Comparison of Real-World Emissions from Two-Wheelers and Passenger Cars

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Introduction

Since tailpipe emissions were first recorded in the 1980s, a great deal of attention has been given to reducing their emissions. This has resulted in notable technical progress, leading to unprecedentedly low exhaust emissions. In the meantime, emissions from motorcycles have been ignored due to their subordinate role in traffic. Even though the motorcycle fleet is small in comparison with the car fleet, and logs lower yearly mileage per vehicle, their contribution to traffic emissions has become disproportionately high. Exhaust emissions of CO, HC, NOx, and CO2 from 8 powered two-wheelers were measured and compared to previous measurements from 17 gasoline-powered passenger cars performed at EMPA with the aim of ascertaining their relevance. Using exhaust emission ratios from both vehicle types, comparisons based on mean unit, mean yearly, and fleet emissions are considered. Present-day aftertreatment technologies for motorcycles are not as efficient as those for cars. A comparison of mean unit emissions shows that motorcycles exceed cars in NOx emissions. All comparisons reveal a significant HC ratio, to the detriment of two-wheelers. Overall, the relevance of emissions from powered two-wheelers is not negligible when compared with modern gasoline-powered passenger cars.

Materials and Methods

Vehicles. The 8 two-wheelers tested were chosen because they were considered to be representative of the Swiss fleet in 2002 with regard to their chassis type, engine capacity, operating principle, and aftertreatment system. Vehicle specifications are shown in Table 1. The vehicles were in use and made available by private owners on request. To ensure the results were as close to reality as possible, all vehicles were tested without prior maintenance or adjustments.

Test Setup. Emissions measurements were performed at EMPA on a chassis dynamometer test bench in a climate chamber (Schenk 1500 GS200 for cars and Siemens IP-23 for two-wheelers). During all the tests presented, the temperature in the chamber was kept at 23 °C with a relative humidity of 60%. A variable-speed fan was placed in front of the vehicles to simulate the cooling air stream from real driving. The volume flow rate of the diluted exhaust gas through the constant volume sampler (CVS) was 4.5 m³/min for vehicles 1–5 and 6 m³/min for vehicles 6–8.

The usual emission testing setup for cars or trucks involves a closed connection between the tailpipe and the CVS dilution system. However, the small engines of two-wheelers produce a comparatively low exhaust gas flow. With a closed connection to the dilution system, the pressure at the tailpipe would be significantly below ambient pressure. The CVS ventilation would support the engine in ejecting the exhaust gas. An aid would clearly falsify the engine load and, thus, the emissions. A more appropriate test setup involving open dilution was therefore chosen. The tailpipe was connected...
to the CVS plant in an open way, such that the exhaust gas was drawn off diluted with room air. The test setups for cars and two-wheelers are shown in Figure 1. The CVS was a HORIBA 9100 for the two-wheelers and a HORIBA 9400 for the cars.

**Emissions and Signals.** A sample of diluted exhaust gas was fed into sampling bags and analyzed offline for its CO, HC, NO\(_x\), and CO\(_2\) content. The standard equipment used for this purpose (HORIBA Mexa 7400 series) fulfills certification requirements. Indeed, there is no statutory limit for CO\(_2\), but it is used to calculate fuel consumption.

In addition to the bag measurements, the diluted exhaust gas and several other signals such as tailpipe temperature, lambda, and engine speed were recorded continuously at a rate of 10 Hz for detailed analysis. All the equipment, i.e., dynamometers, CVS, and analyzers, is approved for homologation.

**Cycles.** Emission measurements were performed on the two-wheelers using the following three real-world driving cycles (Figure 2). All tests started with warm engines.

**CADC.** The Common ARTEMIS Driving Cycle developed within the European research project ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) represents mean European driving behavior for passenger cars. This real-world driving cycle is more dynamic and is divided into patterns for urban, rural, and highway driving. Every vehicle was tested in those patterns which were suitable in view of its maximum power.

**WMTC (Worldwide Harmonized Motorcycle Emissions Certification Procedure).** This cycle was developed to replace various existing legislative cycles for two-wheelers (such as ECE for Europe) with a standard worldwide real-world driving cycle. As for the CADC, it is divided into urban, rural, and highway driving.

**FHB (Fachhochschule Biel Cycles).** These cycles were developed by the Biel University of Applied Science to reflect driving in and around this Swiss town. The “center” pattern represents inner-city driving, and, combined with the “periphery” pattern, models urban driving behavior.

The characteristics of the test cycles are given in Table 2 in comparison to the statutory cycles ECE (Europe) and FTP (United States). The cycles used here were developed comparatively from driving behavior studies on the road. It is important to use representative real-world tests that consist of urban, rural, and highway cycles for emission inventories. As different studies confirm, emission factors derived from statutory cycles are consistently lower than those from real-world cycles. In addition, the statutory cycles do not allow separate mapping of cold start and warm emissions for urban, rural, and highway driving.

**Fuels.** The same fuel was used for both test fleets. It was a commercial unleaded fuel of 95 ROZ standard with an octane number of 95.3 ROZ, containing 37.8 mass% aromatics and in compliance with the EU 2000 regulations.

**Results.** The obtained emission factors are shown in Table 3. It is known that two-wheelers and cars are driven in different ways. However, there are two reasons why the same driving cycle may be used for the comparison made in this study. First, all two-wheelers produce similar emissions in all urban cycles. The same holds true for all rural and highway cycles too, although some are developed for motorcycles and others for cars. It is therefore not so critical which test is used for comparison. Second, the comparison is most systematic if the same cycle is used for both vehicle classes. It is for that reason that this study is based on measurements in the CADC.

The measurements obtained from the two-wheelers in the CADC cycle are shown in Figure 3. The plots highlight the large differences between individual vehicles employing the various technical concepts. Because of its low engine power, vehicle 1 was only tested in the urban part of the cycle, and vehicles 2 and 3 were tested only in the urban and rural parts.

The oil in the two-cycle fuel and incomplete combustion resulted in high HC emissions for vehicles 1 and 2. In addition, vehicle 2 also produced high CO and almost no NO\(_x\) emissions, a result that indicates a very rich mixture. The lambda signals for vehicles 3, 4, and 6 indicated a consistently

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**TABLE 1. Specifications of Two-Wheelers by Vehicle Number**

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yamaha</td>
<td>YN 50</td>
<td>1998</td>
<td>49</td>
<td>64</td>
<td>2.9</td>
<td>11,222</td>
<td>88</td>
</tr>
<tr>
<td>2</td>
<td>Piaggio</td>
<td>Skipper</td>
<td>1995</td>
<td>124</td>
<td>99</td>
<td>9.5</td>
<td>15,472</td>
<td>113</td>
</tr>
<tr>
<td>3</td>
<td>Piaggio</td>
<td>Vespa</td>
<td>1997</td>
<td>124</td>
<td>93</td>
<td>7.9</td>
<td>13,951</td>
<td>113</td>
</tr>
<tr>
<td>4</td>
<td>Yamaha</td>
<td>VP 250</td>
<td>1996</td>
<td>250</td>
<td>120</td>
<td>17.9</td>
<td>22,724</td>
<td>113</td>
</tr>
<tr>
<td>5</td>
<td>Honda</td>
<td>Shadow</td>
<td>1993</td>
<td>583</td>
<td>125</td>
<td>15.5</td>
<td>5364</td>
<td>170</td>
</tr>
<tr>
<td>6</td>
<td>Suzuki</td>
<td>VS 800 GLP</td>
<td>1993</td>
<td>805</td>
<td>155</td>
<td>29.4</td>
<td>29,466</td>
<td>170</td>
</tr>
<tr>
<td>7</td>
<td>Honda</td>
<td>VFR 800 Fi</td>
<td>1998</td>
<td>782</td>
<td>250</td>
<td>70</td>
<td>32,223</td>
<td>170</td>
</tr>
<tr>
<td>8</td>
<td>BMW</td>
<td>R1150GS</td>
<td>1999</td>
<td>1130</td>
<td>195</td>
<td>62</td>
<td>31,474</td>
<td>170</td>
</tr>
</tbody>
</table>

**FIGURE 1. Test setup for emissions testing of cars and two-wheelers.**
rich mixture with values around 0.8 to 0.9, while vehicle 5 was lean in the urban part of the cycle, roughly stoichiometric in the rural part, and rich in the highway part. The secondary air valve in vehicle 6 seemed to be the main reason for its low HC emissions.

Vehicles 7 and 8 both had a controlled 3-way catalytic converter and fuel injection systems. Their technology was thus similar to that of modern passenger vehicles. Nevertheless, their lambda values were not the same as for cars and differed from one motorcycle to another. The mixture of vehicle 7 stayed lean, with lambda around 1.1 in urban and rural parts, which resulted in very low CO and HC levels. The additional power required for the highway part was produced using a rich mixture with lambda values decreasing to 0.8. This considerably increased CO emissions. In contrast, vehicle 8’s catalytic converter performed poorly in the urban and rural parts, where lambda values fluctuated with large amplitudes around one. Only on the highway part was the mixture mainly stoichiometric, enabling the catalytic converter to efficiently reduce CO and HC.

Five of the eight vehicles exceeded the limit for CO and two of these vehicles also exceeded the HC limit in the ECE statutory driving cycle. More than half the vehicles therefore failed the statutory test.

Car Measurements Used for Comparison. The emissions of 17 gasoline-powered passenger cars from the Euro 3 statutory period were measured at EMPA in 2001 and 2002 (9). These in-use vehicles were loaned from private owners in order to create a realistic maintenance situation. They were chosen to reflect the real-life composition of Switzerland’s vehicle fleet. Like the two-wheelers, the cars were driven on a chassis dynamometer test bench with a cooling fan in a climate chamber at temperature of 23 °C. In contrast to the measurements on the two-wheelers, a closed connection was used to hitch the tailpipe to the CVS dilution system in accordance with common practice (see Figure 1). Emissions of CO, HC, NOx, and CO2 were sampled in several driving cycles, one being the CADC, the emissions from which are compared here. Table 4 lists the mean values of the cars’ emissions.

Emission Comparison

The values from Tables 3 and 4 were used to compare emissions from the powered two-wheelers with those of the gasoline passenger cars. The two-wheelers met FAV 3 and
Euro 1 standards, while the cars complied with Euro 3. Thus, the vehicles’ emission behavior was the same as that of vehicles on sale in 2001.

Test repeatability for the two-wheelers displays an average standard deviation of 4% for CO2, 10% for CO and HC, and 15% for NOx. For the cars these values are 2%, 15%, and 15% respectively. These are typical values for chassis dynamometer tests (10). Thus the repeatability deviation is significantly smaller than the scatter between the vehicles (Figure 2, Table 3).

It is well-known that vehicles’ emission variability is large. However, since the samples were intentionally chosen so as to be representative of the engine sizes, makes, engine concepts, transmission types, vehicle masses, and chassis types, etc., of the Swiss population, standard statistical analysis results in misleadingly high uncertainties. The

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>CO2 [g/km]</th>
<th>HC [g/km]</th>
<th>NOx [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CADC urban</td>
<td>46.4</td>
<td>80.1</td>
<td>44.0</td>
</tr>
<tr>
<td>rural</td>
<td>45.8</td>
<td>59.8</td>
<td>35.6</td>
</tr>
<tr>
<td>highway</td>
<td>47.7</td>
<td>58.8</td>
<td>35.6</td>
</tr>
</tbody>
</table>

**TABLE 3. Emissions from Two-Wheelers in Different Driving Cycles**

<table>
<thead>
<tr>
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<th>CO2 [g/km]</th>
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**FIGURE 3. Emissions from two-wheelers in CADC driving cycle; shaded background groups vehicles into two-cycles, four-cycles, and vehicles with a three-way catalytic converter.**
calculated 95% confidence intervals for the comparisons given below range from 50 to 100% for CO, HC, and NO\textsubscript{x}, and from 20 to 45% for CO\textsubscript{2}. Although it is impossible to prove, the authors assume that the selection of representative vehicles from fleet statistics has produced values that are reasonably close to the real values of the entire fleets. It is possible that the error in the following comparisons (Figures 4–6) is no greater than 30% for CO, HC, and NO\textsubscript{x}, and less than 15% for CO\textsubscript{2}. Using 5–10 vehicles per sample is also recommended as sufficient in ref 11, provided that selection is done representatively on the basis of fleet statistics.

**Comparison of Mean Unit Emissions**. First, two-wheelers’ mean unit emissions in g/km are compared with those of passenger cars. It should be noted that immediate measurements that yield emission concentrations, i.e., measurements in ppm, are not discussed here, since they are meaningless. The basic values (unit emissions) used to compare two vehicles or, as in this case, two average vehicles, are given as absolute values in g/km. The ratio of the mean unit emission of all two-wheelers and all cars is calculated for every driving pattern. Because of their low power it was possible to test only seven out of eight two-wheelers in the “urban” part of the cycle and only 5 in the “highway” part. However, the two-wheelers were selected so as to be representative of the Swiss fleet, which means that the results should yield realistic proportions.

Figure 4 shows the ratios of mean emissions in g/km from two-wheelers and cars. For CO and HC this ratio is largest at slower speeds, while the opposite is true for NO\textsubscript{x}. Frequent acceleration and load changes in urban driving result in enrichment and incomplete combustion. This is assumed to be the main reason for this observation. The emissions ratio is particularly high for HC (factor of 222) in urban driving, and this can be attributed to two-cycle vehicles and four-cycle vehicles with a very rich mixture. The NO\textsubscript{x} emission ratio may appear surprising, as the two-wheelers’ generally rich mixture should create very little NO\textsubscript{x}. Obviously, there is more thermal NO\textsubscript{x} in the two-wheelers’ emissions greater than in the catalyzed exhaust gas of the passenger cars.

Since two-wheelers are lighter than passenger cars, their fuel consumption and CO\textsubscript{2} emissions are also lower. Nevertheless, the weight- and payload-specific fuel consumption of the two-wheelers is still quite high.

**Calculation of Fleet Emissions**. In Switzerland, as in other European countries, motorcycles and cars are used on different occasions. Two-wheelers are used primarily as local urban transport and leisure. Their use obviously depends on weather conditions, which is why the average two-wheeler has a lower yearly mileage than a passenger car. In this section, we therefore present two different comparisons: First, the yearly emissions from the average motorcycle are compared to the average car, and the unit emissions from above are therefore multiplied by the average yearly mileages. Second, the emissions from both fleets are compared, thus accounting for the total numbers of vehicles in both groups.

The number of vehicles sold in 2001 is given in ref 8, along with yearly mileages on urban, rural, and highway routes. With regard to the test bench measurements, it was assumed that two-wheelers with engine capacities of less than 50 cm\textsuperscript{3} are to be found only in urban regions, while vehicles with engine capacities up to 125 cm\textsuperscript{3} are used in urban and rural situations, and the rest are used in all driving patterns. Fleet mileages and average mileage per vehicle are presented in Table 5.

In Switzerland, as in other European countries, two-wheelers are often used for leisure or for short trips in conurbations. The average motorcycle therefore clocks up a lower yearly mileage than a car. As a direct result, Figure 5 shows the ratio of yearly emissions from the average two-wheeler to yearly emissions from the average car. The ratios are lower in comparison with Figure 4 because of two-wheelers’ lower mileages, but they are still quite high. The yearly HC emission of the average two-wheeler in urban traffic is up to 49 times that of the average car.

Finally, to demonstrate the overall impact of emissions at a national level, the yearly output of both fleets is compared. Using the mileages and stocks from Table 5, emissions from both fleets are compared in Figure 6. Despite the lower mileage and smaller number of vehicles, the motorcycle fleet produces CO emissions that are higher by a factor of up to 2.7, and HC emissions that are higher by a factor of 16 in urban conditions. It may be supposed that two-wheelers clock

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up most of their mileage in good weather conditions. As these conditions are also conducive to the formation of tropospheric ozone, emissions of HC and NOx gain additional significance (12). It must therefore be borne in mind that the ratios presented here refer to an average value over the year and are probably higher on ozone-critical days.

**Discussion**

Several comparisons showed that the powered two-wheelers on the market in 2001 produced significantly higher emissions of all pollutants except CO2 than gasoline-powered passenger cars from the same sales period. Whether in a direct comparison of mean unit emissions (in g/km), mean yearly emissions (in kg/vehicle/year), or fleet emissions (in tons/year), the two-wheelers’ HC and CO emissions were all, and often significantly, higher. In addition, the NOx contribution of the motorcycle fleet is roughly one-fifth that of the car fleet and is thus not negligible.

CO emissions may cause local health problems and further oxidize to CO2, contributing to the greenhouse effect. However, limit values have not been exceeded in Switzerland for several years, with the result that this gas has become less significant.

The situation is different for HC. The HC values used here are the sum of unburned hydrocarbons. Some of them contribute to the greenhouse effect, while others have been proven to be carcinogenic or to contribute to ozone formation. It was shown that powered two-wheelers emit substantially more HC than passenger cars. The significant ratios in the urban pattern (222 for mean unit emissions [g/km], 49 for yearly vehicle emissions, and 16 for yearly fleet emissions) are mainly caused by two-cycle machines, which emit more HC than motorcycles with four-cycle engines (1, 2, 13). However, the use of technologies similar to those employed in cars—such as regulated three-way catalytic converters with fuel injection (vehicles 7 and 8)—does not yield similar results either. It must be assumed that work on implementing the lambda control loop has not been performed with the same care as for cars.

It has to be stressed again that all the comparisons discussed here are subject to the uncertainties mentioned above. From a purely statistical point of view these seem to be unacceptably large, but as the vehicles are intentionally chosen to represent the variety of the fleet with regard to engine size, manufacturer, technical solutions etc., the results appear to be fairly representative of the fleet.

Overall, emissions from motorcycles have become relevant compared to those from modern passenger cars. Even if they account for a comparatively small number of vehicles, motorcycles’ impact on traffic emissions cannot be overlooked. Directive 2002/51/EC of the European Parliament and Council is a step in the right direction. With the introduction in 2006 of new emissions limits which are intended to correspond to Euro 3 gasoline cars, and with checking procedures for the correct operation of emission control systems, motorcycle emissions are expected to decrease. However, the fact that more than half of the two-wheelers failed the statutory test is indicative of the need for periodical inspection and maintenance. With regard to this study, the introduction of similar regulations as for passenger cars such as checking the durability of the aftertreatment system and periodic testing of exhaust gases should be considered. It would therefore be expedient to repeat this study two to three years after introduction of the new rules.

**Acknowledgments**

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**FIGURE 6. Ratios of fleet emissions [tons/year] from two-wheelers and passenger cars for the Swiss fleet.**