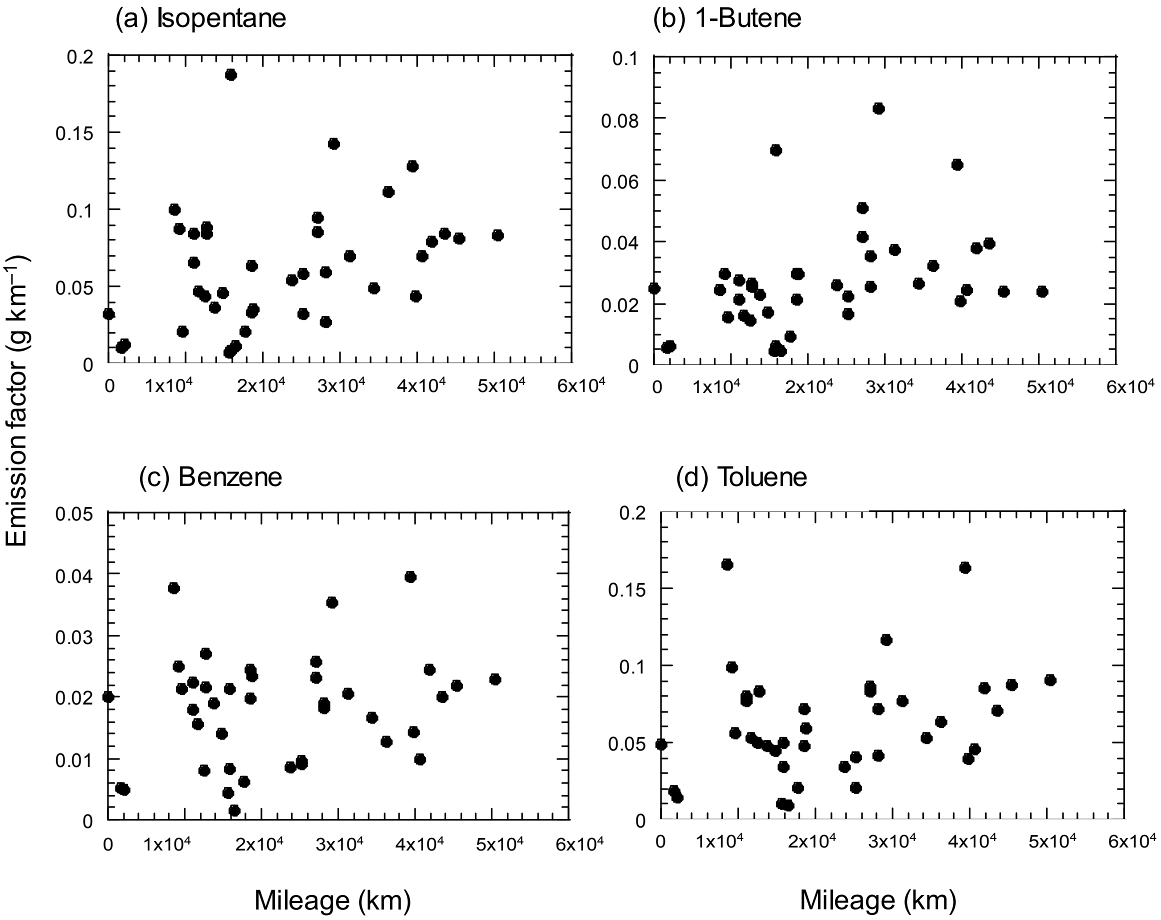

Fig. 3. Isopentane, 1-butene, benzene and toluene emission of motorcycles for various mileages.

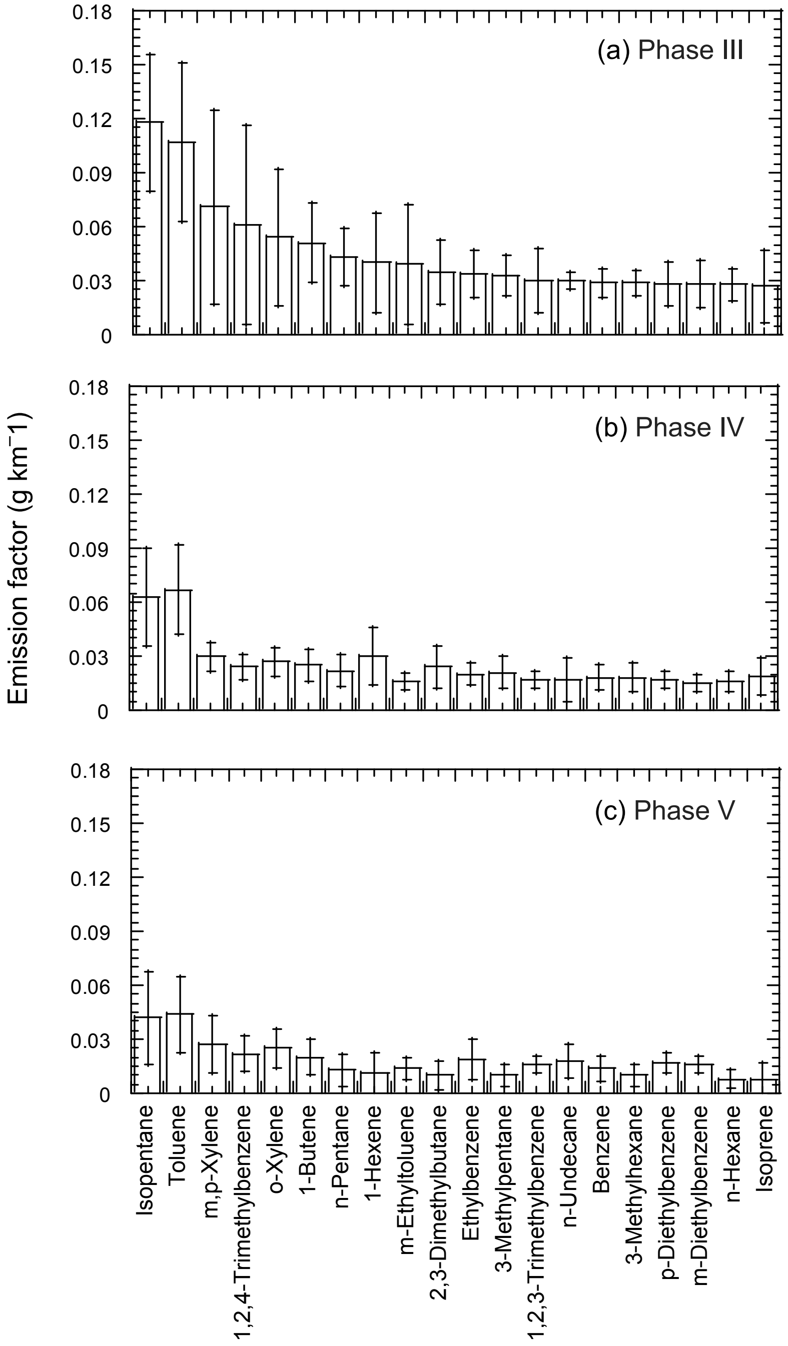

Fig. 4. Emission factors of 20 VOC species for various motorcycle emission standards (Phase III, Phase IV and Phase V).

p-xylene), ethyltoluene isomers (*o*-ethyltoluene, *m*-ethyltoluene and *p*-ethyltoluene) and trimethylbenzene isomers (1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene and 1,3,5-trimethylbenzene)) and fatty groups (ethylene, methane, acetaldehyde, ethanol, butene, pentane and hexane) were the major compounds in four-stroke motorcycle engine exhaust. Some abundant VOC species and high aromatic groups were similar to those in this study.

Benzene, toluene, ethylbenzene, and xylene (BTEX) were selected as toxic air pollutants, and their emission reduction for Phase IV and V motorcycles was calculated and compared to Phase III (shown in Table 4). BTEX emissions decreased for both Phase IV and V motorcycles. The emission reductions of BTEX ranged from 37–58% (Phase IV motorcycles) and 44–62% (Phase V motorcycles) of those of Phase III motorcycles. However, the highest emission factors of paraffins, olefins and aromatics were determined in Phase III. For the VOC group fraction, higher aromatic and olefin fractions were determined for Phase IV and Phase V motorcycles than for Phase III.

The age of Phase V motorcycles was lower than those of Phase III and IV, and the engine condition was better. The running mileage of Phase III motorcycles ranged from 40,825 ± 6,850 km and that of Phase IV motorcycles from

27,423 ± 7,934 km (Table 3); therefore, the running mileage of both Phase III and IV motorcycles was 2–3 times higher than the regulatory guaranteed mileage (Table 1) of motorcycles, which could be associated with failure of the exhaust system. However, most of the Phase V motorcycles were in the acceptable mileage range (i.e., < 15,000 km), so the catalytic converter could be used to reduce exhaust emission. In addition, Phase V motorcycles are equipped with fuel injection engines in Taiwan. The various sensors (such as engine and air temperature, throttle and crankshaft position, manifold pressure, and oxygen sensor, etc.), combined with the electric control unit to provide information on operating conditions and load on the fuel injection engine, will adjust the mixture ratio of air and fuel to optimize conditions, which in turn reduces exhaust emission (Milton, 1998) and is favorable for the cold start of motorcycles.

The effects of mileage and age on motorcycle emissions under the same regulation phases were not clearly determined, which is a limitation of this study. According to the motorcycle emission characteristics determined in the study, the criteria pollutant emissions seemed to depend on mileage, and each toxic component was affected by the regulation phases.

Ozone Formation Potential of VOC Species

VOC species emission factors of motorcycle exhaust associated with the maximum incremental reactivity factors (Carter, 2009) were applied to determine the ozone formation potential (OFP, in g-O_3 produced per km) from motorcycle exhaust. The values of OFP in the exhaust of a total of 52 VOCs were ranked as follows: Phase III (5.84 g-O_3 km^{-1}) > Phase IV (3.11 g-O_3 km^{-1}) > Phase V (2.48 g-O_3 km^{-1}). Results indicated that the OFPs in the newer motorcycles (Phase V) were lower than those of the older motorcycles with high mileage.

For the different groups of motorcycles, the OFPs for the VOC group profiles were similar. OFPs of VOC groups were 11–13% for paraffins, 27–31% for olefins and 56–62% for aromatics. The aromatic chemicals showed the highest contribution of ozone formation regardless of test vehicles. Fig. 5 presents the OFPs of the top 20 VOC compounds for the various groups of tested motorcycles. The dominant species of the OFP were m,p-xylene, 1,2,4-trimethylbenzene, 1-butene, toluene, *o*-xylene, and 1,2,3-trimethylbenzene for the various groups of motorcycles. However, the contribution of each species is different in the different emission standard phases. A higher contribution of OFP is observed in Phase III motorcycles, where the OFP values of each compound ranged from 0.4 to 0.55 g-O_3 km^{-1}. For the motorcycles that complied with Phase IV standards, the OFP values of each VOC compound were lower than 0.3 g-O_3 km^{-1}, and they were less than 0.2 g-O_3 km^{-1} for Phase V motorcycles.

In brief, the data indicated that low OFP was associated with low age and mileage (Phase V), with reductions of 20% and 57% compared to those of Phase IV and Phase III motorcycles, respectively. The dominant VOC species of the OFP were similar, and aromatic chemicals showed the highest contribution of OFP.

CONCLUSIONS

This study examined the emission factors of air pollutants from 40 four-stroke motorcycles of various emission standard phases, ages, and mileage. The average annual mileage of selected motorcycles was 3,450 km, and a high correlation was observed between age and mileage. For different regulated standards of motorcycles, the sequence of emissions of CO and HC was Phase III > Phase IV > Phase V. However, the relationship was insignificant between CO_2 emission factor and motorcycle age. Total emissions of 52 VOCs were 1.38, 0.77, and 0.59 g km^{-1} for Phase III, IV, and V motorcycles, respectively. Toluene, isopentane, m,p-xylene, 1,2,4-trimethylbenzene, and *o*-xylene presented high levels of VOC species in motorcycle exhaust. Aromatics and olefins were the high fraction VOC groups for Phase IV and V motorcycles compared with Phase III; however, the highest emission factor was determined in Phase III. For organic air toxics, the lowest BTEX emissions were also observed in Phase V motorcycles. Motorcycles in compliance with Phase III standards, i.e., high age and mileage, presented low engine combustion efficiency and exhibited high emission in this study. Phase V motorcycles are equipped with fuel injection engines in Taiwan. An electric control unit with an oxygen sensor in these engines will adjust the mixture ratio of air and fuel to optimize conditions, which in turn affects exhaust emission. The ozone formation potentials were 5.84 g-O_3 km^{-1} for Phase III motorcycles, 3.11 g-O_3 km^{-1} for Phase IV motorcycles, and 2.48 g-O_3 km^{-1} for Phase V motorcycles. A high potential of ozone formation in motorcycle exhaust was presented by m,p-xylene,1,2,4-trimethylbenzen, 1-butene,toluene, o-xylene, and 1,2,3-trimethylbenzene.

In brief, the data indicated that the emissions of CO, HC, total VOCs, four organic air toxics, and the ozone formation potential increase with increasing age and mileage of motorcycles. Low exhaust was observed in the motorcycles

Table 4. Emission factor of BETX for different phase regulated motorcycles.

Emission Factor (g km^{-1})	Phase III	Phase IV	Phase V
Benzene	0.029 ± 0.008[1]	0.018 ± 0.007 (–37%)[2]	0.014 ± 0.007 (–52%)
Toluene	0.107 ± 0.044	0.067 ± 0.025 (–38%)	0.044 ± 0.021 (–59%)
Ethylbenzene	0.034 ± 0.013	0.020 ± 0.006 (–39%)	0.019 ± 0.011 (–44%)
m,p-Xylene	0.071 ± 0.054	0.030 ± 0.008 (–58%)	0.027 ± 0.016 (–62%)
o-Xylene	0.054 ± 0.038	0.027 ± 0.008 (–51%)	0.025 ± 0.011 (–53%)

[1] emission factor (g km^{-1}): mean value ± standard deviation.

[2] percentage of emission reduction compared to the phase III motorcycles.

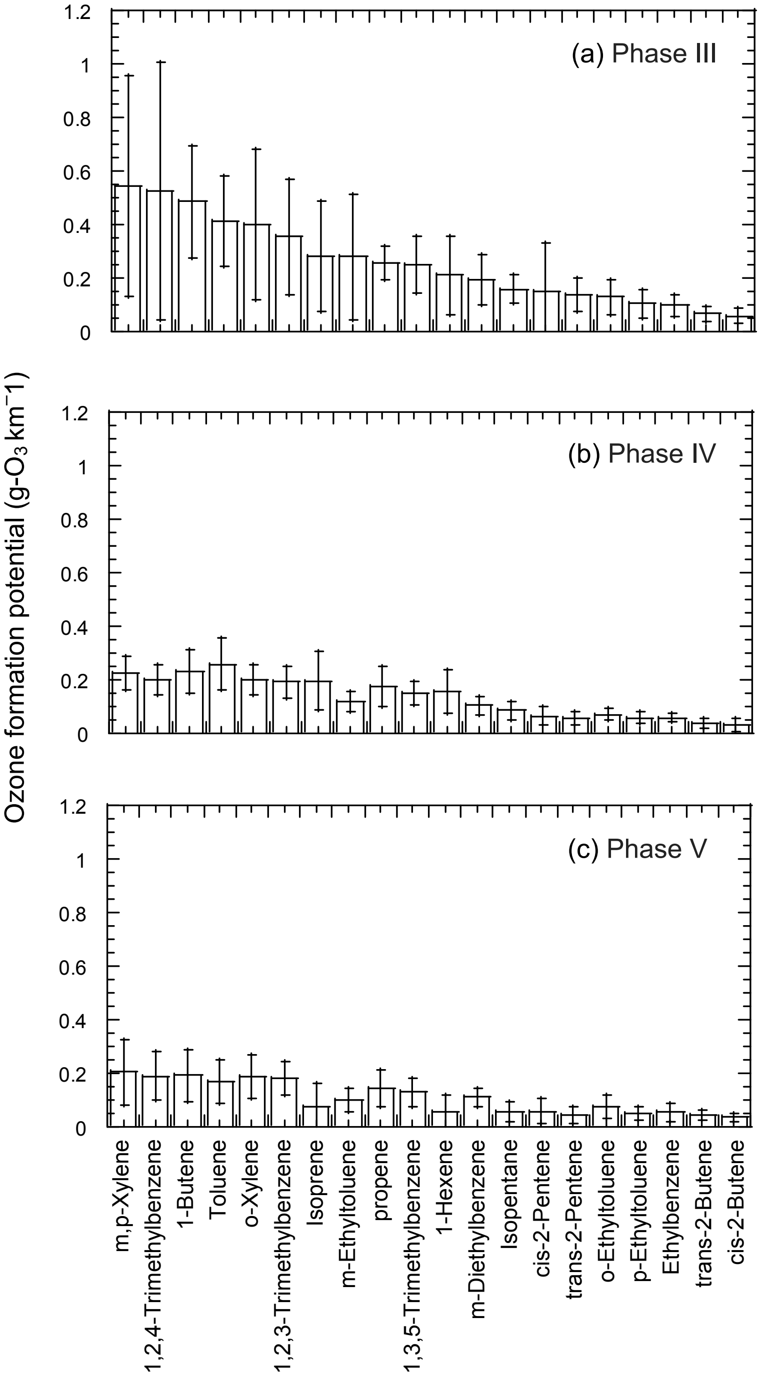

Fig. 5. Ozone formation potential of 20 VOC species for various motorcycle emission standards (Phase III, Phase IV and Phase V).

that complied with the newer emission standards. Results implied that tightened emission standards indeed encourage motorcycle manufacturers to improve engine technology and combustion efficiency, resulting in reduced emission of air pollutants.

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