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ORIGINAL PAPER

Exhaust emissions of new high-performance motorcycles in hot and cold conditions

P. Iodice · A. Senatore

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Abstract An experimental–analytical investigation on the emissive behavior of two high-performance motorcycles belonging to the most recent European legislative category was being performed by the Department of Industrial Engineering of the University of Naples Federico II. The study was focused on these vehicles because the pertinent information was not very exhaustive in the scientific literature, with particular reference to the assessment of cold-start extra emissions of this particular two-wheeler vehicular class (Euro-3 legislative category and displacement >750 cm^3), that is playing a rising central role in private mobility, also in urban context. From this motivation, in this study a calculation procedure was designed and optimized to model the cold-start transient behavior of motorcycles; through this methodology, it is possible to evaluate the cold transient duration, the emitted quantities during the cold phase and the relevant time-dependence function. The whole procedure was applied on the carbon monoxide and unburned hydrocarbon exhaust cold extra emissions of the selected motorcycles, which were measured on the chassis dynamometer. Experimental tests were performed in cold and hot operating conditions, during both driving cycle regulated by law and real-world driving cycles.

Keywords Cold-start emissions · Driving characteristics · Emission model · Motorcycle emission factors

P. Iodice (✉) · A. Senatore
Department of Industrial Engineering, University of Naples Federico II, Via Claudio 21, 80125 Naples, Italy
e-mail: paolo.iodice@unina.it

Introduction

This study derives from the need to evaluate the impact on the urban air quality of two-wheeler vehicular class, mostly used as popular means of daily moving in the major cities of southern Europe (Vasic and Weilemann 2006), where mopeds and motorcycles represent a great proportion of vehicles. In the last years, powered two-wheelers accounted for over 32 million vehicles in EU-27, representing about 8 % of passenger mobility fleet (European Commission 2010); in Italy, where traffic congestion and parking difficulty influence the choice of transportation mode, the share of the two-wheelers to the whole passenger vehicle fleet is about 25 % (Iodice and Senatore 2013a). With over nine million two-wheelers, Italian fleet contributed for 28 % to EU-27 figures (Prati et al. 2011). Always with reference to the Italian situation, powered two-wheeler fleet included about 33.3 % of mopeds (vehicles with an engine capacity lower than 50 cm^3), while motorcycles (engine displacement higher than 50 cm^3) accounted for about 66.7 % (ACI 2012; ANCMA 2011).

Because of the main use in urban environments, experimental determination of emissions from these vehicles is then very important for estimating their contribution to total emissions attributable to road transport and then for studying the most realistic ways of making progresses to ground-level air quality (European Commission 2013).

Comparison and appraisal of emissions produced by two-wheelers and passenger cars disclose that the absolute emission level of passenger cars has been reduced noticeably in the last two decades, due to the introduction of legislation together with tightening the applicable limits on regulated emissions for these vehicles, while, on the other hand, the after-treatment technologies used for mopeds and motorcycles have not been as efficient as those for cars (Prati and Costagliola 2009). Existing strategies to control emissions already in use on passenger cars, in fact, are often not used on two-wheelers because they are too expensive in relation to vehicle cost and their real effectiveness (Ntziachristos et al. 2006). As a result, motorcycles and mopeds make a significant impact to carbon monoxide (CO) and unburned hydrocarbon (HC); in a study pertinent to the city of Genoa between 1992 and 2010 (Zamboni et al. 2009), motorcycles and moped contributions to CO and HC total emissions were estimated to be around 38 and 27 %, respectively, in 2010. Besides, two-wheeler vehicles are a main urban source of unregulated pollutants hazardous to environmental and human health. The reduced combustion quality occurring in two-stroke motorcycle engines or in four-strokes not regulated in terms of air/fuel ratio is regularly responsible for high HC and particle emission levels (Yang et al. 2005a, b).

Nowadays, due to catalyst improvements, the most significant part of the total emission during a trip takes place during the cold phase when engine and catalyst are cold, if compared with those exhausted in hot conditions; in fact, all the experimental investigations performed in the last years on newly sold motorcycle equipped with a catalytic converter and electronic mixture control clearly indicate that CO and HC cold-start emissions represent an important proportion of total emissions, with a consequent consequence on air quality (Iodice and Senatore 2013b). Moreover, incomplete combustion occurring during cold-start causes high toxicity due to the presence of toxic VOCs (Chang and Chen 2008). Broadly investigated three-way catalyst technology for four-stroke motorbikes failed to reduce aromatic HC emissions at cold-start which is 2–3 orders of scale higher than those of recent passenger cars (Saxer et al. 2006).

Consequently, calculation programmes to estimate emissions from road transports should take into consideration this effect. The current emission models available in Europe for calculating emissions from road traffic (Gkatzoflias et al. 2012; Elst et al. 2006), however, are mainly based on fixed legislative driving standards, not on the local driving conditions underestimating cycle dynamics, and do not take into consideration in detail the warm-up behavior of motorcycles. The emission factors measured in such conditions might not be sufficiently representative of real-world driving cycles, because it is assumed that most cold-starts of powered two-wheelers occur in an urban environment and thus are driven under urban driving conditions after the start.

Taking into account these considerations, a reliable evaluation of the emissive behavior of motorcycles in hot and cold conditions is of the greatest importance. Consequently, an experimental investigation focusing on these issues was carried out by the Department of Industrial Engineering of the University of Naples Federico on the basis of roller test bench measurements. Emissions of regulated pollutants (CO, HC and NO_X) were evaluated in the exhaust of two high-performance motorcycles of 1,000 cm^3 swept volume, belonging to the Euro-3 legislative category. The tested vehicles were selected for similar engine and after-treatment system characteristics, thus allowing a comparison between them, and are equipped with sophisticated devices for improving combustion efficiency, and the abatement of exhaust pollutants. These vehicles are representative of the newly sold high-performance motorcycles that in the last years are very used also in urban environment and then play a growing central role in private mobility.

The main goals of this research activity are a deeper comprehension of the engine and after-treatment system behavior within the cold-start transient through the development of a methodology focused on the calculation of cold emissions as a time-dependence function; processing measured data, by means of this calculation procedure, allows to quantify the cold transient duration, the emitted quantities during the cold phase and the cold-start emission factors. This methodology also analyzes the influence of different speed patterns on motorcycles emission factors during the cold-start. The emission performance of these motorcycles was determined in the statutory driving cycle for Europe (UDC + EUDC) and in two different real-world driving cycles: the World-wide Motorcycle Test Cycle (WMTC) and the Urban Cold driving cycle, while other experimental tests were performed at constant speed. The results obtained in this study are also useful and precious for assisting planners in evaluating and selecting future projects of urban expansion.

The experimental activities discussed in this study were performed in the emission laboratories E4 of Istituto Motori of the National Research Council (CNR) between 2012 and 2013.

Materials and methods

Vehicles

The main characteristics of the motorcycle vehicle sample employed in the test series are summarized in Table 1. These motorcycles are equipped with four-stroke engines, and for pollutants abatement, three-way catalytic converters. For all motorcycles, a precise tuning of air/fuel ratio is reached throughout an electronic fuel injection, and closed-loop exhaust after-treatment control systems are thus assumed to be implemented. These in-use motorcycles were selected from private owners based on sales and

Table 1 Main characteristics of the considered motorcycle sample

	Make (–)	Model (–)	Empty mass (kg)	Displ. (cm^3)	Power (kW)	Compression ratio (–)	European cert. class (–)
A	Agusta	Brutale	185	982	104 @ 10,900 rpm	12.2:1	Euro-3
B	Aprilia	RSV	189	999	132 @ 12,500 rpm	13:1	Euro-3

registration statistics available at the time of the investigation in order to reflect the Italian fleet distribution of the high-performance motorcycles.

The fuel was commercial unleaded gasoline with a research octane number (RON) of 95, with oxygenated additive (8.1 v/v%), while the carbon, oxygen, benzene and aromatic contents were 85.56 wt%, 1.8 wt%, 0.67 vol% and 33.3 vol%, respectively.

Experimental apparatus

The two motorcycles were tested on a two-wheeler chassis dynamometer (AVL Zollner 20″—single roller) which simulated vehicle inertia and road load resistance (Fig. 1). This bench is designed to simulate the road load (including vehicle inertia) and to measure the exhaust emissions during dynamic speed cycles. Using this system, it is also possible to carry out tests in constant speed mode, constant tractive force mode and constant acceleration mode. The chassis dynamometer was set by using the running resistance table according to the procedures laid down in Directive 2003/77/EC. Before each test in cold-start conditions, the motorcycles were kept at a relatively constant temperature between 20 and 25 °C for at least 8 h.

A driver's aid displayed speed trace of the driving cycle to follow with a tolerance of ±1 km/h. A variable speed blower, positioned in front of the two-wheeler vehicle, acted as the cooling wind on the road. During the tests, the exhaust gases were diluted with purified ambient air by a Constant Volume Sampling with Critical Flow Venturi (AVL CFV-CVS) unit. The diluted exhaust gas was passed throughout a dilution tunnel for reaching stable flow conditions. A part of diluted exhaust was sampled downstream the dilution tunnel for continuously measuring the concentration of CO, HC, nitrogen oxides (NOx) and carbon dioxide (CO_2) by an exhaust gas analysis system (AVL AMA 4000). The signals were corrected for the time delay respect to the speed; no other compensation (i.e., mixing dynamics) or signal treatment was applied (Ajtay et al. 2005). Simultaneously, the average values of regulated pollutants were measured in a sample bag filled during the test.

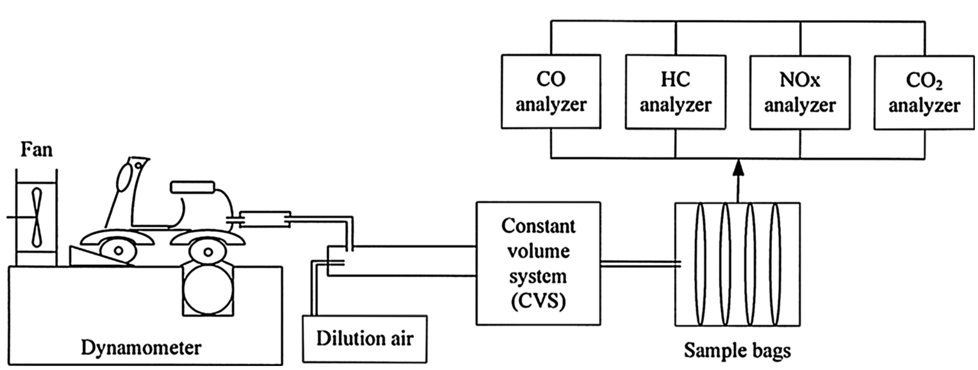
Driving cycles

The motorcycles were tested over the following transient and steady-state driving cycles (DCs):

- European type-approval driving cycle (ECE + EUDC)
- World-wide Motorcycle Emissions Test Cycle (WMTC)
- Artemis Urban Cold
- Constant speed between 20 and 120 km/h (stepwise 10 km/h)

Transient DCs were carried out with cold-start (engine off for at least 8 h before DC starting). ECE + EUDC is composed by an urban (ECE) and an extra urban part (EUDC). Urban part is divided in two phases: cold (UDC_cold including two base modules) and hot (UDC_hot including four base modules). WMTC regulated in 2006/72/EC directive states, for motorcycle with maximum speed higher than 140 km/h, the execution of three phases (cold WMTC_1, WMTC_2 and WMTC_3). Artemis Urban Cold was proposed within EU Artemis framework in order to study cold-start influence on the exhaust emissions (André 2004). It includes 15 repetitions of a base module. During this experimental activity, measurements relative to Artemis Urban Cold were performed over three

Fig. 1 Schematic diagram of the test setup



parts, each including five base modules. Main kinematic characteristics are reported in Table 2.

Results and discussion

Statutory emission performance

CO, NOx and HC emissions measured for the two motorcycles throughout ECE + EUDC and WMTC driving cycles are reported in Fig. 2. The mean emissions obtained of the regulated pollutant are expressed as mass emitted per kilometer travelled and are presented for all the phases and for the whole DCs. It is clear in this figure that the two motorcycles fulfill the European statutory emission requirements for all regulated pollutants. The motorcycle B, however, shows higher emissions of CO and HC than motorcycle A, and this difference could be imputable not only to the catalytic converter efficiency, but also to partial combustion in driving situations characterized by rapid steep increase in engine speed that is no longer compensated by the catalytic converter of the vehicle B. A rich air–fuel mix is thus supposed often to be provided to the combustion process of the motorcycle B in such driving conditions, which causes the highest emissions of CO observed (Zamboni et al. 2011), while it is well known that a three-way catalytic converter requires conditions of lambda very close to one permitting the oxidation of CO and HC and at the same time a reduction of NO_X to elemental nitrogen. It appears, therefore, that the fuel management system and the capacity of the catalytic converter have not been designed suitably for the motorcycle B, as well as, on the contrary, can be deduced for the vehicle A. A lessening enrichment, for the motorcycle A, is probably the effect of internal engine improvement and more correct mixture control of fuel injection systems used on these vehicles, consenting a better control of fuel feeding and rising catalyst efficiency (Alvarez et al. 2009).

Nevertheless, it is clear that for the newer motorcycles, if the mixture enrichment is reduced to the smallest values, a greater possibility exists for the mixture to be lean, ultimately producing an overall increase of the NOx emission; anyhow, this effect did not occur clearly for these two vehicles, which are characterized by NOx emission factors below the standard limits. About NOx, it is evident that emissions of the motorcycle B increase considerably in the motorway section (WMTC_3) of the WMTC DC due to the more dynamic speed-time profile of this phase (see Table 2); in this operating conditions, in fact, the peak combustion temperatures at high engine load and the high exhaust mass flow that limits the residence time of the exhaust in the catalytic converter cause high levels of engine-out NOx emissions. However, it is also probable that NOx emissions of vehicle B, during the WMTC_3 phase, increased as effect of higher cylinder temperature, driving an increase in the thermal NOx formation rate; higher temperatures would result from greater compression ratios of motorcycle B, increased charge air temperature and faster burn rates (Kumar et al. 2011).

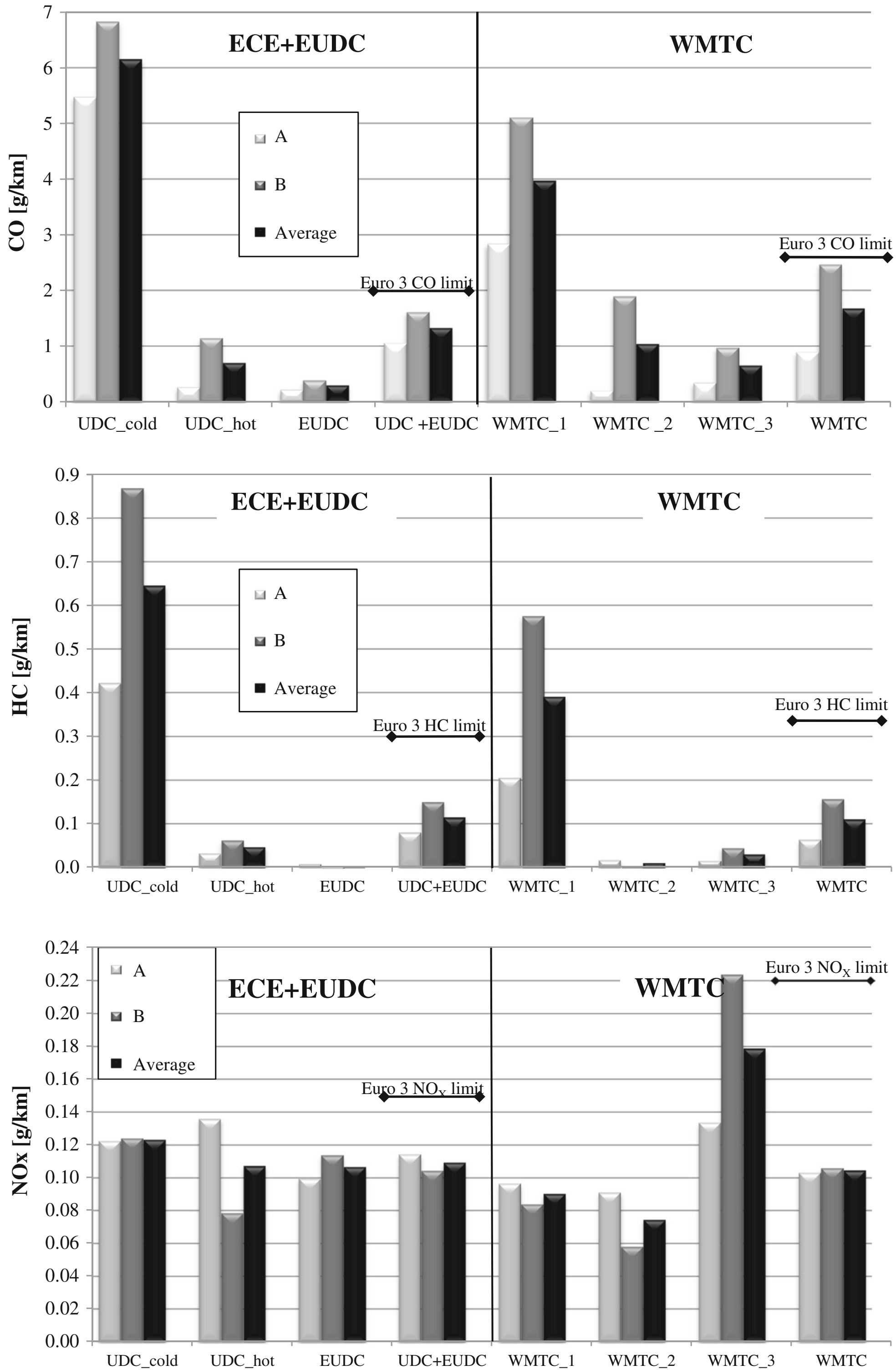
About the differences of the CO and HC hot emissions obtained between the different hot phases of the ECE + EUDC and WMTC driving cycles, the kinematic characteristics of the different driving patterns should be examined. For constant values of average speed, higher levels of acceleration generally correspond to an increase in energy request for the execution of the considered driving pattern, with consequent enrichment of the fuel–air mixture (outside the optimal range of catalyst efficiency); on the other hand, for lower engine loads, corresponding to lower values of average speed, the pertinent leaning of the fuel–air mix could result in less regular operating condition of the engine for these high-performance motorcycles (Bozza et al. 2008, 2011). These two effects compete, and so the results show that lowest CO hot emissions were recorded over the EUDC phase of the ECE + EUDC DC, while lowest hot emissions of HC were acquired during the

Table 2 Kinematic properties of driving cycles

	Duration (s)	Length (km)	Maximum speed (km/h)	Mean speed (km/h)	Idle time (%)	Accel. time (%)
European type-approval driving cycle						
UDC_cold	390	2	50	18.4	32.3	21.5
UDC_hot	780	4	50	18.4	32.3	21.5
EUDC	400	6.9	120	62.6	10.2	25.7
World-wide Motorcycle Emissions Test Cycle						
WMTC_1	600	4.1	60	24.3	18.5	28.7
WMTC_2	600	9.1	95	54.6	7.8	35.7
WMTC_3	600	15.8	125	94.7	2.3	29.7
Artemis Urban cold	945	5	44	19	16.4	35

Constant speed test (10–120, stepwise 10 km/h)

Fig. 2 CO, HC and NO_X emission factors in ECE + EUDC and WMTC driving cycles of the individual motorcycles and average values



EUDC and WMTC_2 phases of the ECE + EUDC and WMTC DCs.

These results also indicate that for the two tested vehicles, a cold-start clearly results in raised emissions of CO and HC compared with those obtained with a warm engine. The cause may be ascribed to various factors. First, the engine during the cold transient needs a rich fuel–air mix (outside the optimal catalyst range) to compensate for the fuel that does not contribute to the combustion because it condenses at the cold internal walls of the engine or for the fuel that has not still evaporated. Second, during the early moments of the cold transient duration, the catalyst efficiency of the converter is too low due to rich values of air–fuel ratio and to exhaust gas temperature levels at the catalyst inlet lower than the light-off conditions. In these conditions, the fuel that is not combusted, or only partly, seeps through the catalytic converter untreated as HC and CO.

Cold-start emission performance: modeling and results

The absolute cold-start extra emission (in gram) is described as the additional emission level obtained under cold conditions compared to the emission value measured on the same driving distance or time period under hot conditions (Joumard et al. 2007). In order to define cold-start additional emissions and the cold-start transient durations, measurements performed on repetitive real-world driving cycles have to be performed, as defined by Weilenmann (2005). However, it is not simple to apply this methodology to motorcycles, as no repetitive driving cycles have been developed for this vehicle category, and only little research on this aspect has been conducted in the last years.

In this section, a calculation procedure is shown to model the cold-start transient of motorcycles. Cold-start extra emissions during the transient duration of the engine can be characterized by a cold instantaneous emission factor $f_{cold}(t)$ (Iodice et al. 2011), expressed as mass per

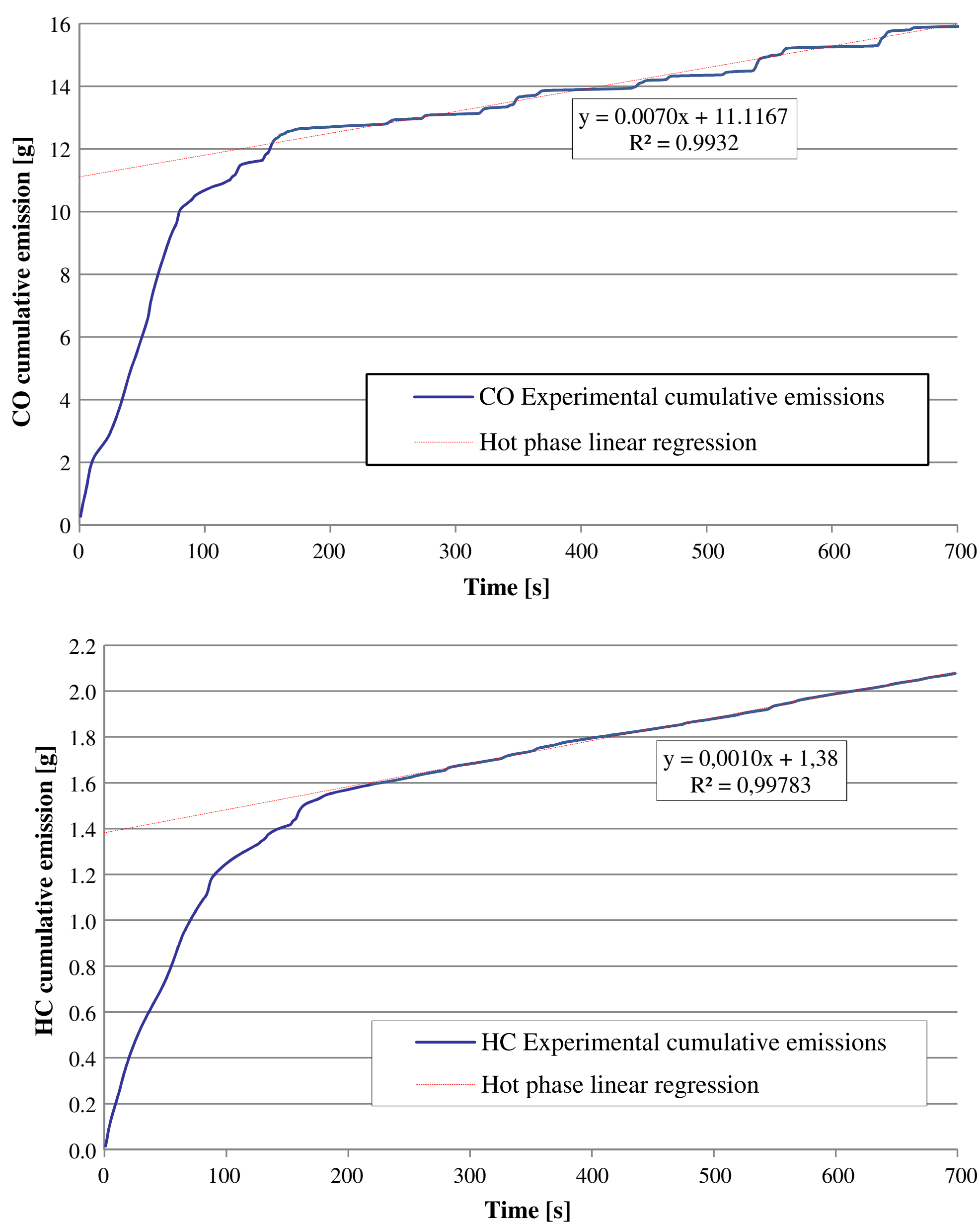


Fig. 3 CO and HC experimental cumulative emissions measured on the motorcycle B during UDC driving cycle

time unit, and with the help of the subsequent assumptions. The shape of the cold instantaneous emission $f_{cold}(t)$ along time, for a certain pollutant, can be split up into three different phases: A first phase characterized by the maximum cold-start emissions due to the lower temperatures of engine and catalyst and to the greatest enrichments of the fuel–air mixture, a second phase with declining cold emissions for the progressive rise of engine and catalyst temperatures and for the lower enrichments, and the last quite stable phase with the smallest cold emissions when the normal temperatures are reached and the mixture ratio is very close to the stoichiometric value. This function, then, must be such as to take zero at the instant T_{reg}, that is, the cold transient duration (1); it is also conceivable that the function always decreases during the transient duration and that its first derivative takes zero value at the end of the cold transient (2). A possible function that satisfies these two boundary conditions is represented by the Eq. (3), which is expressed through two parameters (T_{reg} and f_0).

Fig. 4 Experimental and calculated CO and HC cold cumulative extra emissions for the motorcycle B during UDC driving cycle

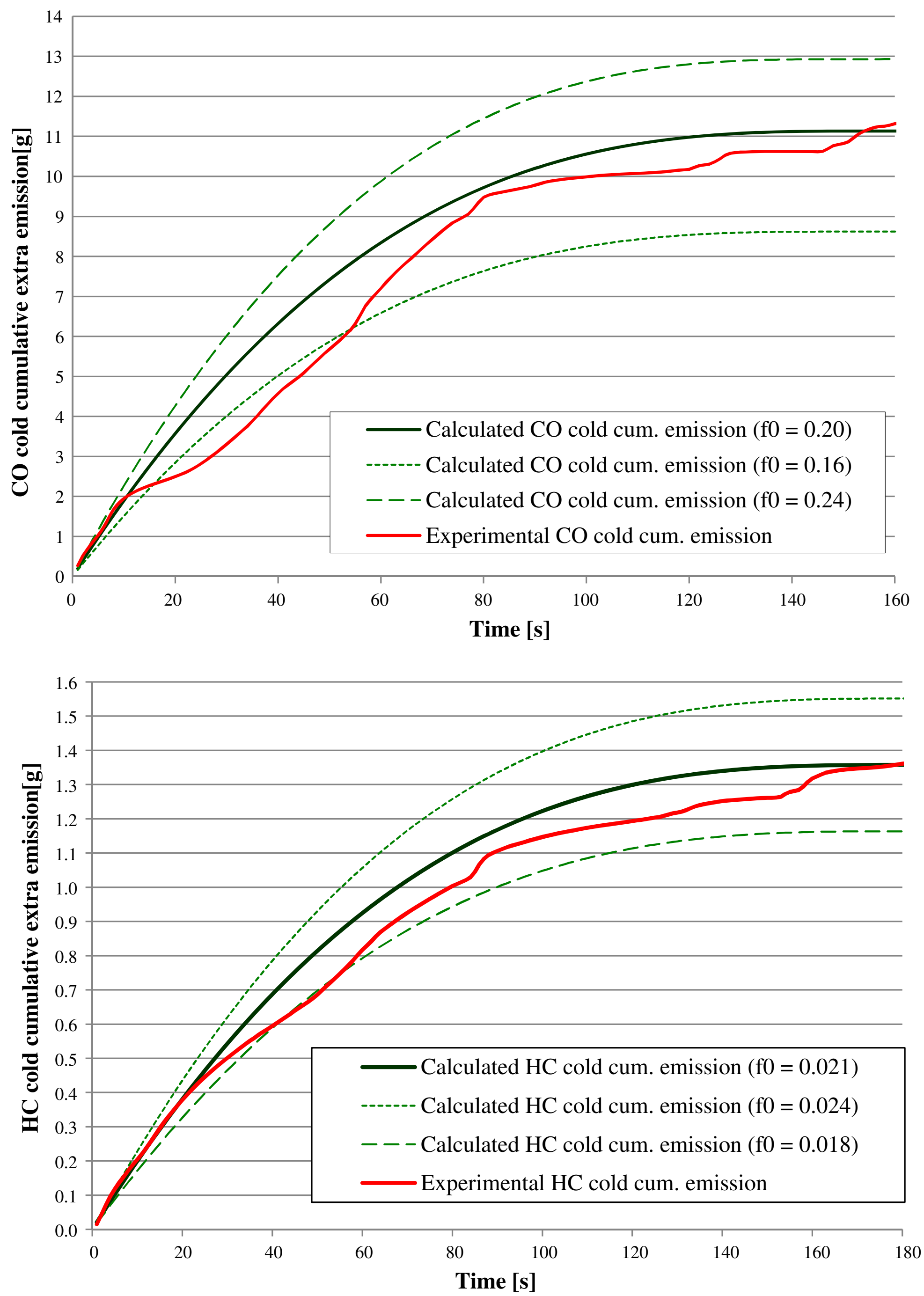


Table 3 Motorcycle B cold transient data of CO and HC obtained for different driving cycles

Driving cycle	Transient duration T_{reg} (s)	Cold-start emission E_C (g)	F_0(g/s)	$E_{cold} = E_C/T_{reg}$ (g/s)	$e^*_{cold} = f_o(e/2-1)$ (g/s)	Cold emission factor (g/km)	e_{hot} (g/s)	Hot emission factor (g/km)	e_{cold}/e_{hot}
CO									
Idle	190	12.99	0.190	0.068	0.068	–	0.0015	–	45.58
20 km/h	205	14.13	0.190	0.069	0.068	12.41	0.0011	0.20	62.66
40 km/h	115	6.84	0.165	0.059	0.059	5.35	0.0009	0.08	66.09
60 km/h	95	5.56	0.160	0.059	0.057	3.51	0.0018	0.11	32.51
80 km/h	95	6.53	0.185	0.069	0.066	3.09	0.0027	0.12	25.46
UDC	155	11.12	0.200	0.072	0.072	15.47	0.0070	1.35	10.25
WMTC	150	10.66	0.200	0.071	0.072	11.40	0.012	1.62	5.92
Urban cold	175	12.45	0.200	0.071	0.072	12.56	0.0202	3.80	3.52
Average values	148	10.04	0.186	0.067	0.067	9.11	0.0059	1.04	31.50
HC									
Idle	200	1.12	0.015	0.0056	0.0054	–	0.00068	–	8.24
20 km/h	225	1.52	0.0185	0.0068	0.0066	1.22	0.00068	0.12	9.93
40 km/h	135	0.83	0.017	0.0061	0.0061	0.55	0.00073	0.07	8.42
60 km/h	150	1.18	0.0215	0.0079	0.0077	0.47	0.00059	0.04	13.33
80 km/h	135	1.11	0.023	0.0082	0.0083	0.37	0.0006	0.03	13.70
UDC	180	1.38	0.021	0.0077	0.0075	1.41	0.00101	0.22	7.59
WMTC	225	1.76	0.021	0.0078	0.0075	1.16	0.00204	0.26	3.83
Urban cold	235	1.82	0.021	0.0077	0.0075	1.44	0.00224	0.41	3.46
Average values	186	1.34	0.020	0.0072	0.0071	0.946	0.0011	0.16	8.54

$$f_{cold}(T_{reg}) = 0 \tag{1}$$

$$f'_{cold}(T_{reg}) = 0 \tag{2}$$

$$f_{cold}(t) = f_0\left(e^{\frac{t}{T_{reg}}} - e \cdot \frac{t}{T_{reg}}\right)(\mathrm{g/s}) \tag{3}$$

For the explanation of these two parameters, information on cold-start extra emissions and on the cold transient phase has to be identified. By processing the experimental exhaust emissions of CO and HC, measured during the UDC + EUDC driving cycle with cold-start for the motorcycle B, the cumulative curves of emissions were obtained in function of the time (the choice of this motorcycle was determined by the plentiful amount of data available for this vehicle in order to demonstrate the whole procedure); CO and HC experimental cumulative emissions are displayed in Fig. 3. As proposed in a methodology of EMPA (Weilenmann 2001) to calculate the cold-start emissions, the contribution of hot emissions on the cumulative curves can be fitted with a line (characterized by high correlation coefficients) whose intercept is considered equal to cold-start extra emission E_C. The duration T_{reg} of the cold transient is calculated as the instant in which the curve of the cumulative emissions diverges from the linear regression and, exactly, cuts the line parallel to the linear regression but with the constant equal to the constant of linear regression—2 × standard deviation of emissions (Joumard 1999).

The next phase, needed for setting the parameter f_0, consists in explaining the experimental and analytical curves of the cold cumulative extra emission. The experimental curve is obtained through the total cumulative curve of emissions by subtracting, during the transient duration, the hot phase linear regression. The analytical curve, on the other hand, is calculated by integration of the function $f_{cold}(t)$ [Eq. (3)], finding the analytical function expressed in Eq. (4).

$$E_{\substack{cold\\cum}}(t) = \int_0^t f_{cold}(t)\mathrm{d}t = f_0\left(T_{reg} \cdot e^{\frac{t}{T_{reg}}} - \frac{e \cdot t^2}{2T_{reg}} - T_{reg}\right)(\mathrm{g}) \tag{4}$$

In Fig. 4, parameter f_0 is chosen in order to adapt the analytical functions to the experimental curves; from the values obtained with this procedure, the cold cumulative extra emissions, the parameter f_0 and the duration of the cold transient T_{reg} evidently depend on the particular pollutant (Iodice and Senatore 2014).

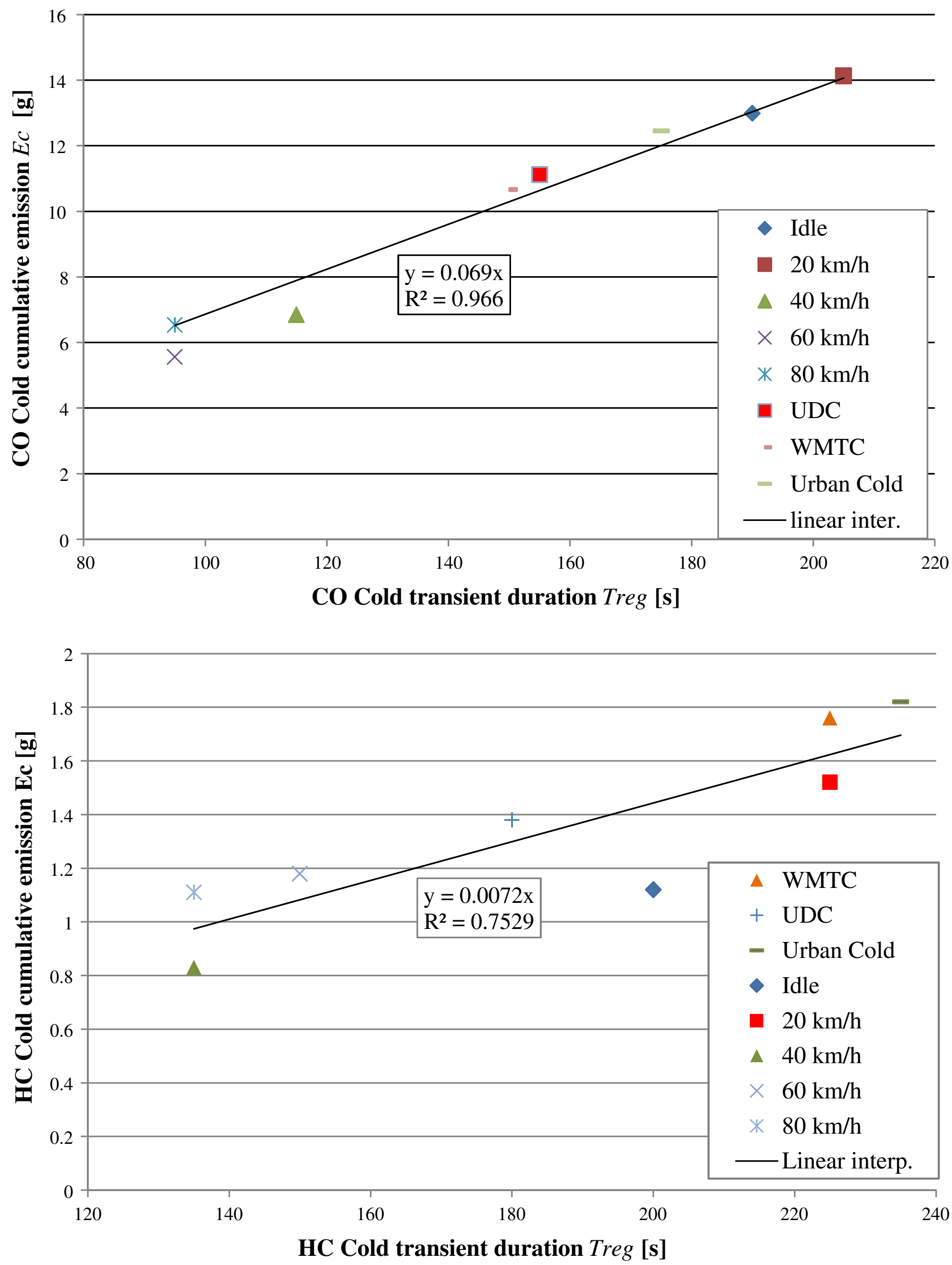


Fig. 5 CO and HC cold-start emissions of motorcycle B estimated against the cold transient duration for each driving cycle

In order to study the effect of diverse driving behaviors on the cold-start emissions and on cold transient duration compared with the type-approval test cycle and thus improving the assessment of the cold emissive performance of this motorcycle, moreover, the experimental tests measured exhaust emissions at different values of constant speed and for WMTC and Urban Cold DCs. Table 3 shows all cold transient data relevant to the motorcycle B, which were obtained by employing the calculation procedure already described.

It is evident that f_0 is the value of function (3) for the instant $t = 0$ [namely: $f_0 = f_{\mathrm{cold}}(t = 0)$], but it would be very hard a matching with the measured cold emissions at initial time, because of an imprecise continuous sampling during the first instants of the cold transient. The usefulness of this value, instead, is derived from the remark that it can be intended constant with the variation in driving cycles, as it represents the emission level at the initial instant and then it's function only of the particular vehicle, pollutant and ambient temperature. In effect, it is evident in Table 3 that the values of f_0 calculated with this method vary not meaningfully with the diverse driving cycles. In order to validate all these procedures, the cold-start extra emission was successively calculated by employing the cold cumulative emission Eq. (4) for $t = T_{reg}$, so achieving E_C^* (5), and the cold emission factor, in terms of mass per time unit, was calculated as $e_{cold}^* = E_C^*/T_{reg}$ (6).

$$E_C^* = E_{\substack{cold\\cum}}(t = T_{reg}) = f_0 \cdot T_{reg}\left(\frac{e}{2} - 1\right)(g) \qquad (5)$$

$$e_{cold}^* = \frac{E_C^*}{T_{reg}} = f_0 \cdot \left(\frac{e}{2} - 1\right)(g/s) \qquad (6)$$

In order to provide a significant proof of validation of this procedure, in Table 3 for the two pollutants the similarity is apparent between these cold emission factors (e_{cold}^*) and those obtained ($e_{cold} = E_C/T_{reg}$) through the analysis of the experimental cumulative emissions exposed in Fig. 3. Moreover, it is evident that the cold emission factor e_{cold}^*, as calculated in (6), is function only of f_0, and so it is independent from the specific driving cycle; this consideration involves the additional conclusion whereby, for a particular vehicle and pollutant, the experimental results of an individual driving cycle are satisfactory for the estimation of the cold emission factor e_{cold}^*.

In this context, the CO and HC cold-start emissions (E_C) of motorcycle B, available from Table 3, were estimated for each driving cycle against the pertinent cold transient durations (T_{reg}) and are shown in Fig. 5; these value pairs (E_C; T_{reg}) have a linear interpolation characterized by an acceptable degree of approximation, and the slope of these lines is exactly the cold-start emission factors concerning the specific vehicle and pollutant in examination. The hot emission factors e_{hot} of all considered driving cycles, also exhibited in Table 3, were calculated by the slopes of the linear regression of the experimental cumulative curves of emissions, already shown in Fig. 3.

In the successive step of the study, in order to evaluate the cold extra emissions and transient durations of the sample of two high-performance motorcycles, the experimental test procedure measured exhaust emissions during ECE + UDC DC of each vehicle. The tested motorcycles are fitted with electronic fuel injection systems, allowing the control of fuel feeding and enhancing catalyst efficiency also in cold transient; the on-board central unit controls the fuel injection strategy with feedback signal from the oxygen sensor placed in the exhaust pipe. In these conditions, the cold-start emissive behavior of these vehicles was investigated under the original fuel injection strategy. Global information on the cold-start transient of the two tested motorcycles was deduced by applying the whole analytical procedure on the measured exhaust emissions of the vehicles. The data so obtained are summarized in Table 4.

It is manifest in Table 4 (above all observing the cold/hot emission quotients for pollutant and vehicles) that a substantial difference exists between emission during the cold-start and the hot phases of the tested Euro-3 motorcycles, as effect of improved engines in combination with catalytic technology used on these vehicles. CO formation in engine, as known, depends mainly on air/fuel mixture equivalence ratio; as regards all the tested vehicles, mixture enrichment during cold-start (outside the optimal catalyst range) increases these emissions in comparison with the levels recorded for steady engine operation. Besides, at low ambient temperatures, the cold engine contrasts fuel vaporization, thus raising the formation of unburned fuel and then leading to increased HC emissions. During the cold-start, therefore, the engine and catalytic converter are not at their ideal functioning conditions; assuming the rich value of the air–fuel mixture and the catalytic converter that fails to reach the light-off temperature, these high-performance motorcycles produce higher cold-start emissions of CO and unburned hydrocarbons.

Conclusion

Two-wheelers are popular means of transportation in Europe, and their contribution to air pollution is generally

Table 4 Cold transient data of CO and HC obtained for individual motorcycles in the ECE + EUDC driving cycle

	Transient duration T_{reg} (s)	Cold-start emission E_C (g)	f_0 (g/s)	$e_{cold} = E_C/T_{reg}$ (g/s)	$e_{cold}^* = f_o(e/2-1)$ (g/s)	Cold emission factor (g/km)	e_{hot} (g/s)	Hot emission factor (g/km)	e_{cold}/e_{hot}
CO									
A	150	9.32	0.165	0.062	0.059	14.27	0.003	0.61	20.71
B	155	11.12	0.200	0.072	0.072	15.47	0.007	1.35	10.25
Average values	152	10.22	0.182	0.067	0.065	14.87	0.005	0.98	15.48
HC									
A	145	0.72	0.014	0.0050	0.0048	1.23	0.00049	0.10	10.13
B	180	1.38	0.021	0.0077	0.0075	1.41	0.00101	0.22	7.59
Average values	162	1.05	0.017	0.0063	0.0061	1.32	0.00075	0.16	8.86

significant, especially in urban environment. Because it is assumed that the most cold-starts of two-wheelers befall in an urban environment and thus are driven under urban driving conditions after the start, an expansion of the cold emission factor database was considered necessary. Starting from this consideration, a test bench series was carried out with a sample of two high-performance motorcycles of certification category Euro-3, and a deep characterization of their emissive behavior was performed in hot and cold conditions, both on the type-approval and on real-world test cycles. Important improvements were observed for the emission levels of these newly sold motorcycles compared with older certification category, in fact the compliance of the tested vehicles with statutory type-approval stipulation was completely satisfactory, with the two motorcycles that meet the specified Euro-3 emission limits of the ECE + EUDC and WMTC DCs.

The main goal of this study, however, is the development of a calculation procedure to model the cold-start transient and to estimate the relevant cold-start extra emissions of CO and HC. By employing this methodology, it was observed that, for all the tested motorcycles, the most evident effect of the use of improved engines, in combination with catalytic technology, consists in the differences between emissions during the cold-start and the hot phase: under hot engine and optimal operating catalyst, emission factors of CO and HC were much lower than those observed at warm engine conditions. For these vehicles equipped with a three-way catalyst, the catalyst temperature and air/fuel ratio determine the functioning of the catalytic converter and thus also the net emissions. In this regard, optimizing the combustion process and the exhaust after-treatment systems is expected to be the key matters in order to reduce the cold emissions of CO and HC of modern high-performance motorcycles.

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