Influence of Driving Cycles on Euro-3 Scooter Emission Levels

P. Iodice, A. Senatore

Abstract— **This study derives from the need to evaluate the impact on the urban air quality of two-wheeler vehicular class. Mopeds and motorcycles, in fact, are increasingly used in recent years, representing a great share of motor-powered vehicles in urban environment. This paper is finalized at the examination of the emissions of the last generation motorcycles, contributing broadly to extend knowledge of two-wheeler emission behavior, with reference to cold and hot operating conditions. For this aim, an experimental investigation was performed on a medium-size motorcycle belonging to the Euro-3 statutory category, evaluating the exhaust emissions of regulated pollutants. This scooter was tested on a dynamometer bench both on a type approval test cycle and on real-world test cycles in order to study the influence of driving cycles on the emission levels. The statistical processing results of the experimental data were compared with recent emission models for estimating emissions from road traffic.**

Index Terms—motorcycle emission factors; driving cycles; chassis dynamometer; Artemis WP500

I. INTRODUCTION

THE steady state performance of the powered two-wheelers has improved conspicuously over the years, both in terms of fuel consumption and emissions quality. This can be attributed to a range of developments including the use of common rail fuel injection, improved lubricants, more complex engine control strategies and the use of catalytic converters on most vehicles. However, the emissions of these vehicles remain problematic, because they are popular means of transport especially in the major cities of southern Europe and southern Asia (Vasic and Weilemann 2006), where mopeds and motorcycles represent a great proportion of morized vehicles..

The absolute emission level of passenger cars have been reduced significantly in the last two decades, due to the introduction of legislation together with tightening the applicable limits on regulated emissions for these vehicles. As a result, in the last years motorcycles and mopeds make a considerable contribution to CO and HC emissions, although the percentage of two-wheelers in the total circulating fleet is lower than that of other vehicle categories [1,2]. Determination of emissions from two-wheelers is then very chief for estimating the relevant contribution to total emissions attributable to road transport. However, the current emission models available in Europe for calculating emissions from road traffic are mainly based (especially for the two-wheelers) 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 motorcycle riding.

Starting from the above considerations, in the last years experimental investigations on 2-wheel vehicles emissive behavior were being performed by the Department of Industrial Engineering of the University of Naples “Federico II” in the Istituto Motori emission laboratory (National Research Council). In this particular study the experimental activity was performed in order to characterize the emissive behavior during different driving cycles of a scooter on the basis of roller test bench measurements. CO, HC and NO_X emissions were evaluated in the exhaust of a motorcycle that belongs to the Euro-3 legislative category, of 250 cm^3 swept volume. The results of this experimental activity, which was partly presented in a previous study [3], are now investigated with additional observations and remarks, thus achieving an improved assessment and some interesting findings.

Specifically, the emission performance of this motorcycle was determined on the statutory driving cycles for Europe (“ECE +EUDC”) and on different real-world driving cycles: the Worldwide Motorcycle Test Cycle (“WMTC”) and the “Artemis Urban Cold” driving cycle. This study, then, analyses the influence of different driving cycles (characterized by different kinematic parameters) on motorcycle emission behavior during the cold and the hot phases. The experimental data of this research and the relevant statistical processing results allowed to develop some interesting comparison with current emission models for calculating emissions from road traffic.

II. BACKGROUND

Emissions from road transport sector can be evaluated with different calculations and models based on the collection of algorithms and road vehicles emission factors. In order to develop a valuable comparison with the results obtained in this study, the attention was focused on the ARTEMIS model. The objective of the ARTEMIS project (Assessment and Reliability of Transport Emission Models and Inventory Systems) was to develop a harmonized

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emission model for all transport modes which aims to provide consistent emission estimates at the international (European), national and regional level. In particular, the ARTEMIS WP500 model dealt with 2-wheel vehicle emissions. The ARTEMIS WP500 model is based on a large number of bag and online emission results both from the ARTEMIS WP500 main measurement programme and from several other studies conducted over the years. The approach to determine emission factors for motorcycles was copied from methodology of the Handbuch emission model (HBEFA) [4].

The vehicle categories for the powered two-wheelers were defined with regard to the engine displacement and legislative category: Euro-0, Euro-1, Euro-2 or Euro-3. Hence, in all 32 categories are identified for which emission factors were determined. Since vehicle emissions depend on the engine operation (i.e. driving situation), exhaust emissions are estimated as a function of average speed The measurement data (both online and bags) were employed to derive by regression analysis emission functions in terms of mass per time in relation to vehicle speed, for each powered two-wheeler vehicle category, obtaining fifth order polynomial functions (1) (with v as vehicle speed in [km/h] and α depending on the specific category). By using these emission functions, emission factors can be predicted for driving patterns or test cycles for which no measurement results are available.

$$E\ [\text{g/km}] = \alpha_5 * v^5 + \alpha_4 * v^4 + \alpha_3 * v^3 + \alpha_2 * v^2 + \alpha_1 * v + \alpha_0 \qquad (1)$$

III. MATERIAL AND METHODS

A. The Vehicle

The main characteristics of the motorcycle employed in the test series are summarized in Table I. This is equipped with four-stroke engines and the technology used for pollutants abatement to meet the latest emissive standards is the use of a three-way catalytic converter, that feature lambda sensors. A precise tuning of air/fuel ratio is reached throughout an electronic fuel injection and a closed-loop exhaust after-treatment control systems are thus assumed to be implemented.

TABLE I
TECHNICAL SPECIFICATIONS OF THE TESTED MOTORCYCLE

Category	Motorcycle
Engine principle	4-stroke
Cubic capacity [cm^3]	250
Compression ratio	11.0:1
Power system	electronic injection
Cooling system	liquid
Max power [kw]	16.2 @ 8250 rpm
Maximum speed [km/h]	125
After-treatment system	catalytic converter
Legislative category	Euro 3

B. The Experimental Apparatus

The motorcycle was tested on a chassis dynamometer (AVL Zollner 20" - single roller) in the Istituto Motori emission laboratory (National Research Council), that enables simulation of vehicle weights from small mopeds up to heavy two-wheel vehicles (range 80-450 kg). This bench is designed to simulate the road load (including vehicle inertia) and to measure the exhaust emissions during dynamic speed cycles. The chassis dynamometer was set by using the running resistance table according to the procedures laid down in Directive 97/24/EC. A variable speed cooling blower was positioned in front of the motorcycle so as to direct the cooling air in a manner which simulates actual operating conditions. Before each test in cold start conditions, the scooter was kept at constant temperature between 20 °C and 25 °C for at least 8 hours.

During the tests the exhaust gases were diluted with purified ambient air by a Mixing Unit connected to a Constant Volume Sampling with Critical Flow Venturi (AVL CFV-CVS) unit. During the tests a continuous sample flow of the mixture filled one or more bags so that concentrations (average test values) of CO, HC, NO_X and CO_2 were determined. Average test values and continuous diluted emissions were measured with an exhaust gas analysis system (AVL AMA 4000). The exhaust pollutants were collected in the dilution tunnel and analyzed at 1Hz. The signals were corrected for the time delay respect to the speed and no other signal treatment was applied. Fig. 1 shows a scheme of this experimental apparatus.

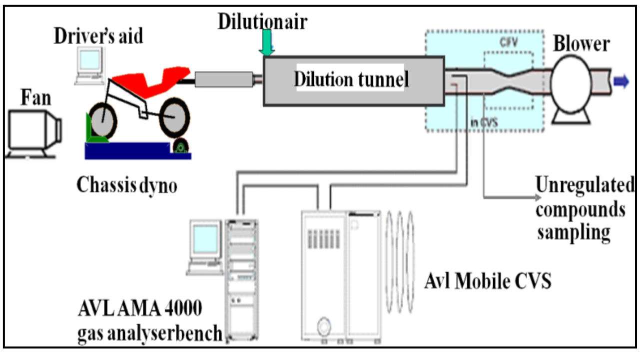

Fig. 1. The experimental apparatus

C. The Driving Cycles Adopted in the Experimental Tests

The motorcycle was tested over the following driving cycles with cold start (engine off for at least 6 hours before starting):

- European type-approval driving cycle for motorcycles ("ECE+EUDC")
- European type-approval driving cycle for mopeds ("ECE-47")
- World-wide Motorcycle Emissions Test Cycle ("WMTC")
- "Artemis Urban Cold"

"ECE+EUDC" is composed by an urban (ECE) and an extra urban part (EUDC). Urban part is divided in two phases: cold (including 2 base modules) and hot (including 4 base modules). The "ECE-47" driving cycle comprises eight elementary cycles; each elementary cycle lasts 112 seconds and includes an acceleration phase and a full speed phase. "WMTC" regulated in 2006/72/EC directive states the execution of two phases (WMTC_1 and WMTC_2).

Artemis Urban Cold was proposed within EU Artemis framework in order to study cold start influence on the exhaust emissions [5]: it includes 15 repetitions of a base module. During this experimental activity, measurements relative to Artemis Urban Cold were performed over three parts, each including 5 base modules. Main kinematic characteristics of all the driving cycles are summarized and reported in Table II.

TABLE II
KINEMATIC CHARACTERISTICS OF DRIVING CYCLES ADOPTED IN THE TESTS

	Duration [s]	Length [km]	Max.speed [km/h]	Mean speed [km/h]
ECE+EUDC				
UDC_cold	390	2	50	18.4
UDC_hot	780	4	50	18.4
EUDC	400	6.9	120	62.6
WMTC				
WMTC_1	600	4.1	60	24.3
WMTC_2	600	9.1	95	54.6
Artemis Urban Cold	945	5	44	19
ECE-47				
ECE-47_cold	448	3.1	45	25.1
ECE-47_hot	448	3.1	45	25.1

IV. RESULTS AND DISCUSSION

A. Results on the European Type-Approval Driving Cycle

Regulation approved for the Euro-3 phase of the Directive 97/24/CE, now in force, introduced important improvement with reference to normalized cycle, including more stringent limits, an extra-urban phase and the evaluation of the cold start transient. In according with this regulation, three bags have been filled during the Type Approval driving cycle ("ECE+EUDC"): the first during the conditioning phase (the first two elementary urban modes), the second during the following four elementary modes, and the third during the EUDC mode.

In Fig. 2, Fig. 3 and Fig. 4 mean experimental emission values of the tested motorcycle, expressed as mass emitted per kilometer travelled, are reported (in green) for each test of five repetitions, for each phase and for the whole cycle, also to verify compliance with Euro-3 emission limits. In these figures the experimental results are reported also as average values of each phase (in blu), with the relevant standard deviations reported in order to evaluate the variability of tests. It's evident in these figures that this motorcycle comply with the Euro3 limits for CO, NOX and HC: in fact, CO emission factors in the whole cycle varied between 0.96 and 2.26 g/km, NOX between 0.11 and 0.22 g/km, while HC ranged between 0.12 and 0.16 g/km. As shown in Fig. 2, CO emission factor obtained during the EUDC phase and the pertinent variation to the average (≈ 72%) were much higher than values of ECE_b phase.

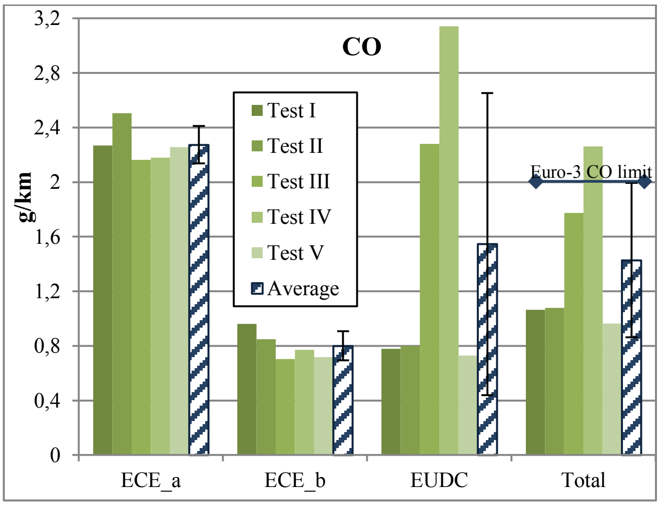

Fig. 2 CO emission factors in ECE+EUDC phases and their covariance

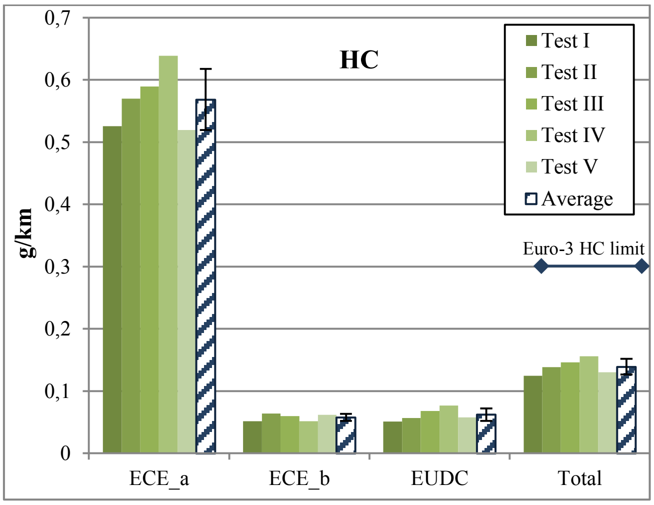

Fig. 3 HC emission factors in ECE+EUDC phases and their covariance

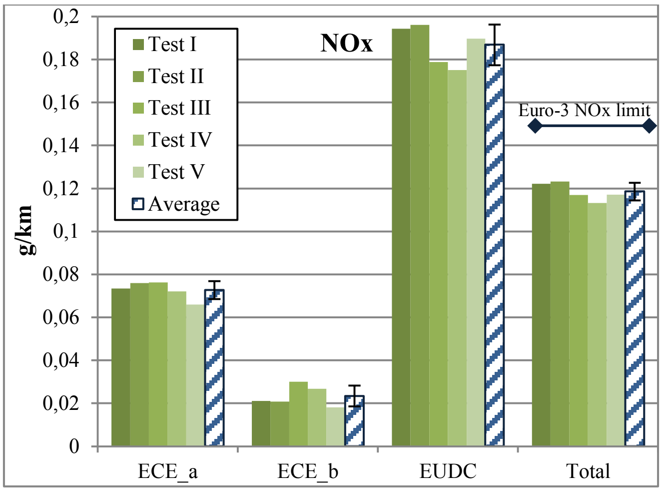

Fig. 4 NO$_X$ emission factors in ECE+EUDC phases and their covariance

This was due to the not completely accurate repeatability of some experimental tests performed by a human driver which failed to properly follow, for those tests, the whole speed-time profile of the driving cycle; besides, when running close to the maximum speed of the motorcycle (around 125 km/h), the engine operates at full load. In these circumstances, and for the particular electronic power management of the motorcycle, open loop operating conditions occurred during the EUDC phase of Test III and Test IV.

To better explain this remark, the values of CO continuous experimental emissions and of real speed profile relevant to Test IV are shown in Fig. 5; it is manifest that the instantaneous emission factor reaches a rapid and very high peak of around 0.6 g/s. The electronic mixture control of the vehicle, in fact, in order to offer definite driving dynamics characterized by high speed (110 km/h) and acceleration, fixes a very rich air-fuel mixture, external to the optimal range of catalyst efficiency, excluding the lambda sensor control and thus involving a considerable rise in CO emissions. On the other hand, the high percentage variance coefficient of HC emissions noticed in the ECE_a cold phase (Fig. 3) was due to the difficulties found in the repeatability of tests in laboratory with different ambient conditions that influence the emission results during the cold transient time [6].

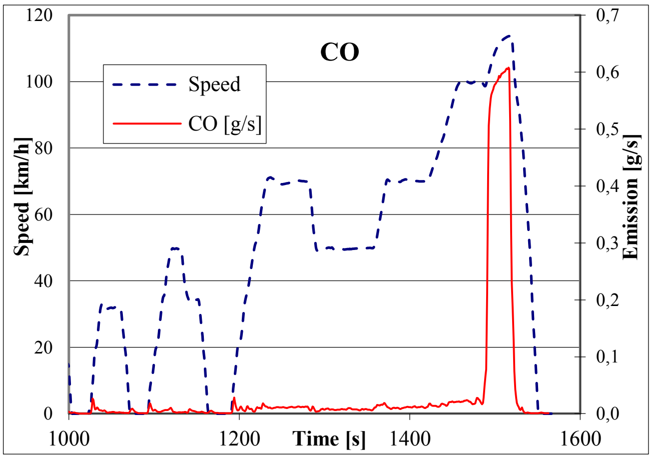

Fig. 5 The open loop operating condition occurred during the EUDC phase of ECE+EUDC test IV

Another important aspect that can be observed in the previous fugures is the differences between emissions during the cold phase and the hot phase of the Type-Approval driving cycle, as consequence of the use of improved engines, in combination with the use of catalytic converter. During the cold start, the engine and catalytic converter are not at their best operating conditions: due to the rich gasoline content in the air–fuel mixture, and with the catalyst failing to reach the light-off temperature, this motorcycle produces high emissions of CO and HC [7]. Since motorcycles are generally driven in residential areas, the cold-start influence must be taken into account in assessing CO and HC emissions attributable to this vehicle category [8].

B. *Influence of Driving Cycles on the Emissive Behavior*

Mean experimental emission values of regulated pollutants are available in the previous figures for cold and hot phase of the Type-Approval driving cycle. However, such emission factors might not be sufficiently representative of real-world motorcycle riding, significantly different from the speed-time pattern of the Type-Approval test cycle on which they were measured. This aspect is related to the kinematic parameters of the “ECE+EUDC” driving cycle that has the shortcoming of underestimating cycle dynamics, in fact, the relevant speed-time profile presents only one level of constant acceleration and a significant percentage of the driving cycle is characterized by constant speed. Besides, current emission models available in Europe to predict emissions are based mainly on the average trip speed, thus they are not sensitive to variations of instantaneous speed and acceleration, which have a strong effect on emissions and fuel consumption.

For all these reasons, it is necessary a more complete assessment of the motorcycle emissive behavior, by evaluating the emissions on other driving cycles, including several acceleration phases; in these phases, an enrichment of the air-fuel mixture is needed, which could affect the catalyst conversion efficiency. For this purpose, additional measurements during real-world test cycles were indispensable to evaluate motorcycle performance under real driving conditions. In this study two real urban driving cycles were considered: the “WMTC” and the “Artemis Urban Cold”. Experimental emission factors of each driving cycle (and their mean speed) are shown in Table III.

TABLE III
EXPERIMENTAL EMISSION FACTORS FOR THE DRIVING CYCLES CONSIDERED AND DATA OF ARTEMIS PROJECT WP 500

Test Cycle (mean speed [km/h])	**CO** [g/km]	**HC** [g/km]	**NOx** [g/km]
ECE+EUDC (m.s.=29,7)	1,42	0,139	0,119
WMTC (m.s.=37,5)	0,73	0,110	0,102
Artemis Urban Cold (m.s.=19)	1,67	0,146	0,086
ECE 47 (m.s.=25,1)	0,89	0,151	0,044
ARTEMIS WP 500	*4,04÷6,17*	*0,26÷0,46*	*0,094÷0,11*

Emission levels detected for real world cycle/speed profiles highlight a clear influence of the average speed, but other considerations are necessary. It’s clear that CO and HC emission factors calculated on the “Artemis Urban Cold” driving cycle are higher than those measured during the other driving cycles, because this cycle is characterized by many acceleration phases of high levels; also for similar values of average speed, in fact, higher levels of acceleration correspond to an increase in energy request for the execution of the driving pattern, with consequent enrichment of the air-fuel mixture (outside the optimum range of catalyst efficiency). On the contrary, NO_X emission factors increase at high speed (during “ECE+EUDC” and “WMTC” driving cycles). This result can be ascribed both to the increased combustion temperatures at higher loads and to the high exhaust mass flow that limit the residence time of the exhaust in the catalytic converter.

Table III also shows the emission factors calculated in the ARTEMIS WP 500 model by employing the emission functions (1) of the examined vehicular category and by entering with speed values equal to the mean speeds of the considered four driving cycles; the range of ARTEMIS estimations is relevant to the minimum and maximum value obtained with these four mean speeds. Experimental emission factors of the same pollutants are then compared to these calculated values. It is manifest to notice that CO and HC emission factors measured on the tested vehicle were always lower than ARTEMIS WP500 values, and these differences must be related to the vehicle fleet considered for the development of the emission database of the considered model. A decreasing enrichment, for the tested vehicle, is maybe the effect of internal engine optimization and more precise mixture control of fuel injection systems, consenting an improved control of fuel feeding and also increasing catalyst efficiency; on the other hand, the poor combustion quality occurring in four-strokes motorcycle engines (belonging to ARTEMIS database), not fine-tuned in terms of air-fuel ratio, is probably responsible for high CO and HC emission results of ARTEMIS WP500 measurement programme.

In order to explain the above emission results for each pollutant, a number of different aspects were considered: the driving cycle characteristics (in particular the acceleration phases with the associated rich values of air-fuel ratio), the further mixture enrichment during the engine warm-up, the catalyst light-off and its related conversion efficiency. Afterwards, to lessen the number of all these variables on which the emissive behaviour depends, experimental tests were performed in hot conditions, so removing the effect of the cold transient that, as analysed, have a strong effect above all on CO and HC emissions.

In Fig. 6-8, the hot emissions factors of CO, HC and NO_X are reported as a function of average vehicle speed for the different five phases of all the driving cycles. Emission levels detected for real world cycle/speed profiles highlight a clear influence of the average speed, above all for CO and NO_X. However, for similar levels of average speed, emissions of CO, HC and NO_X calculated on the "Urban Cold" driving cycle are higher than those measured during the "UDC_hot" phase. For CO and HC emissions, this could be ascribed to incomplete combustion in driving situations with sudden steep increase in engine speed that is no longer compensated by the catalytic converter. A rich fuel/air mixture could be thus assumed to be provided to the combustion process of this motorcycle in such driving situations, which accounts for the very high emissions of CO and HC observed on the "Urban Cold" driving cycle.

However, these differences are less pronounced for HC emissions because for lower engine loads, consequential to driving cycles ("UDC_hot" and "ECE_47") characterized by lesser values of acceleration and by speed-time profiles with a considerable share at constant and low speed, the excessive leaning of the air/fuel mixture could cause irregular operating conditions in the engine. This aspect compensates for the previous consideration and make no great difference on hot emissions of HC among all the driving cycles. About NO_X emissions, the differences are due to excessive engine-temperatures produced by the frequent accelerations that characterize particularly the "Urban Cold" driving cycle.

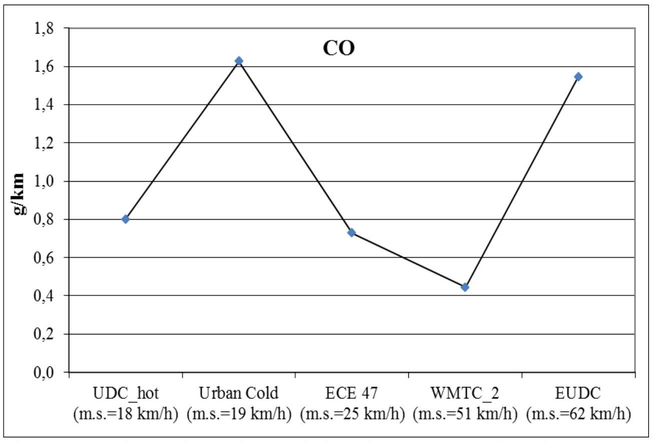

Fig. 6. Experimental CO hot emission factors reported against average speed of each driving cycle

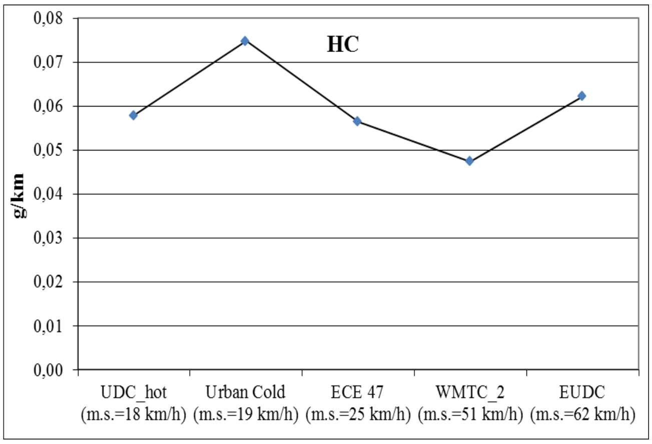

Fig. 7. Experimental HC hot emission factors reported against average speed of each driving cycle

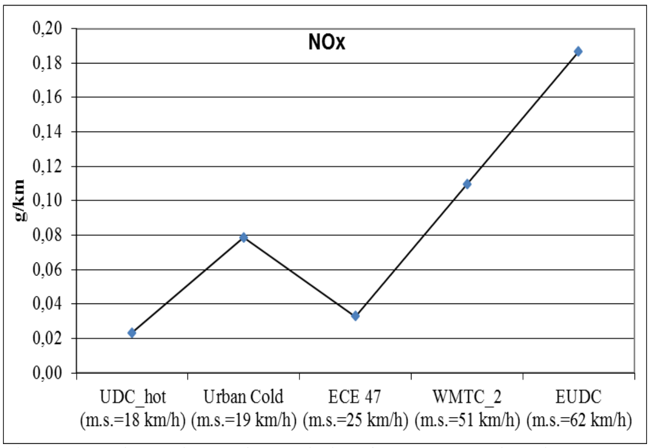

Fig. 8. Experimental NO_X hot emission factors reported against average speed of each driving cycle

V. CONCLUSIONS

An experimental activity was conducted on the emissive behavior of a medium-size motorcycle, belonging to the Euro-3 legislative category. Statistical elaborations of the exhaust emissions of the regulated pollutants (CO, HC and NO_X) were performed both on a type approval cycle and on real-world cycles. Emission levels of this vehicle depend on considered driving cycles, due to the differences in kinematic parameters, such as speed and acceleration. All the experimental tests visibly indicate raised CO and HC cold additional emissions, if related with those obtained in hot conditions. This statistical approach improves vehicles emission assessment in comparison with the modelling approaches that are only based on average speed. Some differences were observed between the experimental emission factors obtained and the calculated values of ARTEMIS WP500 emission model: these differences are correlated to the characteristics of the vehicle fleet considered for the development of the emission database of the considered model.

REFERENCES

[1] P. Iodice and A. Senatore, "Evaluation of Dispersion Models for Predicting Carbon Monoxide Concentrations from Motor Vehicles in a Metropolitan Area," International Review on Modelling and Simulations, 2013, Vol. 6 No. 6, pp. 1928-1932

[2] P. Iodice and A. Senatore, "Experimental-analytical investigation to estimate an emission inventory from road transport sector," IAENG Transactions on Engineering Sciences-Special Issue of International MultiConference of Engineers and Computer Scientists, IMECS 2013 and World Congress on Engineering, 2014, pp. 141-149

[3] P. Iodice and A. Senatore, "Experimental investigation on the chassis dynamometer for the evaluation of exhaust emissions," 6th IEEE Workshop on Environmental, Energy and Structural Monitoring Systems, EESMS 2014, Naples, Sep.17-18, 2014.

[4] D. Elst, N. Gense, R. Vermeule, and H. Steven, "Artemis WP500 Final report," 2006, TNO Automotive report, Delft, the Netherlands.

[5] M. André, "The ARTEMIS European driving cycles for measuring car pollutant emissions," in Science of The Total Environment 334–335, pp.73–84

[6] F. Bozza, A. Gimelli, S. Fontanesi, and E. Severi, "1D and 3D CFD Investigation of Burning Process and Knock Occurrence in a Gasoline or CNG fuelled Two-Stroke SI Engine," Small Engine Technology Conference, 2011. SAE Technical Paper 2011-32-0526

[7] P. Iodice, A. Senatore, and M. V. Prati, "A calculation procedure for the evaluation of cold emissive behavior of high-performance motorcycles," 2011, SAE Technical Paper 2011-24-0200

[8] P. Iodice and A. Senatore, "Cold start emissions of a motorcycle using ethanol-gasoline blended fuels," Energy Procedia, 2014, Vol. 45, pp. 809-818