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Assessing the real-world performance of modern pollutant abatement systems on motorcycles

Robert Alvarez*, Martin Weilenmann, Jean-Yves Favez

Empa, Swiss Federal Laboratories for Materials Testing and Research, Laboratory for Internal Combustion Engines; Ueberlandstrasse 129, CH-8600 Duebendorf, Zuerich, Switzerland

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ABSTRACT

The present statutory pollutant emission limits Euro-3 for motorcycles imply the use of modern emission abatement systems such as three-way catalytic converters. Determining the quality of implementation of these new systems in different driving situations such as real-world driving is important, since motorcycles are commonly used for personal transportation in urban areas. For this reason, a test bench series was carried out with a sample of 10 motorcycles of state-of-the-art certification category Euro-3. Emission factors of regulated pollutants and CO_2 are presented on the basis of the statutory driving cycle, the latest version of the real-world Worldwide Motorcycle Test Cycle (WMTC) and the real-world Common Artemis Driving Cycle (CADC).

The results of the statutory driving cycle show that 7 out of 10 motorcycles fail to comply with the present emission limits. The results of both real-world driving cycles confirm notable emissions of HC in urban and NO_x in motorway driving conditions. CO emissions of motorcycles with small displacement increase significantly in the urban and extra-urban sections of the CADC, which has a more dynamic velocity profile than the equivalent WMTC. Although pollutant emissions of motorcycles show a marked improvement compared with earlier certification classes, they clearly exceed the emission levels of modern light gasoline passenger cars, especially for CO and HC.

1. Introduction

The latest tightening of statutory pollutant emission limits for motorcycles has led to the implementation of modern pollutant emission abatement systems in motorcycles set into traffic within the current certification category Euro-3. This has become necessary for the first time, since previous certification directives were still achievable with classic technologies such as two-stroke engines and carburetors, resulting in poor in-use emission performance (Tsai et al., 2000), especially compared with passenger cars (Vasic and Weilenmann, 2006). The relevance of this measure is evident when taking into account that motorcycles represent a widely used form of personal transportation in urban areas at present (Yannis et al., 2007) and in the future, especially in emerging countries (Singh, 2006), and as such have a substantial environmental impact (Borken et al., 2007; Ntziachristos et al., 2006). Investigating the quality of implementation of these pollutant emission abatement systems in real-world driving conditions is thus of great interest in relation to human health related air quality issues (Brugge et al., 2007), particularly in urban areas (Sitaras and Panayotis, 2008; Han and Naeher, 2006).

Consequently, an experimental investigation focusing on these issues was carried out on the basis of roller test bench measurements. A sample of 10 motorcycles of state-of-the-art certification category Euro-3 was selected, reflecting the Swiss vehicle fleet distribution. The emission performance of these motorcycles was determined in the statutory driving cycle for Europe and in two different real-world driving cycles: the Worldwide Motorcycle Test Cycle (WMTC) and the Common Artemis Driving Cycle (CADC). A specific cycle based on the WMTC has also been included to investigate the cold start behavior of motorcycles. Representative vehicle emission factors for the individual motorcycles were derived for the different driving patterns reproduced in the individual cycles in order to reflect their real-world emission behavior.

2. Methodology

2.1. Vehicle sample

The main characteristics of the motorcycle vehicle sample employed in the test series are summarized in Table 1. All motorcycles are equipped with four-stroke engines and three-way

* Corresponding author. Tel.: +41 44 823 48 69; fax: +41 44 823 40 44.
E-mail address: robert.alvarez@empa.ch (R. Alvarez).

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Table 1
Main characteristics of the considered motorcycle sample; displ.: displacement, reg.: registration, cert.: certification.

	Make [–]	Model [–]	Empty mass [kg]	Displ. [cm^3]	Power [kW]	Gearbox [–]	1st reg. [mmm jj]	Mileage [km]	Cert. class [–]	WMTC class [–]
B3-01	Suzuki	GSX R 1000	283	999	136.1	m6	Feb 07	2064	Euro-3	3–2
B3-02	Honda	SH 125	134	125	10.1	aut	May 05	17,615	Euro-3	2–1
B3-03	Kawasaki	ER-6 N	277	649	53	m6	Mar 06	15,133	Euro-3	3–2
B3-04	BMW	R 1200 GS	300	1170	74	m6	Apr 06	23,665	Euro-3	3–2
B3-05	Suzuki	GSX R 750	268	750	110	m6	Jul 06	7982	Euro-3	3–2
B3-06	Honda	CBR600RR	259	599	88	m6	Apr 07	10,947	Euro-3	3–2
B3-07	Yamaha	FZ1	289	998	110	m6	Apr 06	26,225	Euro-3	3–2
B3-08	Piaggio	X8	249	244	16	aut	Mar 06	9447	Euro-3	2–2
B3-09	Harley Davidson	FXDC	385	1584	56	m6	Mar 07	6448	Euro-3	3–2
B3-10	Piaggio	VESPA LX 125	190	124	7.65	aut	Jun 07	3306	Euro-3	1

catalytic converters that feature lambda sensors except motorcycle B3-10. Closed-loop exhaust after-treatment control systems are thus assumed to be implemented. The in-use motorcycles were selected from private owners based on sales and registration statistics available at the time of the investigation in order to reflect the Swiss fleet distribution with regard to displacement and power. The selected motorcycles were not serviced before the test runs. Note that both the displacement and the rated power of the individual motorcycles are quite high and their mileage is fairly low indicating the leisure-oriented usage of motorcycles in Switzerland.

2.2. Experimental program

Several driving cycles were employed in the test series in order to determine the emission behavior of the individual motorcycles. The statutory cold start driving cycle for Europe (European Council Directive 2002/51/EC) was included as well as two real-world driving cycles: the latest version 9 at that time of the Worldwide Motorcycle Test Cycle (WMTC) and the Common Artemis Driving Cycle (CADC). The cold start cycle WMTC is based on a large number of studies of real-world motorcycle driving and further adapted to test bench operation (ECE/TRANS/180/Add. 2/Appendix 1/Rev 1). The final version is under development and is intended for international use for statutory purposes in the future. The warm start cycle CADC was derived from car driving behavior studies within the ARTEMIS research program and represents European real-world driving behavior for cars (André, 2004). In order to investigate the cold start effect on pollutant emissions separately, an additional cold start cycle (CSC) was executed with some motorcycles that features three repetitions of the urban section of the WMTC. There, the measured values within each section are not distorted by changing driving pattern.

The cycle sections, representing urban, rural and motorway driving and the velocity profile of the WMTC applied for an individual motorcycle are set according to a vehicle-specific classification based on the displacement of the engine and the maximum speed of the motorcycle, see also Table 1. Furthermore, a gearshift calculation procedure based on the power-to-mass ratio of the individual motorcycle determines its individual gearshift points to be used for the velocity profile in the WMTC (ECE/TRANS/180/Add. 2/Appendix 1/Rev 1). The selection of the cycle sections and the calculation method for determining the individual gearshift points have also been applied to the real-world cycles CSC and CADC. Note that there are no prescribed vehicle-specific gearshift points for certification measurements in the case of the statutory cycle for Europe, only defined margins for gearshifts, see Council Directive 2002/51/EC. However, a compatible, speed-dependent gearshift strategy was used for the present test series for the sake of comparability of the measurement data obtained, in which up and down gearshifts were executed at 20 km h^{-1}, 35 km h^{-1}, 50 km h^{-1}, 70 km h^{-1}and 100 km h^{-1}, respectively.

2.3. Experimental setup

The roller test bench and its settings were applied according to the provisions of Council Directive 2002/51/EC. The inertia settings were chosen according to the given flywheel class, and the ambient conditions of the test cell were set to 23 °C temperature and 50% relative air humidity. The CSC cycle was also performed in low ambient temperature conditions of 7 °C and 50% relative air humidity. The same standard fuel with research octane number 95.9 and low sulfur content (<10 ppm) has been employed for all motorcycles to ensure real-world operating conditions.

2.4. Sampling, analyzing and data processing

The exhaust was sampled with a Constant Volume Sampling (CVS) system, see Fig. 1. Open dilution of the exhaust was applied owing to the rather low exhaust volume flow of small-displacement motorcycles, with the aim of avoiding possible engine assistance by low-pressure conditions at the tailpipe. The diluted exhaust was measured both online and offline. The offline measurement was performed according to the statutory procedure of storing a sample of diluted exhaust in a tedlar bag and analyzing its content offline after completion of the test run. Regulated pollutants were detected using standard vehicle exhaust analyzers as specified by Council Directive 2002/51/EC.

Undiluted online concentration profiles were obtained by scaling the measured diluted signal traces with a dilution factor calculated from the measured diluted CO_2 concentration $c(CO_2)_{tot}(t)$. In fact, a total and CO_2 mass balance at the dilution point depicted in Fig. 1 gives the following relations:

$$\dot{m}_{tot}(t) = \dot{m}_{air}(t) + \dot{m}_{exh}(t) \tag{1}$$

$$\dot{m}_{tot}(t)\cdot c(CO_2)_{tot}(t) = \dot{m}_{air}(t)\cdot c(CO_2)_{air} + \dot{m}_{exh}(t)\cdot c(CO_2)_{exh}(t) \tag{2}$$

Here, the ambient air concentration of CO_2 $c(CO_2)_{air}$ is assumed to be constant and is detected within the statutory offline measurement procedure for each cycle section. Finally, when assuming stoichiometric combustion, the concentration of CO_2 in the exhaust $c(CO_2)_{exh}$ can be set to a constant value depending on the fuel composition and the dilution factor attained can be deduced as follows:

$$\frac{\dot{m}_{tot}(t)}{\dot{m}_{air}(t)} = \frac{c(CO_2)_{air} - c(CO_2)_{exh}}{c(CO_2)_{tot}(t) - c(CO_2)_{exh}} \tag{3}$$

Additionally, the signal traces were corrected with respect to time and mixing delay due to the length of the sample lines and the measuring delay time of the analyzers by applying a specifically developed methodology (Ajtay and Weilenmann, 2004).

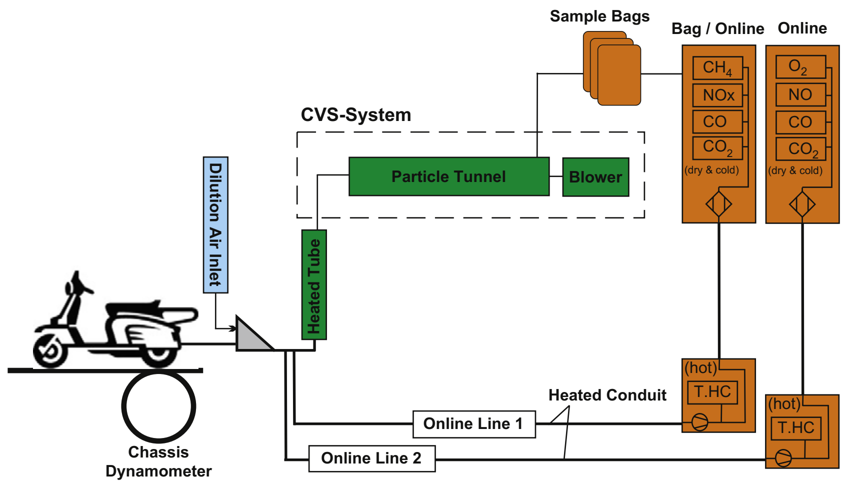

Fig. 1. Schematic diagram of the test setup.

The real-world urban cold start extra emissions (CSEEs) presented subsequently are determined by applying a simple model approach: assuming that the motorcycles run the last cycle section of the CSC with a hot engine, the difference between the sum of absolute pollutant emissions in the first two sections and twice the emissions in the third section gives the CSEE of a pollutant (Favez et al., in press).

3. Results

3.1. Statutory emission performance

Fig. 2 shows the emission performance of the regulated pollutants and CO_2 of the individual motorcycles in the statutory cycle together with the respective motorcycle class averages. The motorcycles are arranged with decreasing engine displacement within the single statutory classes and the respective limit values are indicated by the frames. Only 3 out of 10 motorcycles fulfill the statutory emission requirements for all regulated pollutants. Small-displacement motorcycles show increased emissions of CO that are attributable not only to the initial catalytic converter light-off, but also to incomplete combustion in driving situations with sudden steep increase in engine speed that is no longer compensated by the catalytic converter, see Fig. 3. Note that motorcycle B3-10 is not equipped with a lambda sensor upstream of the catalytic converter and uses an electric carburetor for the fuel-mixture generation. A rich fuel–air mixture is thus assumed often to be provided to the combustion process of this motorcycle in such driving situations,

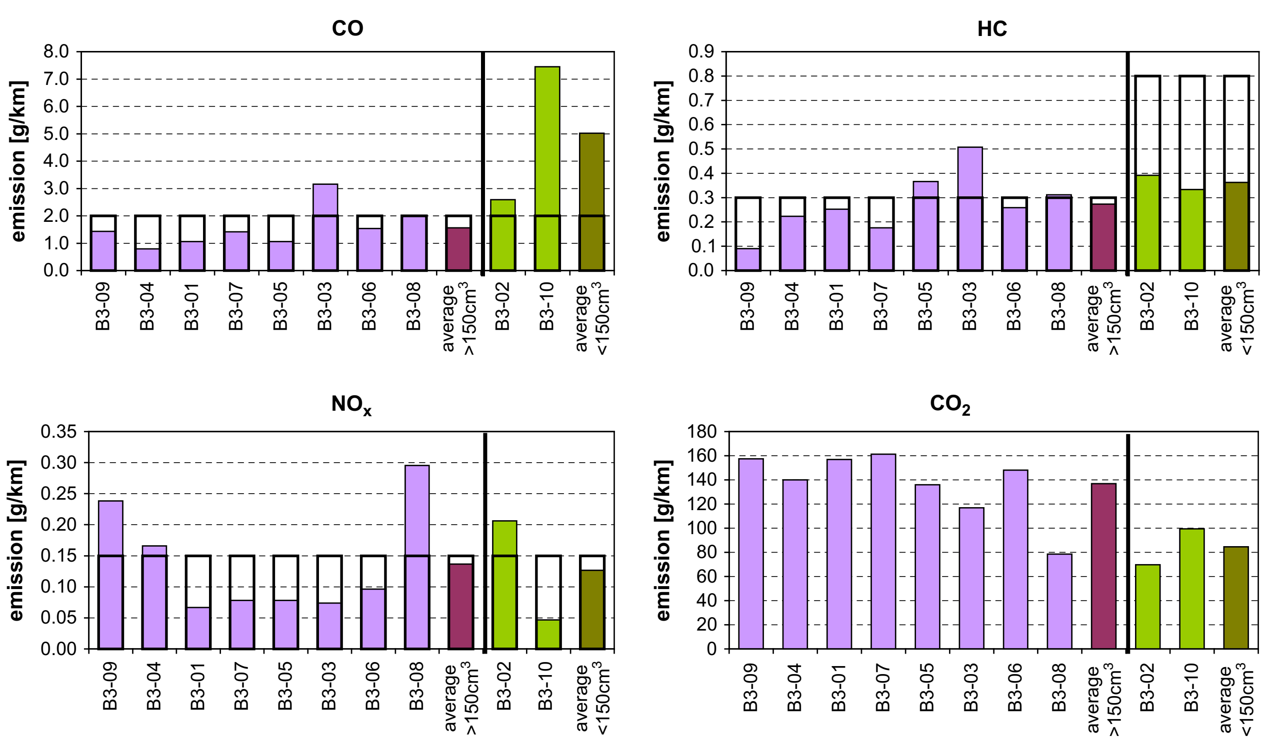

Fig. 2. Emissions of regulated pollutants and CO_2 of the individual motorcycles in the statutory cycle together with the vehicle class averages. The motorcycles are arranged with decreasing engine displacement within the single statutory classes and the respective limit values are indicated by the frames.

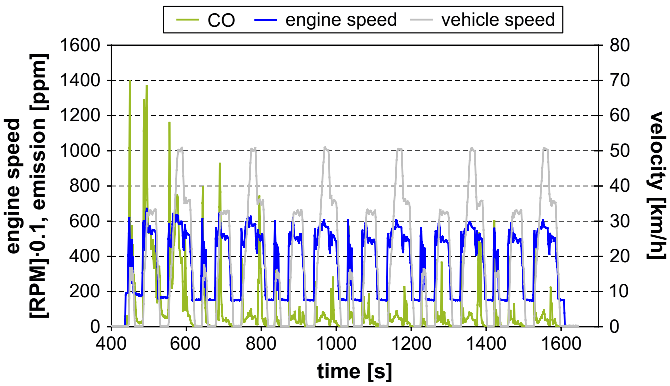

Fig. 3. Course of CO emissions and engine speed over vehicle speed in the statutory cycle for motorcycle B3-02.

which accounts for the very high emissions of CO observed combined with the low emission level of NO_x.

The motorcycles with large displacement generally remain within their respective CO emission limits, but show some disadvantages with regard to HC emissions. In this case it can be stated that peaks in HC emissions occur in most overrun fuel cut-off situations, see Fig. 4. It appears that the fuel management system and the capacity of the catalytic converter have not been designed adequately in these cases. Besides, the driving phase before catalytic converter light-off also contributes to higher HC emissions. By contrast, NO_x emissions arise at higher loads. This finding can be attributed to the increased combustion temperatures, which cause pronounced engine-out NO_x emissions that, combined with the high exhaust mass flow, limit the residence time of the exhaust in the catalytic converter.

3.2. Real-world emission performance

Fig. 5 shows the emission performance of regulated pollutants and CO_2 of the individual motorcycles in the real-world cold start cycle WMTC. The motorcycles are grouped according to the respective WMTC vehicle classification given in Table 1 and arranged with decreasing engine displacement within the single WMTC classes. Pronounced pollutant emission levels of CO and HC occur in the first section of the cycle, which features an urban-like driving profile with cold start. CO and HC emissions generally tend to increase in the single cycle sections with decreasing engine displacement. Additionally, CO emissions of small-displacement motorcycles are notable in the section representing rural driving conditions for the same reasons as stated above. NO_x emissions increase considerably in the motorway section of the WMTC, again due to peak combustion temperatures at high engine load.

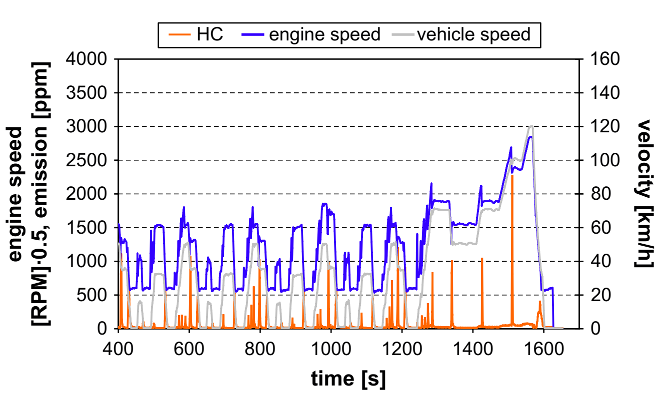

Fig. 4. Course of HC emissions and engine speed over vehicle speed in the statutory cycle for motorcycle B3-03.

The observations made for the real-world emission performance of the motorcycles based on the cycle WMTC are confirmed in general by the results obtained in the warm start cycle CADC, see Fig. S1. The only difference there is the already moderate CO and HC emissions in the first section, as the cycle is started with a warm engine. But CO emissions of motorcycles with small displacement increase substantially in the urban and rural sections of the CADC, which is attributable to the more dynamic velocity profile compared with the respective emissions of the WMTC. The same explanation accounts for CO emissions of large-displacement motorcycles in the motorway section of the CADC, where higher speed levels are also achieved compared to the WMTC. Interestingly, this circumstance barely affects real-world NO_x emissions per unit distance of Euro-3 motorcycles.

3.3. Cold start emission performance

Fig. 6 shows the CSEE for regulated pollutants and CO_2 of motorcycles that have been tested at 23 °C and 7 °C ambient temperature with the CSC, which represents urban real-world driving conditions. CSEE of CO and HC clearly rise for low ambient temperatures, especially for motorcycle B3-03. An air-fuel enrichment strategy is obviously adopted for this motorcycle in these ambient conditions. CSEEs of NO_x are moderate and generally decrease for low ambient temperatures with the exception of motorcycle B3-10. This finding, together with its moderate CO and HC CSEE, indicates that this motorcycle apparently operates in slight lean-burn mode in this case. Its electric carburetor presumably underestimates the intake air flow at low ambient temperatures. CSEEs of CO_2 are also pronounced and rise in most cases at lower ambient temperatures.

3.4. Comparison of emission results

The measurement results with the CADC make it possible to draw a comparison in terms of real-world emission performance with emissions of Euro-1 motorcycles (B1) (Vasic and Weilenmann, 2006) and gasoline passenger cars of the present certification category Euro-4 (PC G4) (Alvarez et al., 2007) obtained in other test series, see Fig. 7. There, the emission performance of both motorcycle samples obtained with different versions of the cycle WMTC is also compared. The motorcycle samples have been grouped according to their statutory vehicle classification. Note that motorcycles B1-01 and B3-08 have been excluded due to incompatibilities in averaging the measurement data of the cycles CADC and WMTC.

Large improvements in pollutant emissions of CO and HC can be observed in both cycles between the Euro-1 and the Euro-3 motorcycle samples, whereas NO_x emission improves only moderately and the emission of CO_2 even increases significantly. This increase is attributable to the rise in average displacement and especially average rated power of the present motorcycle sample. The quality of implementation of modern motorcycle after-treatment systems can also be observed in their cold start behavior: pollutant emissions of Euro-3 motorcycles improve in the hot start urban section of the CADC compared to the cold start urban section of the WMTC despite the more dynamic velocity profile and the longer stop time of the urban section of the CADC. This finding is not observed for the Euro-1 motorcycle sample, indicating poor implementation of their exhaust after-treatment systems with regard to cold start and transient behavior, in contrast to the Euro-3 motorcycle sample.

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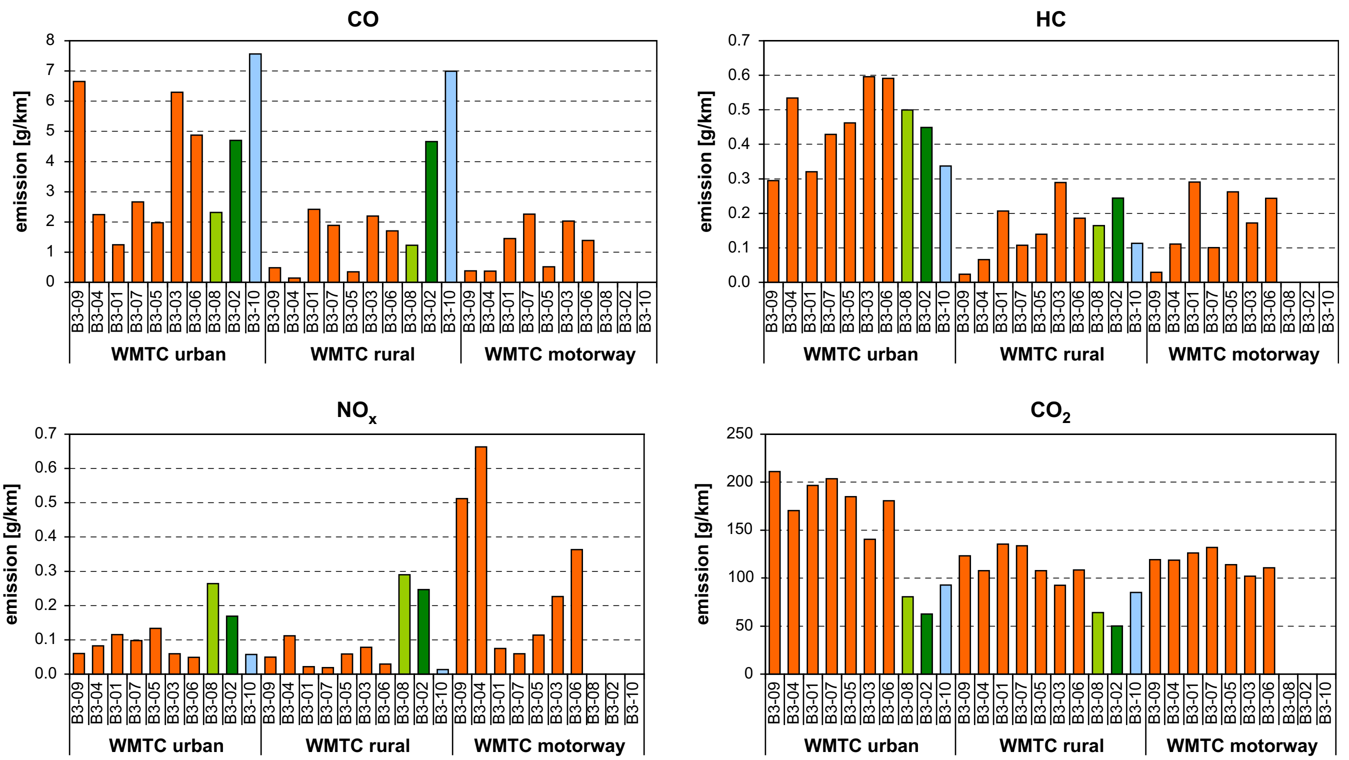

Fig. 5. Emissions of regulated pollutants and CO_2 of the individual motorcycles in the driving cycle WMTC. Motorcycles are grouped according to the WMTC vehicle classification and arranged with decreasing engine displacement within the single WMTC classes.

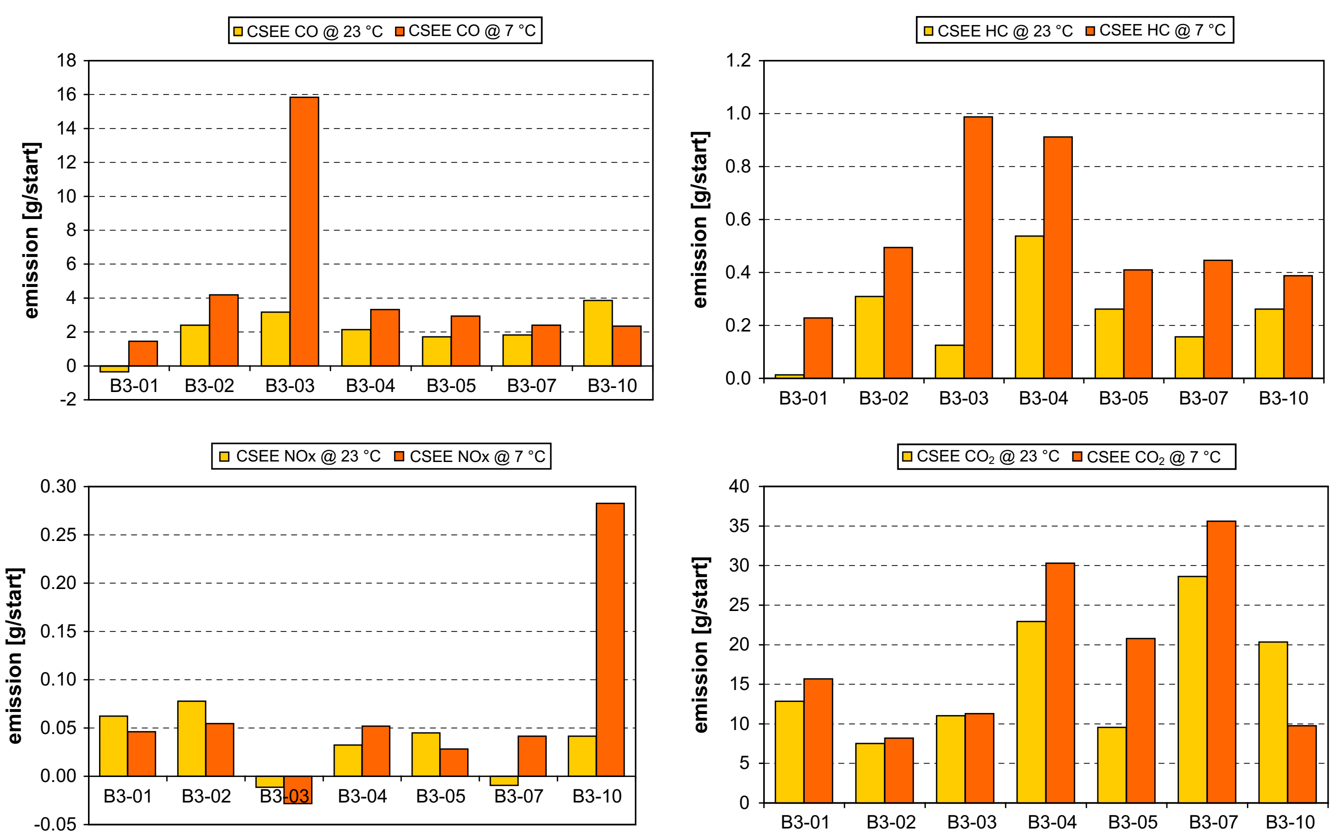

Fig. 6. Cold start extra emissions (CSEEs) of regulated pollutants and CO_2 of individual motorcycles at normal and low ambient temperatures.

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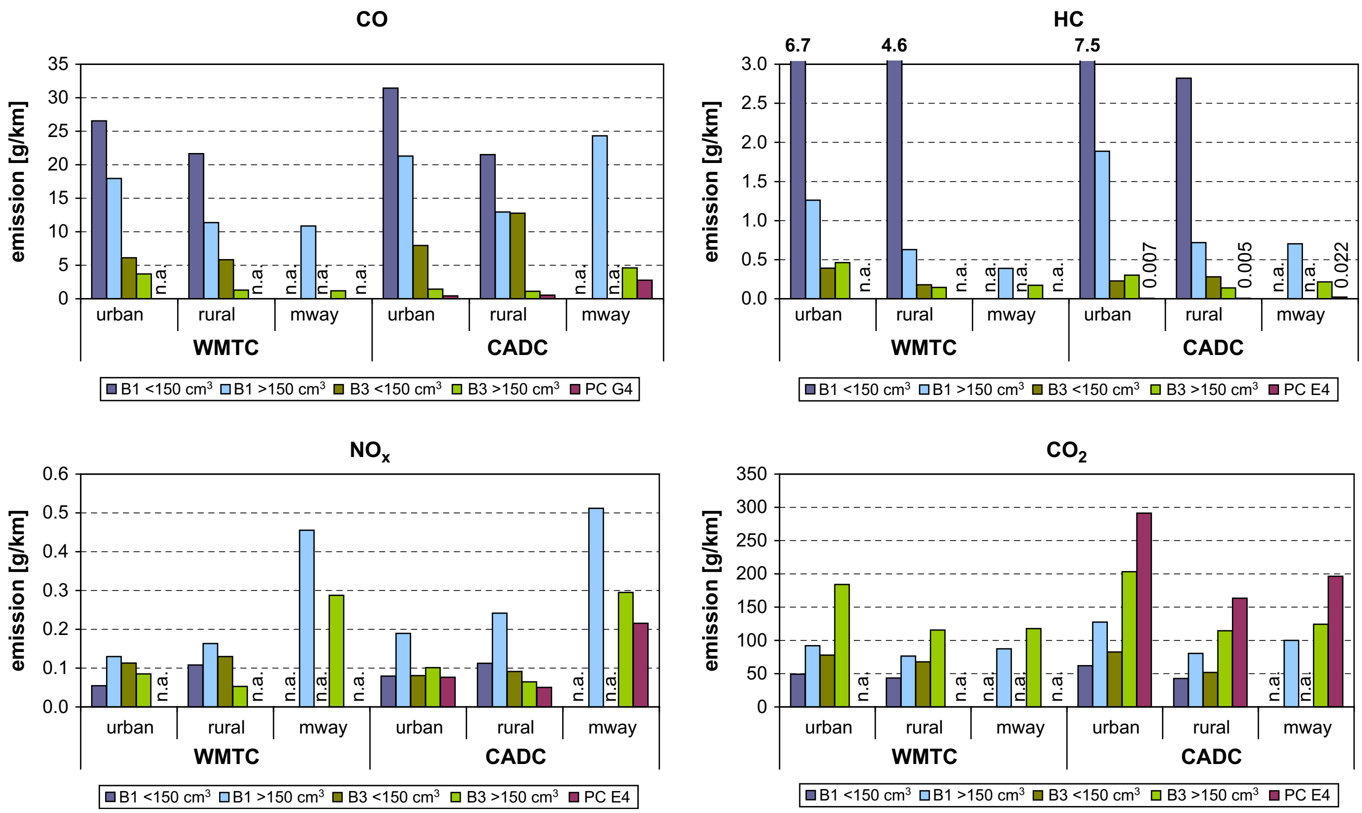

Fig. 7. Comparison of real-world sample emissions of regulated pollutants and CO_2 of previous and present motorcycle and passenger car certification categories.

Large-displacement motorcycles generally show better pollutant emission performance, especially in real-world urban and rural driving conditions. But emission levels of CO and HC for motorcycles of the present certification category in the cycle CADC are still appreciably higher than the respective emission levels of gasoline cars, whereas the difference in NO_x emissions is less pronounced. Only NO_x emissions of small-displacement motorcycles in urban driving conditions reach comparable levels to passenger car emissions. It is evident that the overall calibration of engine management and the design of exhaust after-treatment systems of passenger cars are still far more elaborate and thus more effective than those of modern motorcycles with regard to minimizing pollutant emissions.

4. Summary and conclusions

The present experimental investigation offers varied insight into the environmental impact of modern motorcycles of certification category Euro-3. Great improvements can be seen for the emission performance of modern Euro-3 motorcycles resumed in Table S2, especially for CO and HC emissions. But their compliance with statutory type approval stipulations is unsatisfactory, with only 3 out of 10 motorcycles meeting the specified Euro-3 emissions limits, despite the low average mileage of 12,200 km of the sample tested. In this case, excessive emissions of CO are a crucial feature of small-displacement motorcycles, mainly resulting from incomplete combustion in driving situations with a sudden steep increase in engine speed. By contrast, large-displacement motorcycles show disadvantages in HC and NO_x emissions due to the emissions of these substances in overrun fuel cut-off and high engine load situations, respectively. However, it appears that the design potential of the exhaust after-treatment system used has not yet been fully exploited. In this regard, statutory measures to durably ensure emission limit compliant operation of these vehicles like in-use compliance or on board diagnostics (OBD) might also be imaginable.

As regards real-world emission performance, it can be stated that the emission of both CO and HC in warm urban and rural driving patterns is pronounced, especially for small-displacement motorcycles. NO_x emissions in real-world motorway driving conditions are also significant. Cold start emissions of CO, HC and CO_2 in urban driving conditions are considerable and even rise for lower ambient conditions. However, the results of urban cycle emissions of both real-world cycles show that the after-treatment systems of Euro-3 motorcycles do reduce pollutant emissions in hot operation mode.

It can be deduced from the results obtained that the pollutant emission levels of modern motorcycles have clearly improved compared with older certification categories, whereas large-displacement motorcycles generally show a better pollutant emission performance per unit distance, except for CO_2. Nevertheless, comparison with the emission performance of gasoline passenger cars of the present certification category indicates that there is still considerable scope for further reducing pollutant emissions of motorcycles. In this respect, optimizing the combustion process and the exhaust after-treatment systems are assumed to be the key issues. Emissions of CO and HC of modern motorcycles recorded in these tests should in fact be further reduced, especially in urban real-world driving conditions.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.atmosenv.2008.11.046.

References

Ajtay, D., Weilenmann, M., 2004. Compensation of the exhaust gas transport dynamics for accurate instantaneous emission measurements. Environmental Science and Technology 38, 5141–5148.

Alvarez, R., Favez, J.-Y., Weilenmann, M., 2007. Gasoline Passenger Cars Euro 4 – Standard Program. EMPA Research Report No. 203270g. EMPA, Duebendorf, Switzerland. 55.

André, M., 2004. The ARTEMIS European driving cycles for measuring car pollutant emissions. Science of the Total Environment 334–335, 73–84.

ARTEMIS: Assessment and Reliability of Transport Emission Models and Inventory Systems. Available from: http://www.trl.co.uk/ARTEMIS.

Borken, J., Steller, H., Meretei, T., Vanhove, F., 2007. Global and country inventory of road passenger and freight transportation: fuel consumption and emissions of air pollutants in year 2000. Transportation Research Record 2011, 127–136.

Brugge, D., Durant, J.L., Rioux, C., 2007. Near-highway pollutants in motor vehicle exhaust: A review of epidemiologic evidence of cardiac and pulmonary health risks. Environmental Health: A Global Access Science Source 6 (Art. No. 23).

Commission Directive 2002/51/EC, 2002. On the Reduction of the Level of Pollutant Emissions from Two- and Three-wheel Motor Vehicles and Amending Directive 97/24/EC Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri = CELEX:32002L0051:EN:HTML.

ECE/TRANS/180/Add. 2/Appendix 1/Rev 1, 2007. Measurement procedure for two-wheeled motorcycles equipped with a positive or compression ignition engine with regard to the emission of gaseous pollutants, CO_2 emissions and fuel consumption.

Favez J.-Y., Weilenmann M., Stilli J. Cold start extra emissions as a function of engine stop time: evolution over the last 10 years. Atmospheric Environment, in press, http://dx.doi.org/10.1016/j.atmosenv.2008.03.037.

Han, X., Naeher, L.P., 2006. A review of traffic-related air pollution exposure assessment studies in the developing world. Environmental International 32, 106–120.

Ntziachristos, L., Mamakos, A., Samaras, Z., Xanthopoulos, A., Iakovou, E., 2006. Emission control options for power two wheelers in Europe. Atmospheric Environment 40, 4547–4561.

Singh, S.K., 2006. Future mobility in India: implications for energy demand and CO_2 emission. Transport Policy 13, 398–412.

Sitaras, I.E., Panayotis, A.S., 2008. The role of primary and secondary air pollutants in atmospheric pollution: Athens urban area as a case study. Environmental Chemistry Letters 6, 59–69.

Tsai, J.-H., Hsu, Y.-C., Weng, H.-C., Lin, W.-Y., Jeng, F.-T., 2000. Air pollutant emission factors from new and in-use motorcycles. Atmospheric Environment 34, 4747–4754.

Vasic, A.-M., Weilenmann, M., 2006. Comparison of real-world emissions from two-wheelers and passenger cars. Environmental Science and Technology 40, 149–154.

Yannis, G., Golias, J., Spyropoulou, I., Papadimitriou, E., 2007. Mobility patterns of motorcycle and moped riders in Greece. Transportation Research Record 2031, 69–75.