

# Air Pollutant Emissions from a Four-Stroke Motorcycle Engine Influenced by Gasoline Aromatic Content

Yungchen Yao<sup>#1</sup>, Jiunhorng Tsai<sup>\*2</sup>, Anlin Chang<sup>\*2</sup>

<sup>#</sup>Green Energy and Environment Research Laboratories, Industrial Technology Research Institute,  
195 Sec. 4 Chung-Hsing Rd. Chutung, Hsinchu, 310, Taiwan, Republic of China

<sup>\*</sup>Department of Environmental Engineering and Research Center for Climate Change and Environmental Quality,  
National Cheng Kung University

<sup>1</sup>University Rd. Tainan City, 701, Taiwan, Republic of China

<sup>1</sup>ycyao@itri.org.tw; <sup>2</sup>jhtsai@mail.ncku.edu.tw

**Abstract**-Motorcycles are one of the dominant sources of air pollutants in many Asian countries. This study focuses on the effect of fuel aromatic content on motorcycle emissions. Two levels of aromatic content test-fuels were designed to investigate the criteria pollutant emissions [CO, total hydrocarbons (THCs), and NOx] and gaseous organic compounds in the exhaust from a non-catalyst four-stroke motorcycle engine. All experiments were operated in a cold start mode. The data indicate that lowering aromatic content in gasoline from 30 to 20% (by volume) reduced the CO and THC emission by 8-17% and 38%, respectively, especially in the cruising test. The NOx emission, however, showed an inverse correlation with the aromatic content in gasoline. Contrary to expectations, the emission factors of four organic groups and ozone formation potential showed that the low aromatic fuel with highest emission factors. While a reduction of aromatic content in gasoline may decrease emissions of benzene and toluene, it will increase the emission of aldehyde. Since the percentage changes of emission factor of THC and air toxics in the motorcycle were larger than those in passenger cars, the benefit of emission reduction due to fuel composition changes in motorcycles may have significant impacts in health risk analysis.

**Keywords**- Motorcycle; Aromatic Contents; Criteria Air Pollutant; Organic Air Pollutants; Ozone Formation Potential

## I. INTRODUCTION

Motorcycles are popular on-road vehicle in many Asian urban areas and they account for 50% to 70% of the total vehicles due to the properties of high mobility, reasonable price, and low fuel-consumption. The population of motorcycles has increased by more than 100% from 1986 to 2000, and is still growing [1]. Therefore, developing and implementing pollution control strategies for emissions from motorcycles are a critical issue for achieving clean and healthy air in these countries. Motorcycles with 50-125 cm<sup>3</sup> displacement are far more popular than heavy-duty motorcycles (displacement > 250 cm<sup>3</sup>) in Taiwan and other Asian countries. In Taiwan, motorcycle emissions contribute a significant part of the air pollutant emission inventory; accounts for 29% of CO, 8% of NOx, and 22% of non-methane hydrocarbons [2].

The key factors affecting air pollutant emissions from vehicles are engine technology, driver behavior, fuel quality,

among others [3-5]. Changes in gasoline composition can reduce vehicle emissions, because certain gasoline modifications allow engine to perform at their optimum levels [6]. The effect of gasoline composition on vehicle exhaust emissions has been investigated since the early 1990s. Two large-scale studies, the Air Quality Improvement Research Program (AQIRP) by automobile and oil companies in the United States in 1989, and the European Programme on Emission, Fuels, and Engine Technologies (EPEFE) by the European Commission in 1992, were conducted to evaluate the impacts of gasoline composition on exhaust emissions and air quality. Moreover, in order to understand the effects of lead-free and reformulated gasoline on vehicle exhaust emissions, several studies have been conducted using various vehicle modes (different model year, new and in-use, or passenger cars and light-duty trucks) to quantify their effects [7-10].

Based on the results obtained previously literatures, the aromatic content of gasoline affects exhaust CO, THC and some air toxics emissions. AQIRP showed that a decrease of aromatic contents in gasoline resulted in reductions in CO, THCs (total hydrocarbons), and air toxics emissions [11, 12]. EPEFE program showed that reducing aromatics content decreased emissions of THC and CO but increased NOx and yielded significant effects on benzene emissions and it was a linear reduction with decreasing aromatics. Formaldehyde and acetaldehyde emissions also showed increasing with aromatics reduction. In contrast, reducing aromatics may increase 1, 3-butadiene emissions [13]. Perry and Gee (1995) [7] showed a positive relation between aromatics content and benzene emission and also effect on other air toxics, such as ethylbenzene, toluene, and m, p-xylene. Prati *et al.* (2000) [14] observed a similar effect in two-stroke moped/motorcycle on benzene emission. Zervas *et al.* (2004) [15] has reported the majority of exhaust benzene comes from fuel benzene, the two-thirds of toluene comes from fuel toluene, and exhaust ethylbenzene is mainly produced from fuel ethylbenzene.

However, no consistency between aromatic content and emission variance has been shown. Gasoline is a complex mixture of 200 to 300 hydrocarbons and its properties will differ depending on which of the various refining and

blending processes were used to make it. This may contribute the different compositions of aromatic compounds in gasoline, and influence the air pollutant species of exhaust. Moreover, almost all of the fuel-effect studies have been conducted by using passenger cars and only rarely have studies been focused on low engine capacity (less than 150 cm<sup>3</sup>) motorcycle<sup>[14, 16]</sup>.

With the different engine and fuel supply systems, it is envisioned that emissions from passenger cars and motorcycles are different. Furthermore, because motorcycles are used primarily as a short distance travel tool and the average travel speed is lower, there is a corresponding increase in pollutant emissions<sup>[5]</sup>. Consequently, information about air pollutant emissions from motorcycles is of importance. To the best of our knowledge, only one study evaluating effects of benzene and aromatics content in gasoline on criteria pollutant and benzene emissions for two-stroke motorcycles was reported<sup>[17]</sup>. Unfortunately, there are no data concerning the effect in organic air pollutant emissions, nor other air toxics information available.

This study was undertaken to evaluate effects of aromatic contents in gasoline on criteria air pollutant emissions (CO, THC, NO<sub>x</sub>), organic compounds [volatile organic compounds (VOCs) and carbonyls], and selected air toxics from a four-stroke motorcycle engine. Two levels of aromatic content gasoline were prepared and tested in the engine to investigate the effects of gasoline composition on the exhaust gases in a dynamometer. The ozone formation potential (OFP) of VOC samples of each test fuel was calculated to provide useful information related to the potential impact of different aromatic content gasolines. The results of this study will provide a basis for regulatory agencies to plan an air quality control strategy for fuel quality in mobile sources.

## II. EXPERIMENTAL DESIGN

### A. Test Fuels and Engine

Two fuels (Fuels A and B) were blended by the largest local refinery in Taiwan; Fuel A presents the high aromatic fuel (30 vol%) and Fuel B was the low aromatic fuel (20 vol%). Each fuel type contains two fuels and treated as replicate. In addition, the sulfur contents in fuel in most Asia Pacific countries are ranged from 50 to 500 ppm. The fuel sulfur was controlled in 150 ppmw, this value presents the sulfur level in Mainland China and is relatively high as compared with the standard of California (30 ppmw for CaRFG3) and European Union (10 ppmw on 2003/17/EC).

Analysis of the test fuels was carried out in the laboratory at the same refinery company. The actual measured values of the fuel compositions are presented in Table I; the fuel compositions for a commercial gasoline are also included for comparison. A new four-stroke motorcycle engine with the displacement of 125 cm<sup>3</sup> was chosen as the test one without catalytic converters. The compression ratio of the engine was 10.1:1. A carburetor was used for the fuel supply system.

TABLE I THE PROPERTIES OF THE STUDIES GASOLINE

Fuel properties <sup>a</sup>	Fuel A	Fuel B
Sulfur (ppmw)	149	146
Aromatics (vol %)	28.6	22.0
Octane number	95	97
Reid Vapor Pressure (kPa)	56.9	58.7

<sup>a</sup>The listed values are the average of two test fuels.

### B. Test Procedures

Air pollutant emissions are affected by engine operating mode, because the combustion mechanism is different between idle and cruising mode. Engine temperature is high while operated in cruising mode and making more complete combustion. Therefore, the measured data were evaluated at two test modes, i.e., idle and cruising mode, in the present study.

The motorcycle engine was linked to the dynamometer and tested at a cold-start mode under different rotation speeds, which were 1718±105 rpm, 4828±4 rpm, and 5763±45 rpm for idle tests, mid-speed tests, and high-speed tests, respectively. The latter two rotation speeds were treated as a cruising test mode.

Prior to each emission test, the engine was soaked in room temperature over six hours prior to the start of the testing process. Exhaust gases were connected to a stainless chamber and filter; criteria pollutants were analyzed simultaneously by an in-situ monitor during 5-min operating time. The data of pollutant concentration and engine speed were recorded every 5 sec by a data acquisition system. The average value of 60 data was used as the air pollutant level. After each test, the fuel tank was drained and replaced by one liter of new test fuel. Immediately then, the engine was kept operating for 5 min to flush fuel tank and pipes to prevent contamination by the previous fuel.

### C. Gas Sampling and Analytical Procedures

CO, THC, and NO<sub>x</sub> in the exhaust filtered samples were measured by an in-situ monitor (MEGA 300 Tail Gas Analyzer, Mastek Technologies). CO was measured by a non-dispersive infrared analyzer with detection range 0-10.00% and with the resolution at 0.01%. THC was monitored by a flame ionization detection analyzer with a range of 0-15000 ppm (as propane, C<sub>3</sub>H<sub>8</sub>) with 1ppm resolution. NO<sub>x</sub> (NO and NO<sub>2</sub>) was monitored by a chemiluminescence detection analyzer with the detection range of 0-5000 ppm with 1 ppm resolution. Four tests of the commercial gasoline were conducted to evaluate the test reproducibility. The average values of reproducibility for CO, THC, and NO<sub>x</sub> were 97, 92 and 86% respectively for the idle mode and 89, 84 and 86% for the cruising mode.

The exhaust filtered samples were also collected for air toxics measurements using a sample bag (10 L) in a vacuum sampling case with the sampling flow rate of 150 mL/min. Air toxics species in the sample gas were quantified by a gas

chromatography/mass spectrometer (Varian Star 3600 GC plus with a Varian Saturn 2000 MS). The GC was equipped with a fused silica capillary column (DB-1, 60 m  $\times$  0.32 mm ID with 1.0  $\mu$ m film thickness). Carbonyl components in the exhaust were collected by silica gel cartridges with 2, 4-dinitrophenylhydrazine, and extracted with acetonitrile in the laboratory. The extracts were analyzed by high performance liquid chromatography (Hewlett Packard 1100 series) equipped with an ultraviolet-visible detector. The method detection limits for target air toxic pollutants were 2.1  $\mu$ g/m<sup>3</sup> (benzene), 3.8  $\mu$ g/m<sup>3</sup> (1, 3-butadiene), 5.5  $\mu$ g/m<sup>3</sup> (toluene), 9.7  $\mu$ g/m<sup>3</sup> (formaldehyde) and 24.1  $\mu$ g/m<sup>3</sup> (acetaldehyde). Except for toluene, all the selected air toxics are carcinogenic.

#### D. Calculation of Emission Factors and Data Analysis

The emission factors of various pollutants were assessed with the exhaust mass, the volume of the exhaust, and the fuel consumption in one test mode. The mean rotating speed  $r$  (rpm) of the engine, the cylinder volume  $V_{motor}$  (cm<sup>3</sup>), and the time  $t$  (min) over the test period were used to derive exhaust volume,  $V$  (m<sup>3</sup>) for a specific driving mode. The measured level (ppm or %) of a pollutant was converted to the corresponding concentration  $W$  (g/Nm<sup>3</sup>) and then the emission factor of a pollutant,  $EF$  (g/L-fuel), was calculated. The detail calculation procedures are presented in our previous articles [5, 16].

In addition, the ozone formation potential (OFP) of VOC samples also was investigated using maximum increment reactivity (MIR). The OFP of a certain VOC mixture in the exhaust is calculated by summing up the concentrations of measured VOC and corresponding MIR factors. The scale developed by Carter (2009) [18] was used to determine the MIR of the individual organic compounds. Since the MIR is a popular method to assess OFP, the detailed calculation method can be found in several previous studies [5, 19].

### III. RESULTS AND DISCUSSION

#### A. Effects on Criteria Air Pollutant Emissions

##### 1) Idle Mode:

The emission factor (g/L-fuel) of fuel aromatic contents on CO, THC, and NOx emissions by a motorcycle in the idle mode is illustrated in Table II. Because the data of THC were unstable during the idle test of Fuel B (high sulfur and low aromatic contents), the test results for that low aromatic content fuels were not analyzed. The data show that decreasing aromatics in gasoline (from 30 to 20 vol%) decreases exhaust CO emissions by 8% and 4% of CO (or 581 to 533 g/L-fuel). But effects of aromatic content on CO showed no statistically significant ( $p = 0.780$  for CO). The low aromatic content test fuel, however, showed a higher NOx emission than those with a high aromatic level and the variance is 14% (Table II). The result of significance analysis, however, indicates no significant effect ( $p = 0.619$ ) on NOx from aromatics content in gasoline.

The observations on the criteria emissions in the idle test show that fuel aromatic content reduction may lower the CO

emission. This is in agreement with the observations from the previous studies for cars [8, 13, 20]. The previous car studies further indicated that reduction in fuel aromatic content may increase NOx emissions as in our case. Presumably, it is attributing to low catalyst NOx conversion efficiency with low aromatic fuels [13]. However, the spark retardation due to high aromatic content may reduce engine temperatures and result in decreases in exhaust NOx [21]. The spark retardation seems to be the probable reason for low NOx emissions observed in the present study.

##### 2) Cruising mode:

The emission factors for motorcycle ranged from 184 to 220 g/L-fuel, 9.1 to 14.7 g/L-fuel, and 3.6 to 6.4 g/L-fuel for CO, THC, and NOx, respectively, in the cruising mode (Table II). The test results indicated that the CO and THC emission factors for a test motorcycle were lower in the cruising mode than those in the idle mode, except for NOx. The NOx emission in cruising mode, exhibiting one order of magnitude higher than those of the idle mode, is due to higher temperature because of high speed at the cruising mode [22].

The observations in Table II showed that a reduction in aromatic content (30 to 20 vol%) in the gasoline may lead to lower CO and THC emissions in the test motorcycle. The decreased percentage for CO emissions was 17%, and was 38% for THC emissions (Table II), but both without statistically significant impact ( $p = 0.275$  for CO, 0.174 for THC). Reducing the aromatics from 30 to 20 vol%, however, increases the NOx emission significantly (from 3.6 to 6.4 g/L-fuel or 76% increases), the  $p$  value was 0.008.

The findings of the effects of gasoline aromatic content on the CO and THC emissions are in agreement with the previous studies for cars [23-25]. Based on the reasoning provided previously describing the idle test, the extended combustion-delay-period may result in low engine temperature and low NOx emission for higher aromatic content gasoline. Because the combustion temperature was higher in cruising condition than that in the idle mode, the NOx emission was increased significantly, or from 0.5 to 3.6-6.4 g/L-fuel.

In conclusion, the present study deduces that a reduction of gasoline aromatic content, from 30 to 20 vol%, may decrease CO and THC emissions from motorcycles, especially in the cruising condition. In contrast, the NOx emissions were related to fuel aromatic content with an inverse correlation.

TABLE II EMISSION FACTORS (G/L-FUEL) OF CRITERIA POLLUTANT IN DIFFERENT TEST FUELS

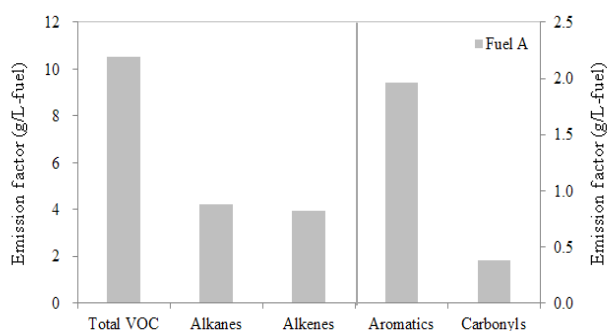
Test fuel	Aromatic content (vol %)	EF at idle mode			EF at cruising mode		
		CO	THC	NOx	CO	THC	NOx
Fuel A	28.6	581	29.9	0.48	220	14.7	3.63
Fuel B	22.0	533	--- <sup>a</sup>	0.54	184	9.1	6.39

<sup>a</sup> The data of THC was unstable during the idle test of Fuel B, the test results for that low aromatic content fuels were not analyzed.

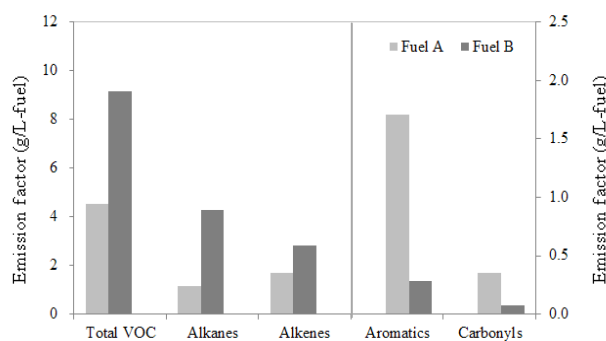
### B. Effects of Aromatic Content on Organic Compound Emissions

The species of analyzed organic air pollutants were divided into four groups: alkanes (26 species), alkenes (10 species), aromatics (16 species), and carbonyls (15 species). Emission factor of total VOCs is the sum of four organic compound groups. Fig. 1 illustrates the emission factors (g/L-fuel) of total VOCs and four organic compound groups of a four-stroke motorcycle exhaust in two driving mode for various test fuels. The test results for that low aromatic content fuels (Fuel B) for the idle test were not analyzed because the data was unstable.

The emission factors of total VOCs were 10.5 g/L-fuel (Fuel A) in idle mode and were 4.5 and 9.1 g/L-fuel for Fuel A and Fuel B, respectively. Contrary to expectations, the low aromatic fuel (Fuel B) showed higher VOCs emission than Fuel A for the motorcycle engine in cruising mode. The emission factor of four organic groups also showed that the Fuel B with highest emission factors, especially for alkanes emission, the value is 4.3 g/L-fuel and is 2.6 folds than Fuel A. Redacting aromatic content in gasoline will make the other fuel composition (i.e. paraffin, olefin) increase, this may contribute the high straight chain compound emissions. When comparing the percentile of organic groups of Fuel A and Fuel B in cruising mode, results indicated that alkanes group contributed the highest emissions in Fuel B (47%), but the percentile of other organic groups in Fuel A was higher than that of Fuel B. The percentile was 37/30/7% for Fuel A and was 31/19/4% for Fuel B in order of alkenes, aromatics, and carbonyls (Fig. 2).



(a) Idle mode



(b) Cruising mode

Fig. 1 Organic compound emissions factors for the test fuels in different driving mode: (a) idle, (b) cruising

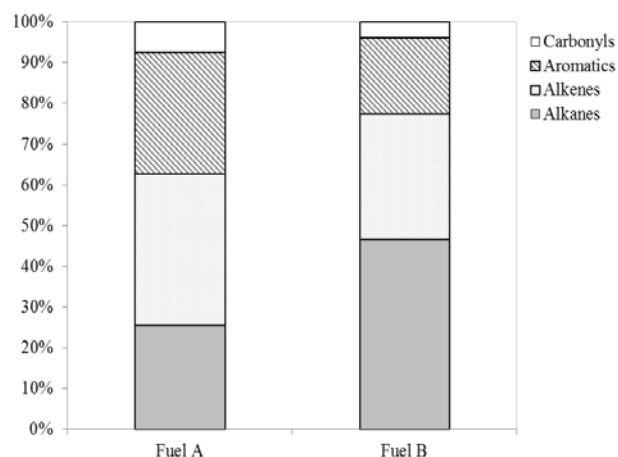


Fig. 2 Percentage contribution of four chemical groups to the analyzed VOCs for two aromatic fuels (The percentage is calculated based on emission factor per liter of fuel)

### C. Effects of Aromatic Content on Ozone Formation Potential

Fig. 3 shows the OFP of motorcycle engine exhaust fuelled with the two aromatic fuels in cruising mode. The OFP in the high aromatic fuel (27.6 g-O<sub>3</sub>/L-fuel) was lower than that of the low aromatic fuel (46.2 g-O<sub>3</sub>/L-fuel). The alkene chemicals showed the highest contribution of ozone formation and followed by aromatic compounds regardless of fuel types. Propylene, 1-butene, toluene, trans-2-butene, and m, p-xylene were the major species revealed in the ozone formation. The highest ozone formation potential was propylene; the value was 8.2 g-O<sub>3</sub>/L-fuel with a contribution of 29% in Fuel A and 14.3 g-O<sub>3</sub>/L-fuel with a contribution of 31% in Fuel B. Results of ozone formation potential indicated the sequence of ozone formation potential was alkenes > aromatics > alkenes > carbonyls.

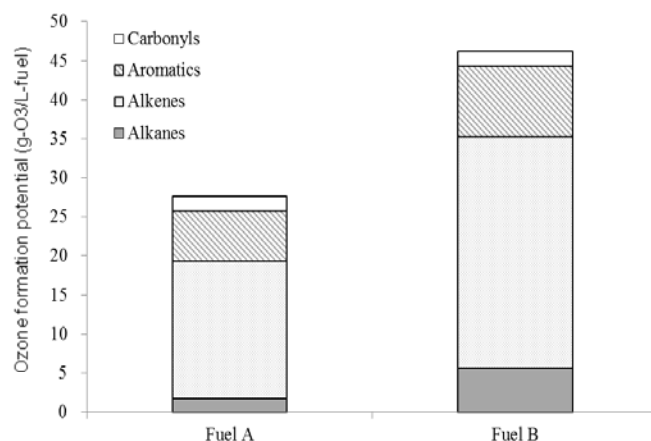


Fig. 3 Ozone formation potentials (g-O<sub>3</sub>/km) of motorcycle engine exhaust in cruising mode for two aromatic fuels

In the view of variance of OFP, the highest variance was appeared in alkanes species while aromatic level changed from high to low; the value was 225% or from 1.7 to 5.7 g-O<sub>3</sub>/L-fuel. The alkene chemicals also showed high OFP variance (which increased by 68%, or from 17.6 to 29.6 g-O<sub>3</sub>/L-fuel). Slight decreasing (2%) appeared in carbonyls

while using low aromatic fuel (Fuel B) as compared to the OFP of high aromatic fuel (Fuel A). Formaldehyde, acetaldehyde, acrolein, propion-aldehydethyde, and crotonaldehyde were major carbonyl compounds that caused ozone formation from the motorcycle engine exhaust for both test fuels. The top five species contributed 98% of the ozone formation potential in carbonyls.

#### D. Effects of Aromatic Content on Organic Toxics Emission

According to the results of previous car studies, air toxics were influenced by aromatic contents in gasoline<sup>[7, 9, 10, 12]</sup>. Therefore, the effect of fuel composition on air toxics was concentrated on aromatic contents in the present study.

Analysis of fuel effects was carried out by calculating the average emission factors of air toxics for different aromatic contents, and the results are illustrated in Table III. As would be expected, the concentrations of most target pollutants, except for acetaldehyde, were higher in the idle test than those in the cruising test. Some of these compounds showed significant reductions (Table III) when changing to the cruising mode, i.e. 1, 3-butadiene (98%), benzene (67-72%), formaldehyde (42-43%) and toluene (28-36%). During the idle mode, the engine, with a higher air/fuel ratio, produces higher hydrocarbon emission than cruising mode. In contrast, the cruising mode may be stabilized with a near-stoichiometric air/fuel ratio. Furthermore, engine rotation speed and temperature were high during the cruising mode resulting in a more complete combustion<sup>[26]</sup>.

TABLE III AIR TOXICS EMISSIONS WHEN REDUCING FUEL AROMATICS CONTENT FROM 30 TO 20 VOL% AT IDLE AND CRUISING MODE

Driving Mode	Air Toxics	Emission Factor (mg/L-fuel)		Variation (%) <sup>a</sup>
		Aromatic 30 vol%	Aromatic 20 vol%	
Idle	Benzene	918	764	-17
	1,3-Butadiene	353	358	1.4
	Toluene	1011	529	-48
	Formaldehyde	219	228	4
	Acetaldehyde	126	129	2
Cruising	Benzene	303	211	-30
	1,3-Butadiene	8	7	-8
	Toluene	648	379	-41
	Formaldehyde	64	88	27
	Acetaldehyde	84	108	22

<sup>a</sup>Negative differences (%) imply reductions in emissions while reducing aromatic content in gasoline.

In all test fuels, toluene and benzene represent the highest emissions among the target air toxics. A decrease in aromatic content from 30 to 20 vol% lowered toluene and benzene emissions by 48% and 17% in the idle test, and 41% and 30% in the cruising test, respectively. Goodfellow *et al.* (1996)<sup>[13]</sup> has reported that the increased benzene and toluene exhaust emissions for higher aromatic fuel are caused by dealkylation during the combustion process. As for 1, 3-butadiene and formaldehyde, the emission factors showed similar results with low or high aromatic fuel used. The 1, 3-butadiene results of motorcycle engine are in

agreement with previous car studies<sup>[7, 27]</sup>. However, 1, 3-butadiene is mainly produced from olefins and naphthene content and is not influenced by aromatics<sup>[27]</sup>.

For acetaldehyde, the data, on the other hand, show increased emissions when low aromatic fuel was used. Acetaldehyde is not present in the gasolines, it is the incomplete combustion products of fuel<sup>[6]</sup>. Decreasing gasoline aromatic content may require additional paraffin content. The higher aldehyde emissions may be the result of the increased fraction of the paraffin. Partial combustion of paraffin would result in an increased formation of methyl and ethyl radicals. These radicals can further undergo reactions to form acetaldehyde<sup>[20, 21]</sup>.

Table IV summarizes the effects of gasoline compositions on the motorcycle exhaust emissions; data for cars are also included for comparison. Again, the results indicate that reducing fuel aromatics contents may result in lower CO, THC, benzene and toluene emissions. Benzene and toluene were presented in great amounts in motorcycle exhaust, thus, any step for reducing their emission should be taken. Although a reduction of fuel aromatics may increase aldehyde emissions, in terms of toxics emission control, a low aromatic content in gasoline may still contribute to an overall diminution in hazardous risk.

The fact that reducing the aromatic content in gasoline may lower the THC in general and air toxics emission in particular which is also observed in catalyst free gasoline engine<sup>[7, 9, 17, 20]</sup>. Our findings are in accordance with the previous car studies as shown in Table IV. However, the percentage changes of emission factors in the motorcycle were larger than those in car studies (typically less than 10%). Because the emission factors of motorcycles are quite higher than those in cars; therefore, the benefit of emission reduction due to fuel composition changes in motorcycles may have significant impacts in air toxics.

TABLE IV SUMMARY OF EFFECTS OF GASOLINE COMPOSITIONS ON THE VEHICLE EMISSIONS

(A) CRITERIA POLLUTANTS					
Test Engine	Change in Fuel Aromatics	CO	THC	NOx	Ref.
New Four-Stroke Motorcycle, w/o Catalyst					
(1) idle	30→20 vol%	↓ <sup>b</sup>	NE	↑	This study
(2) cruising	30→20 vol%	↓	↓	↑ <sup>c*</sup>	This study
In-Use Two-Stroke Motorcycles					
	33→28 vol%	↓	↓	↑	[17]
In-Use Carburetor Cars, w/o Catalyst					
	40→25 vol%	↓	↓	↓	[20]
	57→20 vol%	---	---	---	[7]
	40→20 vol%	↑	↓	↓ <sup>*</sup>	[9]

(B) AIR TOXICS							
Test Engine	Change In Fuel Aromatics	Bz <sub>a</sub>	B <sub>d</sub>	T <sub>ol</sub>	Fa	A <sub>c</sub>	Ref.
New Four-Stroke Motorcycle, w/o Catalyst							
(1) idle	30→20 vol%	↓	↑	↓	N E	↑	This study
(2) cruising	30→20 vol%	↓	N E	↓	N E	↑	This study

In-Use Two-Stroke Motorcycles							
	33→28 vol%	↓	---	---	---	---	[17]
In-Use Carburetor Cars, w/o Catalyst							
	40→25 vol%	↓*	N E	---	↑	↑	[20]
	57→20 vol%	↓	↓	↓	---	---	[7]
	40→20 vol%	↓	↓	---	↓	↓	[9]

<sup>a</sup>Bz: benzene; Bd: 1, 3-butadiene; Tol: toluene; Fa: formaldehyde; Ac: Acetaldehyde

<sup>b</sup>↑: increase; ↓: reduction; NE: variation less than 5% in the present study or no effect in other studies; ---: data not measured or not available

<sup>c</sup>\* significant at the 95% confidence level

#### IV. CONCLUSIONS

This paper presents the correlation between fuel compositions and air pollutant emissions (CO, THC<sub>s</sub>, NO<sub>x</sub> and air toxics) of a non-catalyst motorcycle engine. A four-stroke new motorcycle engine was linked to the dynamometer and operated in a cold start mode. The measurement of emissions was conducted during the idle and the cruising test mode.

The test fuels showing low emissions for CO and THC were those that had consistently low aromatic content, especially in the cruising condition. In contrast, reducing aromatic content from 30 to 20 vol% increases NO<sub>x</sub> emission in the test motorcycle. Contrary to expectations, the low aromatic fuel showed high total VOC<sub>s</sub> emissions for the motorcycle engine in cruising mode. The emission factors of four organic groups also showed that the low aromatic fuel with highest emission factors, especially for alkanes emission. The effects of aromatic contents in gasoline are complex, probably because the aromatic compounds in gasoline are so diverse. The low aromatic fuel also had the high ozone formation potential, propylene contributed the highest ozone formation potential among all analyzed organic species. Results of ozone formation potential indicated the sequence of ozone formation potential was alkenes > aromatics > alkenes > carbonyls. For air toxics emissions, a reduction in fuel aromatic content from 30 to 20 vol% decreased benzene and toluene emissions in both test modes, but increased the aldehyde emissions. Since the percentage changes of emission factors of air toxics in the motorcycle were larger than those in cars, the benefit of emission reduction due to fuel composition changes in motorcycles may have significant impacts in health risk analysis.

According to our findings, in order to reduce the exhaust THC and air toxics emissions, a lower aromatic gasoline is suggested. However, lower aromatics in fuel may increase NO<sub>x</sub>, ozone formation potential, and aldehyde emissions.

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