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

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Passenger cars are the primary means of transportation in Europe. Over the past decade, a great deal of attention has therefore been paid 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, NO_x, and CO_2 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 NO_x 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.

Introduction

Since tailpipe emissions were first recorded in the 1980s, a great deal of attention has been given to passenger cars because their number and fleet mileage outweigh those of all other vehicles. In the past 20 years, statutory limits have been successively reduced, and the technologies implemented have led to notable reductions in emissions of pollutants such as CO, HC, and NO_x.

As in other European countries, two-wheelers are not the primary means of transportation in Switzerland. Their number and mileage per vehicle are lower than those of passenger cars. As a consequence, the importance of their emissions has been underestimated in legislation, giving manufacturers little motivation to improve aftertreatment systems. Only slight progress has therefore been made in reducing emissions from powered two-wheelers.

The real significance of their emissions in comparison with modern passenger vehicles is the key topic of this study. The emissions of CO, HC, NO_x and CO_2 from two-wheelers are contrasted with those from gasoline-powered passenger cars. The investigations are based on measurements from vehicles of both types which were on the market in 2001.

A similar study was performed in 1995 by Chan et al. using gasoline cars available at that time (*1*). Compared with cars with catalytic converters, cars without catalytic converters and two-cycle motorcycles were found to emit 12 times more HC and CO. However, these emissions ratios have since increased again due to technical progress in reducing emissions from cars. In contrast to earlier measurements, which used statutory driving cycles such as the ECE (*1*, *2*), the measurements presented here were obtained using several real-world cycles—i.e., cycles derived from driving behavior studies, which thus give a more realistic representation of the situation on the road. For the sake of comparison, the same real-world driving cycle was used for both vehicle types.

The measurement of tailpipe emissions of CO, HC, NO_x, and CO_2 from 8 two-wheelers is described in the Materials and Methods section. Different comparisons with 17 Euro 3 gasoline-powered passenger cars are given in the section on Emission Comparison. In a first step, an average two-wheeler is directly compared with an average car. The second analysis compares the yearly emissions from the average two-wheeler with those from the average car, thus weighting the original results with yearly mileage. The study concludes with a consideration of the emissions from both vehicle fleets, thus stressing the overall relevance of emissions from two-wheelers compared with those of present-day gasoline 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.

The vehicles were from statutory periods FAV 3 (Swiss emission regulations for two wheelers (*3*), similar to Euro 1 regulations) and Euro 1. Since the changeover from one to the other involved no tightening of the emission limit values, but instead lowered two-cycle HC emissions requirements, it was assumed that the emission behavior of the vehicles had not changed.

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 m^3/min for vehicles 1−5 and 6 m^3/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. This 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

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TABLE 1. Specifications of Two-Wheelers by Vehicle Number

	1	2	3	4	5	6	7	8
make	Yamaha	Piaggio	Piaggio	Yamaha	Honda	Suzuki	Honda	BMW
model	YN 50	Skipper	Vespa	YP 250	Shadow	VS 800 GLP	VFR 800 FI	R1150GS
type	scooter	scooter	scooter	scooter	motorcycle	motorcycle	motorcycle	motorcycle
first registration	1998	1995	1997	1996	1993	1993	1998	1999
emission class	97/24/EG	FAV3	97/24/EG	97/24/EG	FAV3	FAV3	97/24/EG	97/24/EG
engine capacity [cc]	49	124	124	250	583	805	782	1130
working principle	2 cycles	2 cycles	4 cycles	4 cycles	4 cycles	4 cycles	4 cycles	4 cycles
fuel system	carb.	carb.	carb.	carb.	carb.	carb.	injection	injection
choke	automatic	automatic	automatic	automatic	manual	manual	no	no
after treatment	oxi-cat	oxi-cat	no	no	no	sec. air valve	3-way cat	3-way cat
gearbox type	semi-aut.	semi-aut.	semi-aut.	semi-aut.	4 gears	5 gears	6 gears	6 gears
max. power [kW]	2.9	9.5	7.9	14.7	15.5	29.4	70	62
max. speed [km/h]	64	99	93	120	125	155	250	195
mileage [km]	11,222	15,472	13,951	22,724	5364	29,466	32,223	31,474
cooling	air	air	air	water	water	water	water	air/oil
weight [kg]	88	113	113	170	213	219	237	277

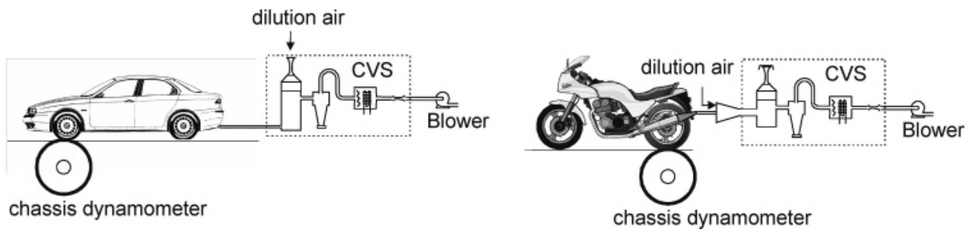

FIGURE 1. Test setup for emissions testing of cars and two-wheelers.

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 (*4*)) represents mean European driving behavior for passenger cars (*5*). 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 (*6*). 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 representatively 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 (*5*, *7*, *8*), 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 (*7*). 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

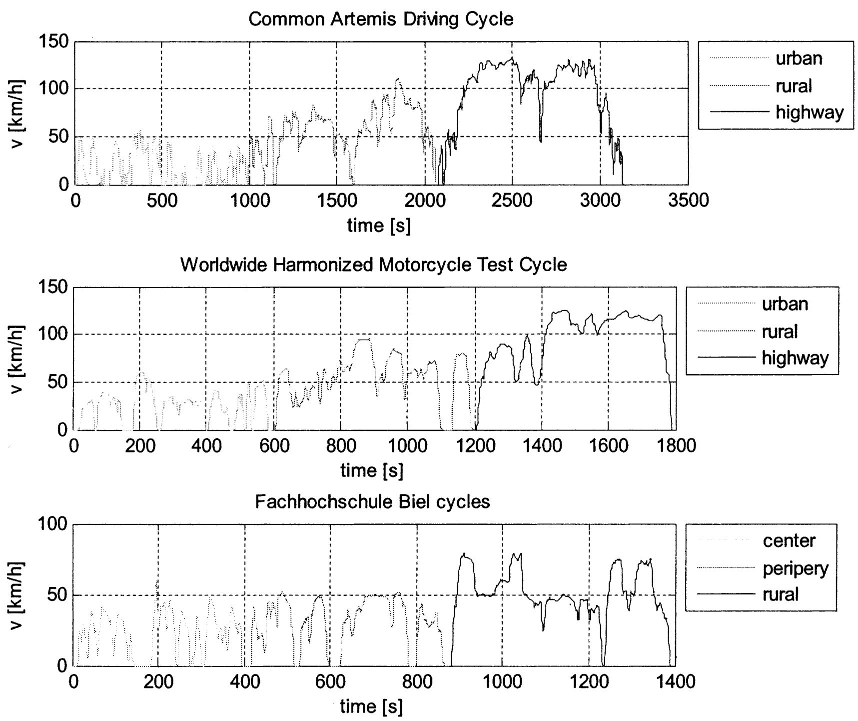

FIGURE 2. Speed patterns of driving cycles.

TABLE 2. Characteristics of Test Cycles.

name	duration (s)	average speed (km/h)	distance (km)	stop fraction (%)	mean pos. acc. (m/s^2)	mean neg. acc. (m/s^2)	maximal pos. acc. (m/s^2)	minimal pos. acc. (m/s^2)
CADC urban	920	17.6	4.49	36	0.57	−0.56	4.18	−3.88
CADC rural	980	60.2	16.39	3	0.41	−0.44	5.34	−5.96
CADC highway	735	116.4	23.76	0	0.21	−0.27	2.14	−3.63
WMTC urban	600	24.5	4.08	22	0.44	−0.48	4.72	−3.20
WMTC rural	600	54.5	9.09	9	0.44	−0.51	4.28	−3.52
WMTC highway	600	93.9	15.65	3	0.37	−0.44	3.20	−3.48
FHB center	401	22.2	2.47	0.21	0.74	−0.63	12.21	−12.02
FHB periphery	466	29.6	3.84	0.18	0.51	−0.46	4.82	−3.13
FHB rural	524	49.8	7.25	0.04	0.38	−0.40	4.34	−2.93
ECE	780	18.7	4.05	35	0.33	−0.36	1.04	−0.93
FTP-1	505	41.12	5.77	23	0.51	−0.51	1.59	−1.52
FTP-2	870	25.70	6.21	18	0.46	−0.52	1.59	−1.59

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, NO_x, and CO_2 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

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

		vehicle									
		1	2	3	4	5	6	7	8	avg	SD
					CO [g/km]						
CADC	urban	8.1	42.1	20.8	19.4	6.6	54.7	2.0	23.7	22.2	18.2
	rural		25.6	17.4	15.3	12.7	25.2	0.8	10.7	15.4	8.6
	highway				20.7	35.1	44.7	19.1	2.0	24.3	16.4
WMTC	urban		34.6	18.5	16.3				19.6	22.3	8.4
	rural		27.0	16.3	15.3				7.4	16.5	8.1
	highway				18.8				2.9	10.9	11.3
FHB	center	5.7	40.6	17.0	16.1	5.1	45.9	2.0	20.4	19.1	16.3
	periphery	6.2	30.8	14.7	13.8	5.1	38.6	0.9	22.5	16.6	13.2
	rural	8.3	23.9	13.1	12.9	7.8	25.2	0.7	13.3	13.1	8.2
					HC [g/km]						
CADC	urban	5.72	12.62	2.40	1.42	1.64	4.25	0.78	1.34	3.77	3.95
	rural		4.47	1.17	0.67	0.66	1.57	0.29	0.40	1.32	1.46
	highway				0.54	0.66	1.12	1.07	0.13	0.70	0.41
WMTC	urban		11.27	2.10	0.97				1.55	3.97	4.89
	rural		4.95	4.16	0.81				0.45	2.59	2.29
	highway				0.61				0.17	0.39	0.31
FHB	center	4.42	9.93	2.56	1.43	1.78	3.84	0.99	1.63	3.32	2.93
	periphery	4.02	8.53	1.71	0.96	1.18	3.22	0.47	1.09	2.65	2.67
	rural	4.49	5.42	1.30	0.78	0.80	1.98	0.34	0.48	1.95	1.94
					NO_x [g/km]						
CADC	urban	0.076	0.007	0.152	0.276	0.414	0.141	0.073	0.042	0.148	0.136
	rural		0.008	0.217	0.224	0.404	0.222	0.246	0.113	0.205	0.122
	highway				0.459	0.680	0.331	0.242	0.848	0.512	0.250
WMTC	urban		0.005	0.104	0.197				0.063	0.092	0.081
	rural		0.006	0.210	0.239				0.088	0.136	0.108
	highway				0.423				0.487	0.455	0.045
FHB	center	0.076	0.005	0.167	0.264	0.413	0.133	0.058	0.058	0.147	0.134
	periphery	0.054	0.004	0.145	0.179	0.306	0.106	0.076	0.049	0.115	0.095
	rural	0.043	0.004	0.212	0.207	0.361	0.170	0.153	0.053	0.150	0.116
					CO_2 [g/km]						
CADC	urban	46.4	80.1	44.0	63.5	104.0	103.5	187.5	178.7	100.9	55.6
	rural		45.8	39.8	42.3	66.7	64.4	116.6	112.5	69.7	32.4
	highway				70.0	93.8	92.1	114.1	129.4	99.9	22.7
WMTC	urban		64.1	34.2	50.3				133.7	70.6	43.8
	rural		47.7	39.1	42.8				110.2	59.9	33.7
	highway				60.3				114.2	87.2	38.1
FHB	center	41.1	68.3	39.2	55.7	91.1	92.2	164.2	149.4	87.6	47.2
	periphery	34.9	58.8	34.2	44.9	81.5	72.3	141.7	132.2	75.1	41.8
	rural	33.5	46.1	35.6	39.6	67.5	60.3	119.3	112.5	64.3	34.0

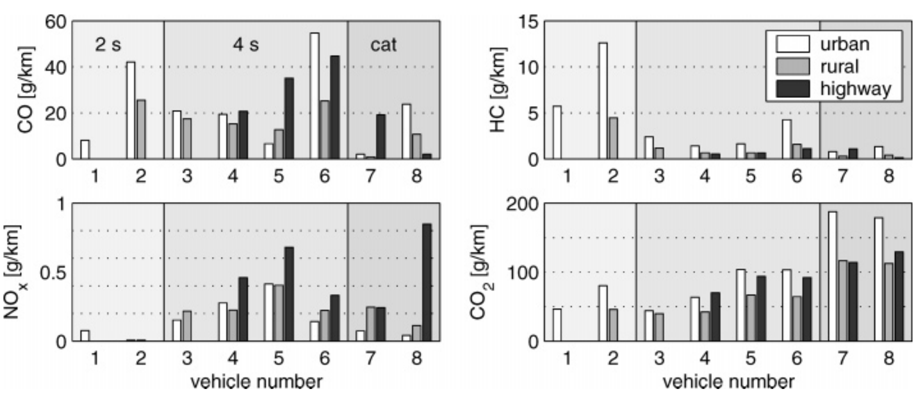

FIGURE 3. Emissions from two-wheelers in CADC driving cycle; shaded background groups vehicles into two-cycles, four-cycles, and vehicles with a three-way catalytic converter.

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 CO_2, 10% for CO and HC, and 15% for NO_x. 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 4. Mean Values and Standard Deviations of 17 Euro-3 Cars' Emissions in Driving Cycle CADC Used for Comparison

	CO [g/km]		HC [g/km]		NO_x [g/km]		CO_2 [g/km]	
	avg.	SD	avg.	SD	avg.	SD	avg.	SD
urban	0.57	0.91	0.017	0.015	0.089	0.069	278.4	53.4
rural	0.85	0.97	0.018	0.016	0.052	0.030	160.4	24.5
highway	3.04	3.00	0.031	0.017	0.065	0.048	192.4	19.4

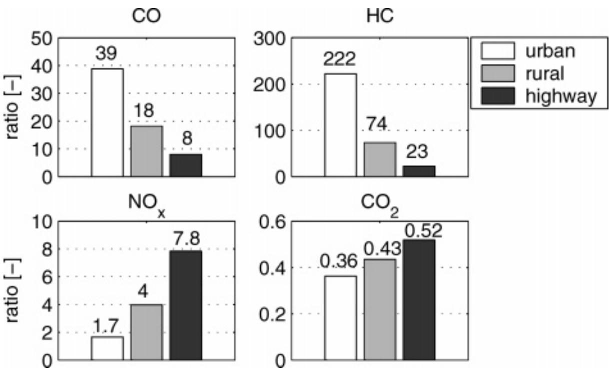

FIGURE 4. Ratios of mean unit emissions [g/km] of two-wheelers and passenger cars.

calculated 95% confidence intervals for the comparisons given below range from 50 to 100% for CO, HC, and NO_x, and from 20 to 45% for CO_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_x and less than 15% for CO_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 "rural" 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_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_x emission ratio may appear surprising, as the two-wheelers' generally rich mixture should create very little NO_x. Obviously, there is more thermal NO_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_2 emissions are also lower. Nevertheless, the weight- and payload-specific fuel consumption of the two-wheelers is still quite high.

TABLE 5. Fleet and Vehicle Mileage[a]

	two-wheelers FAV3 and Euro-1			passenger cars Euro-3		
		yearly mileage			yearly mileage	
	sales	fleet [10^6 km]	vehicle [km]	sales	fleet [10^6 km]	vehicle [km]
urban	48,077	57	1194	151,867	821	5406
rural	27,001	44	1640	151,867	856	5635
highway	25,717	31	1200	151,867	839	5524

[a] Data from ref 6.

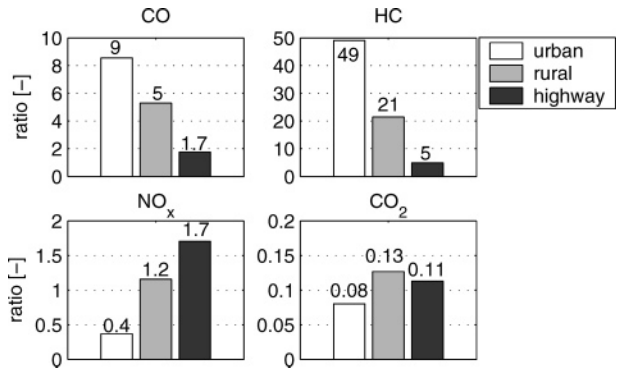

FIGURE 5. Ratios of mean *yearly* emissions [kg/vehicle/year] from two-wheelers and passenger cars.

Comparison 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^3 are to be found only in urban regions, while vehicles with engine capacities up to 125 cm^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

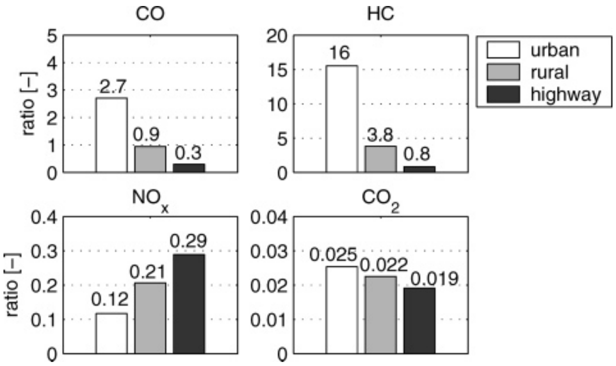

FIGURE 6. Ratios of *fleet* emissions [tons/year] from two-wheelers and passenger cars for the Swiss fleet.

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 NO_x 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 show that the powered two-wheelers on the market in 2001 produced significantly higher emissions of all pollutants except CO_2 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 NO_x 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 CO_2, 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.

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Literature Cited

(1) Chan, C. C.; Nien, C. K.; Tsai, C. Y.; Her, G. R. Comparison of tail-pipe emissions from motorcycles and passenger cars. *J. Air Waste Manage. Assoc.* **1995**, *45* (2), 116–124.

(2) Tsai, J. H.; Hsu, Y. C.; Weng, H. C.; Lin, W. Y.; Jeng, F. T. Air pollutant emission factors from new and in-use motorcycles. *Atmos. Environ.* **2000**, *34*, 4747–4754.

(3) *Verordnung über die Abgasemissionen von Motorrädern*; Swiss Governement, EDMZ 1988-763: Bern, 1988.

(4) *ARTEMIS, Assessment and reliability of transport emission models and inventory systems;* A project within the 5th EU Frame Program. http://www.trl.co.uk/ARTEMIS.

(5) De Haan, P.; Keller, M. *Real-world driving cycles for emission measurements: ARTEMIS and Swiss cycles.* BUWAL SRU Nr. 255: Bern, 2001.

(6) WMTC. *Worldwide Harmonized Motorcycle Emissions Certification Procedure*; United Nations Economic Commission for Europe: Geneva, Switzerland. http://www.unece.org/trans/main/wp29/wp29wgs/wp29grpe/wmtc.html.

(7) Gense, R.; Elst, D. Towards meaningful real-world emission factors for motorcycles: An evaluation of several recent TNO projects. In *Proceedings of the 12th International Symposium on Transport and Air Pollution*; Avignon, 2003; 161–168.

(8) INFRAS. *Luftschadstoff-Emissionen des Strassenverkehrs 1980–2030.* BUWAL report 355; BUWAL (Swiss Agency for the Environment, Forests and Landscape): Bern, Sept. 2004.

(9) Stettler, P.; Forss, A. M.; Mattrel, P.; Saxer, C.; Weilenmann, M. Nachführung der Emissionsgrundlagen Strassenverkehr, Messungen 01-02, Benzinpersonenwagen Euro-0 und Euro-3 sowie Dieselpersonenwagen Euro-2; EMPA report 202114; EMPA: Dübendorf, 2004.

(10) Hausberger, S.; Wiesmayr, J.; Zallinger, M. *Emission Stability*; Artemis 3122 report; Technical University Graz, 2004.

(11) André, J.-M. *Vehicles Sampling Methods for Emission Measurement*; Artemis 3131 report, Inrets report no LTE 0228; Lyon-Bron, 2002.

(12) Tsai, J. H.; Liu, Y. Y.; Yang, C. Y.; Chiang, H. L.; Chang, L. P. Volatile organic profiles and photochemical potentials from motorcycle engine exhaust. *J. Air Waste Manage. Assoc.* **2003**, *53* (5), 516–522.

(13) Chen, K. S.; Wang, W. C.; Chen, H. M.; Lin, C. F.; Hsu, H. C.; Kao, J. H.; Hu, M. T. Motorcycle emissions and fuel consumption in urban and rural driving conditions. *Sci. Total Environ.* **2003**, *312*, 113–122.

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