An assessment of gasoline motorcycle emissions performance and understanding their contribution to Tehran air pollution

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Abstract

Motorcycles are the third most common means of transportation in the megacity of Tehran. Hence, measurements of emission factors are essential for Tehran motorcycle fleets. In this study, 60 carburetor motorcycles of various mileages and engine displacement volumes were tested in a chassis dynamometer laboratory according to cold start Euro-3 emissions certification test procedures. For almost all of the tested samples, the average carbon monoxide (CO) emission factors were about seven times higher than the limits for Euro-3 certification. No motorcycle fell within the Euro-3 certification limit on CO emissions. 125 cc engine displacement volume motorcycles, which are dominant in Tehran, have the most total unburned hydrocarbons and CO emission rates, and they have less nitrous oxides ($NO_x$) emission rates and fuel consumption compared to those of larger engine volume motorcycles. Calculation of fuel-based emission factors and moles of combustion products shows that about 40% of fuel consumed by 125 cc engine volume motorcycles burns to incomplete combustion products. This proportion is lower for larger engine volume motorcycles. Approximation of relative air–fuel ratio results shows very rich combustion in selected motorcycles. Using a carburetor fuel supply system, low engine compression ratio, aging, and no catalyst could be reasons for high emission rates. These reasons could possibly result in high ultrafine particles emission rates from motorcycles. Comparison of total motorcycle pollutant emissions to that of passenger cars from previous studies in Tehran shows that motorcycles contribute to pollutant much higher than their contribution to the total fleet or total travels.

Introduction

Tehran is one of the world largest metropolitan areas. Like many other megacities, Tehran has serious air quality problems. Every year, more than 40% of the days of the year have been marked as unhealthy and unhealthy for sensitive groups. There has been incidents of city-wide shut-down due to episodes of air pollution during winter. Tehran emissions inventory in the base year of 2014 showed a large contribution of mobile sources to total emissions. Mobile emissions sources in the city of Tehran include more than 3.5 million light duty gasoline vehicles, more than 100 thousands diesel heavy-duty vehicles, and more than 1 million gasoline 4-stroke motorcycles. Motorcycles are used in the city of Tehran for both personal transportation and small parcel deliveries. Limited public transit options and traffic restrictions for vehicles at the city center have encouraged use of motorcycles in recent years. In October 2002, the Iranian government legislated ECE-R40.01 as the
first national emissions standard for motorcycles. The standard became implemented in 2004 and remained in place afterward. Since 2013, the production or import of motorcycles is allowed only within a minimum emissions standards level equivalent to the Euro-3 emission standard.

As motorcycles are used in Iran as means of transportation rather than leisure, the situation is similar to that of Southeast Asian countries. In Southeast Asia, motorcycles are one of the main means of transportation. For instance, in many Asian countries, including China, India, Indonesia, Taiwan, Vietnam, and Thailand, the proportion of motorcycles is 60–75% among all on-road vehicles (Schipper et al., 2008; Tsai et al., 2000; Chan et al., 1995). Several studies examined motorcycles emissions in Southeast Asia and in Europe. These studies included measurements of emission factors and volatile organic compounds (VOCs) composition (Costagliola et al., 2014; Chen et al., 2003; Chiang et al., 2014). The effects of mileage, maintenance, catalyst installation, and fuel injection system usage on motorcycles emissions were also studied (Alvarez et al., 2008; Tsai et al., 2000; Yao et al., 2009) and comparisons were made between emissions and performance of motorcycles and passenger cars (Chan et al., 1995; Vasic and Weilenmann, 2006; Costagliola et al., 2014). Moreover, an emissions inventory was developed for estimation of motorcycle air pollution emissions in Vietnam, based on the emissions factors that had been developed for motorcycles with a European driving cycle (Tung et al., 2011). In Europe, one of the working packages of the assessment and reliability of transport emission models and inventory systems project was dedicated to two-wheel vehicle emissions (Boulter, 2007).

Previous studies by Tehran AQCC1 show that despite small engine volume and low fuel consumption, motorcycles could potentially be major contributors to VOCs, HC, CO, and UFPs. The contribution to total emissions is even stronger in places like Tehran. No study has been done before to quantify motorcycle emission rates and their contribution to total emissions. These are essential data for further studies, such as emission inventories and photochemical pollution distribution models that can be used not only in Tehran, but also in the region. The motorcycle contributions to emissions are high enough that neglecting them produces large errors. Furthermore, measures to mitigate air pollution require accurate motorcycle emissions information to calculate external cost. The current paper summarizes test results and conclusions of the measurements of emission factors of Tehran gasoline motorcycle fleet.

Materials and methods

Method of measurement

There are various methods for the measurement of tail pipe emission in vehicles. More popular techniques are the use of chassis dynamometers with a standard driving cycle and the use of on-board portable emission measurement systems in real-world driving conditions. In the portable emission measurement method, pollutant emissions are measured under real-world driving behavior. Emission factors derived from portable emissions measurement systems are more suitable for use in emissions inventories. The chassis dynamometer method is used in type-approval tests. In the chassis dynamometer method, environmental conditions are controlled. Higher repeatability and accuracy of results is one of the advantages of this method. In order to test a vehicle on a chassis dynamometer, a defined driving cycle is needed. A driving cycle is the pattern of speed versus time which represents the most probable driving conditions of a vehicle in certain environments, such as urban roads or highways (Franco et al., 2013; Frey et al., 2003). Even if real-world driving cycles are used in chassis dynamometer tests, portable emission measurement results are more appropriate for developing real-world emission factors (May et al., 2014; Tong et al., 2000). Nevertheless, in the case of motorcycles, chassis dynamometer tests are the most practical and easy-to-conduct way to develop emissions factors. This is because portable emissions measurement tests require a minimum amount of space and cannot be carried safely by motorcycles. In addition, the weight of portable emission measurement devices is considerable compared to that of the motorcycle. As such, in order to obtain the first data of motorcycle emissions, a standard chassis dynamometer laboratory was used.

Tehran motorcycles driving behavior

Using a GPS tracking method, real-world driving cycle data were collected for a few motorcycles that were used for delivery services. The share of such motorcycles in the total fleet is not known. However, their contribution to the total emission is large as vehicle kilometers traveled is quite considerable compared to those of personal use. While the mileage is generally much higher, the driving behavior is similar to those of personal use. The study was conducted under the assumption of similarity of driving cycles between the two groups. Fig. 1 shows the average speed and the average positive acceleration of motorcycles speed profiles on highways and urban streets in the city of Tehran, compared with those of ECE driving cycles. These measurements were made despite the fact that the operation of motorcycles on highways is prohibited by law, as this law is not enforced. Further, as motorcycles normally do not follow the flow of traffic, their pattern of driving is different than that of other vehicles, even in congested arterial streets.

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1 Air Quality Control Company, a subsidiary of Tehran Municipality responsible for air quality monitoring.
Average and maximum speeds, proportion of cruise, proportion of acceleration, average positive acceleration, and relative positive acceleration for 393 km of collected motorcycle driving data were computed and compared to those of standard European motorcycle test cycles. Results of this comparison are summarized in Table 1.

The differences in parameters between motorcycle driving behavior in the city of Tehran and standard ECE driving cycles is obvious in Table 1. Larger relative positive acceleration in Tehran is an indication of more energy consumption and more dynamic driving behavior (Boulter, 2007; van de Weijer, 1997). As such, it was expected that, emission factors for motorcycles obtained from chassis dynamometer results are different from those of real-world driving conditions. However, results of chassis dynamometer tests are still valuable as a first look into the emissions production of Tehran motorcycles and can be used as a basis for comparison of various technologies under repeatable test conditions. In order to compare the effect of standard driving cycles on emission rates, six pre-tests were conducted on the chassis dynamometer, using three different motorcycles that were also used in both the ECE and WMTC driving cycles. The differences in emission rates measured using WMTC driving cycle from those measured using ECE cycle were 20% to $0\%$ in CO, $0\%$ to $33\%$ in THC, and $16\%$ to $2\%$ in NOX. This difference is not significant compared to the variation of emission rates between various test subjects. Thus, considering that there is no real-world motorcycle driving cycle for the city of Tehran, the ECE driving cycle was used for the rest of measurements. ECE test cycle is shown in Fig. 2.

**Instrumentation and test setup**

All tests were conducted in a certified motorcycle test center’s chassis dynamometer laboratory. The laboratory is equipped with an AVL ROADSIM 25c chassis dynamometer and an AVL CVS-I60 critical venturi flow constant volume sampler. Volumetric concentrations of CO2 and CO were measured using the NDIR2 method by an AVL IRD i60 CO2 L/CO L analyzer. NOX was measured by AVL CLD i60LC analyzer using the CLD3 method, and the THC measurement was performed via the FID4 method by AVL FID i60LC analyzers. Lowest possible measurement range for CO2, CO, THC, and NOX analyzers were 0–0.5%, 0–50 ppm, 0–10 ppm C3, and 0–3 ppm respectively. Automation and data collection were done via PUAM IGEM software developed by AVL. All tests were performed according to directive 2013/60/EU chapter 5. Calibration of devices was done before each test according to directive 2013/60/EU chapter 5.

Each set of test subjects was moved to the laboratory every morning and was pre-conditioned until the engine and oil cartel temperature reached below 30 °C. Fuel density was measured and then the subject was tested on a chassis dynamometer under the proper ECE driving cycle for cold start Euro-3 emissions tests, as based on motorcycle engine size and weight. In all tests, pollutant concentrations were measured both in emission bags and instantaneous concentration measurements.

**Test fleet selection**

Fig. 3 shows the Tehran motorcycle fleet composition, classified based on engine displacement volume, according to motorcycle registration statistics in Tehran between 2011 and 2014. As seen in Fig. 3, more than 70% of Tehran’s motorcycles consist of 125 cc displacement volume engines, followed by 150 cc, 180 cc, and 200 cc. Almost all of Tehran’s motorcycle fleet consists of carburetor fuel delivery systems.

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2 Non-dispersive Infrared.
3 Chemiluminescence detector.
4 Flame ionization detector.
A test fleet of thirty-six 125 cc, eight 150 cc, nine 180 cc, and six 200 cc motorcycles were selected for emissions testing. The test fleet consisted only of carburetor motorcycles, without catalytic converters, which were rented from various private owners. Table 2 summarizes the test fleet.

Variability and uncertainty analysis methodology

In this study, the coefficient of variation, as defined by Eq. (1), was used to describe variability in results. The coefficient of variation provides a normalized indication of the dispersion of data values (Frey and Zheng, 2001).

\[
\text{Coefficient of variation (\%) = } \frac{\text{Sample standard deviation}}{\text{Sample mean}} \times 100
\]  

(1)

Bootstrap simulation is a numerical method which can provide solutions for confidence intervals for situations in which exact analytical solutions may be unavailable (Efron and Tibshirani, 1994). In this study, parametric bootstrap simulation was used for estimation of confidence intervals of mean emission factors. So, parametric probability distributions were fitted.
to emission factors data sets. Parametric distributions offer the advantage of enabling interpolation within the range of the measured data and extrapolation to the tails of the distribution beyond the range of measured data (Cullen and Frey, 1999). In this study, the method of maximum likelihood estimation (MLE) was used to estimate parameters of fitted distributions. Normal, lognormal, Weibull, and gamma distributions were considered when fitting emission factors data sets in this work. Because of the small sample sizes for most engine volumes, statistical goodness-of-fit tests are inapplicable or inappropriate. Instead, the distribution which maximized the likelihood function was chosen as the best-fit for each data set. A key advantage of bootstrap simulation for estimation of confidence intervals, in comparison to common analytical methods, is that no restrictive assumptions regarding normality are required to develop confidence intervals (Frey and Li, 2003; Frey and Bammi, 2002).

Results and discussion

Chassis dynamometer test results

Chassis dynamometer test results are presented in Fig. 4, along with an indication of Euro-3 standard emission limits for motorcycles. For the entire sample fleet, the averaged CO emission factors are several times higher than the limit of Euro-3 certification. With the exception of NOX emissions for the larger-volume engine fleet, the rest of the emission factors, including THC, for the entire sample fleet were reported close to Euro-3 certification levels. Nevertheless, it should be noted that the Euro-3 certification limit for the THC emissions for motorcycles is about 8 and 4 times greater than that for passenger cars in Euro-4 and Euro-3 emission standards. This makes motorcycles a potential for the main source of THC emissions. It also can be seen from Fig. 4 that CO and THC emission rates increase as engine displacement volume decreases.

Combustion of rich air–fuel ratios as a result of using carburetor fuel supply system, and low engine compression ratios results in low NOX and high CO and THC emission rates in tested motorcycles. The raw emissions of the engine is emitted from the exhaust as there is no any after-treatment device such as an oxidation catalyst in the exhaust. These reasons could possibly result in high UFPs emission rates in motorcycles. In carburetor fuel supply systems, the mixture air–fuel ratio is rich. This factor results in inefficient combustion, decreased combustion temperatures, and increased misfires. As a result, emission rates of CO, THC, and particulate matter would increase (Fergusen, 2001). Another result of combustion of a rich air–fuel ratio mixture is increased fuel consumption due to inefficient combustion.

Fig. 5 represents mean value of the ratio of CO emissions factors to CO2 emissions factors for tested motorcycles along with their standard deviation for various engine displacement volumes. It shows that by increasing engine volume, the mass ratio of CO to CO2 is decreased which confirms more complete combustion. Less perfect mixing of air and fuel and more fuel-rich mixture at lower engine displacement volumes are the possible reasons for such high level of incomplete combustion.

Average fuel-based CO and THC emissions factors for different motorcycle types are shown in Fig. 6. By comparing motorcycles in these plots, it can be seen that 125 cc engine displacement volume motorcycles produce more CO and THC in burning one kilogram of fuel compared to larger engine displacement volume motorcycles. Furthermore, a typical combustion equation was considered in Eq. (2), in which THC is considered as CH2.

\[
C_xH_y + n(O_2 + 3.76N_2) \rightarrow aCO_2 + bCO + dCH_2 + eH_2O + fO_2 + 3.76nN_2
\]

By converting grams of pollutants from burning one kilogram of fuel to moles, it is possible to have insight regarding combustion equation coefficients. Fig. 7 depicts molar contributions of CO2, CO, and THC for the products of combustion of one kilogram of fuel in motorcycles with different engine displacement volumes. According to Fig. 7, in 125 cc engine displacement volume motorcycles, 40% of fuel was emitted as CO. Ratio of moles of CO to moles of CO2 produced per burning one kilogram of fuel is 0.7 in these motorcycles. These results indicate that 125 cc engine displacement volume motorcycles,
which are dominant in the Tehran motorcycle fleet, have the poorest combustion quality compared to larger motorcycles. Lower combustion temperatures and the resulting lower NOX emissions and higher THC emissions in 125 cc engine volume motorcycles is another result of this rich and incomplete combustion, as NOX emission is a strong function of temperature (Heywood, 1988).

**Instantaneous emissions measurement results**

Instantaneous volumetric concentrations of diluted CO₂, CO, THC, and NOX were measured in each test. The concentrations were converted to instantaneous mass emissions using volumetric flow rate of constant volume sampler and using a dilution factor estimated by Eq. (3), in which SPCO₂ is stoichiometric percentage of CO₂ in complete combustion of fuel; and \( C_{CO₂ dig}, C_{CO dig}, \) and \( C_{THC dig} \) are pollutant concentrations in diluted exhaust gas. The mass emissions of pollutants in exhaust gas were calculated using Eq. (4), in which \( V_{dil dig} \) is total volumetric flow rate through a dilution tunnel, \( ρ_{pollutant} \) is the density of the desired pollutant; and \( C_{pollutant_{amb}} \) and \( C_{pollutant_{dig}} \) are background and diluted pollutant concentrations respectively.

**Fig. 4.** (a) CO, (b) THC, (c) NOx, and (d) fuel consumption emission factors for selected Tehrani motorcycles. Results procured from cold start Euro 3 chassis dynamometer tests, along with Euro 3 emission limits.

**Fig. 5.** Mean value and standard deviation of ratio of CO to CO₂ emission factors for selected motorcycles of private owners in city of Tehran resulted from cold start Euro 3 chassis dynamometer tests.
Assuming Eq. (2) as the combustion equation, relative air–fuel ratios could be approximated by Eq. (5), which is derived from element conservation expressions. In Eq. (5), HCR is the hydrogen to carbon ratio of fuel; M is a constant calculated based on fuel molar weight and stoichiometric air–fuel ratio; and $X_{CO_2}$, $X_{CO}$, $X_{THC}$, and $X_{O_2}$ are the molar fractions of the products, which can be assumed equal to their volumetric concentrations.

$$\lambda = M \left[ \frac{HCR}{4} + \frac{1}{2} \frac{X_{CO} + 2X_{CO_2} - X_{THC} + X_{O_2}}{X_{CO} + X_{CO_2} + X_{THC}} \right]$$  \hspace{1cm} (5)$$

As no data was available regarding $O_2$ concentrations in combustion products and because overall driving cycle emissions factors showed very rich combustion, $O_2$ concentration in combustion products was ignored in relative air–fuel ratio approximation. A sensitivity analysis was done to ensure that the error caused by ignoring $O_2$ in relative air–fuel ratio approximation was not considerable. The effects of $O_2$ concentrations in the evaluation of relative air–fuel ratios was calculated by Eq. (6). The effects of ignoring $O_2$ concentrations in the relative air–fuel ratio calculation were evaluated at various points in the driving cycle in one sample test. As no data was available regarding $O_2$ concentrations in combustion products, $O_2$ concentration at each data point was approximated using an equilibrium code. Analysis revealed that error caused by ignoring $O_2$ concentrations in relative air–fuel ratio approximations for rich mixtures is less than 0.5%, a value which is sufficiently low.

$$\text{Error} = \frac{1}{2} \frac{M}{X_{CO} + X_{CO_2} + X_{THC}}$$  \hspace{1cm} (6)$$

Results of instantaneous mass emissions, instantaneous speed, and relative air–fuel ratio for a sample 125 cc engine displacement volume motorcycle are presented in Fig. 8. Relative air–fuel ratio varies between 0.94 and 0.55, and its mean value is 0.81. Generally, same results were seen in the test results of other test subjects although there were a few number of test subjects with better air–fuel mixture control. This confirms that tested motorcycles are burning rich air–fuel mixtures,
which lowers combustion efficiency and temperature; causes high CO, THC, and possibly UFPs concentrations; and results in low NOX concentration in exhaust gas (Heywood, 1988). Additionally, it appears from Fig. 8 that, in some tested motorcycles, mostly in the aged ones, because of the absence of a closed loop air–fuel mixture control system, air–fuel mixture ratios became richer during testing process as engines warmed up. This led to increases in incomplete combustion product emission rates and decreases in relative air–fuel ratios.

**Emission degradation by age**

According to Iranian government laws, shelf life of motorcycles in Iran is 5 years. However, there is no control over this law. So, information about changes in motorcycles emission performance over time is important. According to the selected motorcycle data from Table 2, assessing the effects of aging on motorcycle emissions performance was available only in 125 cc engine volume motorcycles. Aging factor was calculated as the ratio of the emissions factor of an aged motorcycle to that of a new motorcycle for different pollutants (Eq. (7)).

\[
\text{Aging factor} = \frac{\text{Emissions factor of aged vehicle}}{\text{Emissions factor of new vehicle}}
\]  

(7)

In order to reduce the scatter of data, 125 cc engine displacement volume motorcycles were grouped into three age groups: less than two years old, between two and five years old, and more than five years old. Aging factors were calculated based on the mean emission factors of each group. In Fig. 9 different pollutant aging factors are presented. Using regression...
analysis, it was found that one year of aging causes a 6% increase in CO emission rate, a 7% increase in THC emission rate, a 2%
increase in fuel consumption, and a 5% reduction in the NOx emission rate. A reason for this could be that reduced effective
compression ratios over time resulted in lower combustion temperatures and, consequently, higher HC, CO, FC, and lower
NOx emissions.

Analysis of uncertainty and variability in results

Coefficients of variation for emission factors of motorcycles in the same engine volume group were calculated and pre-
sented in Table 3. The high coefficients of variation for most emission factors and engine volume groups comes from the vari-
ability of test subjects, as they were selected randomly from the actual fleet. Different producers, various maintenance
conditions, and age difference are among the influential parameters for variability.

Average travel-based emission factors, along with their 95% confidence intervals of the mean, for motorcycles of different
engine displacement volumes are presented in Table 4. Table 4 indicates that the 95% range of uncertainty in the mean emis-
sion factor ranges from ±4% to ±33%. The range of uncertainty is influenced by the small number of data points and the wide
range of variability of the data. Hence, as evident from Table 4, larger engine volume motorcycles have wider confidence
intervals.

Comparison of mean emission factors in Table 4 reveals that mean motorcycle emission factors of CO are 6–8 times higher
than Euro 3 standard emissions limits. THC emission rates in 125 cc engine volume motorcycles is the highest. Mean NOx
emission factors of 125 and 180 cc motorcycles are less than Euro-3 certification emission limit; although, 150 and 200 cc
engine volume motorcycles NOx emission factors exceed the Euro-3 certification NOx emission limit. Among different
motorcycles, discrepancy in fuel consumption is less than 15%. By considering confidence intervals, 180 cc motorcycles fuel
consumption is approximately equal to those of 125 cc motorcycles. It was expected that travel-based emission factors
would increase for larger engine volumes, but 180 cc engine volume motorcycles have the least average CO and THC emis-
sion factors in comparison to other engine volumes.

<table>
<thead>
<tr>
<th>Engine displacement volume (cc)</th>
<th>Coefficient of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO EF (g/km)</td>
</tr>
<tr>
<td>125</td>
<td>34</td>
</tr>
<tr>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>180</td>
<td>42</td>
</tr>
<tr>
<td>200</td>
<td>41</td>
</tr>
</tbody>
</table>

Fig. 9. Effect of aging on emissions of (a) CO, (b) THC, (c) NOX, and (d) fuel consumption in the 125 cc engine volume motorcycle group versus average motorcycle age.

Table 3
Coefficients of variation in the percentage of emission factors for different motorcycles engine volumes.

<table>
<thead>
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<tr>
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<td>41</td>
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</tbody>
</table>
Contribution of motorcycles fleet in Tehran emission inventory

Considering the aforementioned fleet composition for motorcycles in the city of Tehran (Fig. 3) and emission factors developed for different motorcycle types in Table 4, pollutant emission factors for the motorcycles fleet in the city of Tehran were developed. Motorcycles fleet emission factors for Tehran, along with emission factors for the Tehran passenger cars

Table 4
Average pollutant emission factors, along with 95% confidence interval of the mean, for different motorcycle engine volumes.

<table>
<thead>
<tr>
<th>Engine displacement volume (cc)</th>
<th>CO</th>
<th>THC</th>
<th>NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emission factor (g/km)</td>
<td>Fuel consumption (l/100 km)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean CI (absolute)</td>
<td>Mean CI (absolute)</td>
<td>Mean CI (absolute)</td>
</tr>
<tr>
<td></td>
<td>CO THC NOx</td>
<td>CO THC NOx</td>
<td>CO THC NOx</td>
</tr>
<tr>
<td>125</td>
<td>15.625 +1.690 +10.8 0.504 +0.069 +13.7 0.074 +0.016 +21.4 2.539 +0.104 +4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>16.782 +1.558 +9.3 0.327 +0.073 +22.2 0.242 +0.060 +24.6 2.800 +0.145 +5.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>12.434 +3.225 +25.9 0.258 +0.074 +28.7 0.127 +0.039 +31.0 2.615 +0.096 +3.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>12.993 +4.024 +31.0 0.330 +0.091 +27.6 0.263 +0.087 +33.2 2.884 +0.118 +4.1</td>
<td></td>
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</tr>
</tbody>
</table>

Table 5
Emission factors for motorcycle and passenger car fleets in the city of Tehran.

<table>
<thead>
<tr>
<th>Emission factor (g/km)</th>
<th>CO</th>
<th>THC</th>
<th>NOx</th>
<th>FC (l/100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The city of Tehran's motorcycles fleet</td>
<td>15.724 ± 1.806</td>
<td>0.492 ± 0.084</td>
<td>0.113 ± 0.017</td>
<td>2.647 ± 0.091</td>
</tr>
<tr>
<td>The city of Tehran's passenger cars fleet</td>
<td>6.2 ± 0.83</td>
<td>0.36 ± 0.020</td>
<td>0.87 ± 0.139</td>
<td>12.3 ± 0.98</td>
</tr>
</tbody>
</table>

Table 6
Total pollutant emissions of motorcycle and passenger car fleets in Tehran during the morning peak hour.

<table>
<thead>
<tr>
<th>CO (kg)</th>
<th>THC (kg)</th>
<th>NOx (kg)</th>
<th>FC (lit)</th>
<th>Total kilometer traveled (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The city of Tehran's motorcycles fleet</td>
<td>11248.4</td>
<td>34541.8</td>
<td>0.33</td>
<td>715,548</td>
</tr>
<tr>
<td>The city of Tehran's passenger cars fleet</td>
<td>350.6</td>
<td>2005.7</td>
<td>0.17</td>
<td>5,571,256</td>
</tr>
<tr>
<td>Ratio of motorcycles to passenger cars</td>
<td>33</td>
<td>17</td>
<td>0.2</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Fig. 10. Relative comparison of the total emissions produced by motorcycles and passenger cars in Tehran during the morning peak hour.

Contribution of motorcycles fleet in Tehran emission inventory

Considering the aforementioned fleet composition for motorcycles in the city of Tehran (Fig. 3) and emission factors developed for different motorcycle types in Table 4, pollutant emission factors for the motorcycles fleet in the city of Tehran were developed. Motorcycles fleet emission factors for Tehran, along with emission factors for the Tehran passenger cars
fleets, are presented in Table 5. Passenger cars fleet emission factors for Tehran were developed earlier by Banitalebi and Hosseini, who collected comprehensive emission factor measurements using PEMS\(^5\) (Banitalebi and Hosseini, 2015).

In order to estimate fleet emissions, either fuel consumption data or traffic data can be used to generate vehicle activity data. In general, direct traffic-based estimates provide a better representation of vehicle activity than those from fuel consumption statistics. Link-based vehicle kilometers traveled obtained from the EMME/2 travel demand model (TDM), performed by TCTTS\(^6\). Company, was used as activity data. TCTTS Co. calculated the traffic volume of seven vehicle categories for each Tehran road using a four-stage traffic model based on EMME/2 Travel Demand Model (TDM) that was calibrated by measured data. Average speeds, volume-capacity ratios, and speed limits of different vehicle categories (including motorcycles and passenger cars) in 17,441 individual links in Tehran are included in TDM model output. Activity data was available for the morning peak hour (between 7:30 and 8:30 a.m.).

Data in Table 5 were used as emission data in conjunction with the aforementioned activity data to estimate total emissions from motorcycles and passenger car fleets in the city of Tehran during the morning peak hour. Results are shown in Table 6. Fig. 10 shows the fraction of motorcycles and passenger cars for the total emissions produced by these two.

The results show that total motorcycles CO and THC emissions are about 1/3 and 1/5 of that of passenger cars, respectively; although, their kilometers traveled is about 1/10 of that of passenger cars. Despite the lower traveled kilometers of motorcycles with respect to passenger cars, motorcycles have considerably more relative contribution to CO, THC, and possibly UFPs emissions in the city of Tehran. Thus, as the number of motorcycles in Tehran is about 1/3 of number of passenger cars, improving motorcycle emissions performance is not only easier, but also a more efficient method, for improving air pollution in Tehran. Upgrading motorcycle fuel supply systems to fuel injection systems and the use of catalytic converters are options to achieve this goal (Muslim et al., 2014; Penteado et al., 2012; Alvarez, 2008; Lin et al., 2006; Chen and Lin, 2006; Hayakawa et al., 2004).

**Conclusions**

Sixty motorcycles from private owners in the city of Tehran were randomly selected and tested in a chassis dynamometer laboratory. Motorcycles were selected based on their engine volume to represent the motorcycle fleet in the city of Tehran. Measurements were done both via emission bags and instantaneous concentration measurements. Molar fractions of CO\(_2\), CO, and THC in an assumed combustion equation were estimated based on fuel-based emission factors. Furthermore, relative air–fuel ratios were approximated by analysis of instantaneous emissions measurement data in the assumed combustion equation. In the final analysis, total pollutant emissions from motorcycles in the city of Tehran were calculated using emission factors developed for motorcycles in this study and activity data obtained from the EMME/2 travel demand model. Results of the measurements and calculations are summarized as follows:

1. The average CO emission factors are several times higher than the limits for Euro-3 certification. With the exception of NO\(_x\) emissions for the larger engine fleet, the rest of the emission factors, including THC for the entire sample fleet, were close to Euro-3 certification levels.
2. 125 cc engine displacement volume motorcycles, which are the greatest component of the Tehran motorcycle fleet, have the greatest CO and THC emission rates. CO emission rates were 8 times greater than the limit for Euro-3 certification. Emission rates of incomplete combustion products increase as engine volume decreases.
3. Between 40% and 30% of carbon in the fuel burns to CO in motorcycles. Among tested motorcycles, 125 cc engine volume motorcycles have the greatest molar fraction of CO and THC in combustion products.
4. Relative air–fuel ratio of the mixtures varied remarkably during the tests for a few test subjects (e.g. from 0.95 to 0.55). High CO and THC emission factors and possibly high UFPs emission rates in the sample test subject is due to very rich air fuel mixture.
5. In some tested motorcycles, mostly in the aged ones, it was seen that mixture air–fuel ratios were enriched during the testing process with engine warm-up. This is a result of the absence of a closed loop air–fuel mixture control system, which leads to increased emission rates of incomplete combustion products.
6. Analysis of results showed that CO, THC, and fuel consumption increased 6%, 7%, and 2%, respectively, and the NO\(_x\) emission factor decreased by 5% with one year of aging for a new motorcycle.
7. As tested motorcycles were selected randomly from private owners, different producers, various maintenance conditions, age differences, and, in the case of larger engine volume motorcycles, small samples size, could be responsible for the quantified high variability and uncertainty in results.
8. Comparison of total emissions from motorcycles and passenger cars in the city of Tehran revealed that the contribution of motorcycles to CO and THC emissions, and possibly UFPs, is higher than their share in Tehran’s transportation fleet.
9. Use of catalytic converters, along with the implementation of a closed loop air–fuel mixture control system, offers the means for improving Tehran’s air quality.

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\(^5\) Portable emission measurement systems.
\(^6\) Tehran Comprehensive Transportation and Traffic Study.
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References