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AN EMISSIONS PERFORMANCE EVALUATION OF STATE-OF-THE-ART MOTORCYCLES OVER EURO 3 AND WMTC DRIVE CYCLES

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ABSTRACT

Four state-of-the-art >500 cc Euro 3 and one 150 cc Indian specification motorcycles were selected and evaluated over the Euro 3 and world harmonized WMTC test cycles for regulated pollutants and particles. The objectives of the work were to examine the correlation between emissions on the WMTC and Euro 3 cycles, to compare those results with previous work completed before the European WMTC limits were set, to examine particulate emissions, and to then evaluate the durability of one machine.

The correlation between Euro 3 and WMTC emissions results was used to extrapolate the appropriate level of WMTC limit values from the emissions limits on the Euro 3 test cycle. These WMTC extrapolated emissions limits were in line with the previous AECC motorcycle test program conducted in 2004 on Euro 2 motorcycles and also confirmed the appropriate level of the WMTC Euro 3 limits set in European Directive 2006/72/EC amending 97/24/EC.

As a result of these 2004 and 2008 test campaigns, two of the selected motorcycles were tested in both Euro 2 and Euro 3 versions, allowing for comparison of the emissions performance improvement realized by the motorcycle manufacturers.

Even though Euro 5 SI passenger car gaseous emissions limits are much lower than Euro 3 motorcycle levels, some of the tested bikes almost met them. All the bikes met the Euro 5 diesel passenger car particle number limit, after recalculation to give a NEDC equivalent value, despite sporadic rich operation giving higher particle numbers.

A further phase of work evaluated durability performance of a selected Euro 3 motorcycle. The durability exercise was cut short as both CO and NOx emissions exceeded the prescribed Euro 3 limits after only a couple of thousands of kilometers accumulated on a chassis dynamometer and had reached double the limit values well before the end of the durability period.

INTRODUCTION

Directive 2002/51/EC was issued by the European Parliament and the Council of the European Union in June 2002 to tighten emission standards for two- and three- wheeled vehicles to the Euro 3 standard. The World-Harmonized Test Cycle (WMTC) of UN-ECE Global Technical Regulation (gtr) n°2 [1] was then introduced, together with a new set of limit values as Directive 2006/72/EC [2]. The new test procedure was introduced from 2007 as an alternative type-approval procedure at the choice of the manufacturer for Euro 3 homologations in accordance with Directive 2002/51/EC provisions.

The Euro 3 test cycle is shown in Figure 1 and 2 and the 3-part WMTC shown in Figures 3 to 5.

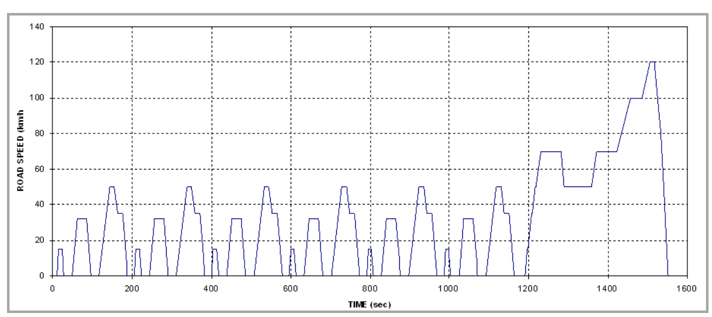

Figure 1: "Euro 3" Emissions Test Cycle (≥150cc)

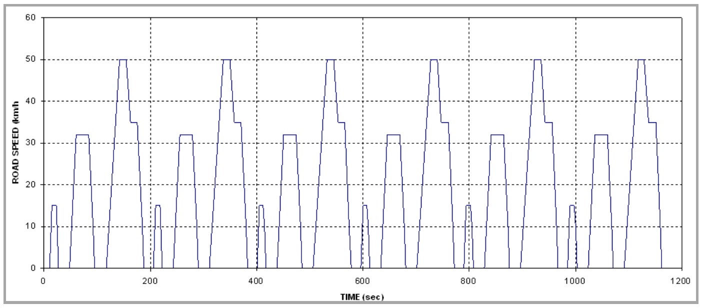

Figure 2: "Euro 3" Emissions Test Cycle (<150cc)

The Euro 3 test cycle is equivalent to the NEDC for passenger cars minus EUDC for motorcycles with engine below 150 cc and with 6 low speed hills. The addition of 2 low speed hills for motorcycle testing skews the emission results to low speed compared to passenger car tests.

The WMTC cycle is a three-phase transient cycle starting at ambient temperature and is designed to be more representative of actual driving conditions. Different versions of the cycle are used according to the vehicle engine displacement and the maximum speed. Some specific classes of motorcycles must be run to the reduced speed parts of the cycle [1].

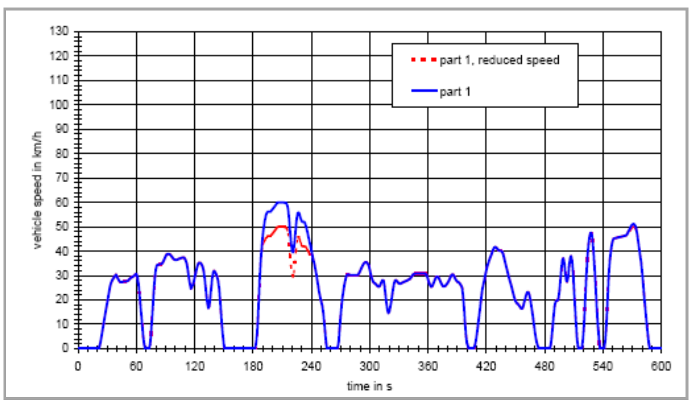

Figure 3: WMTC part 1

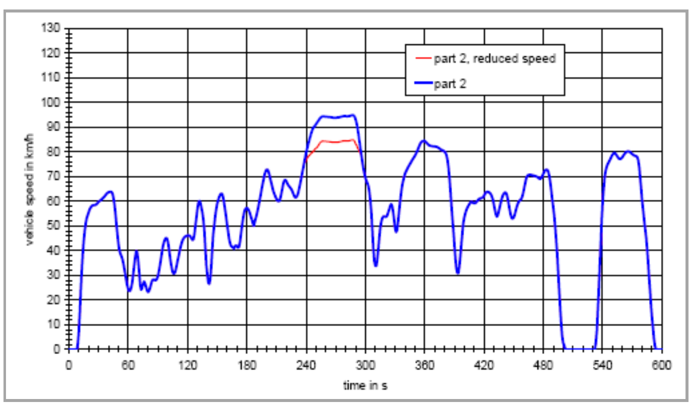

Figure 4: WMTC part 2, for vehicle classes 2 and 3

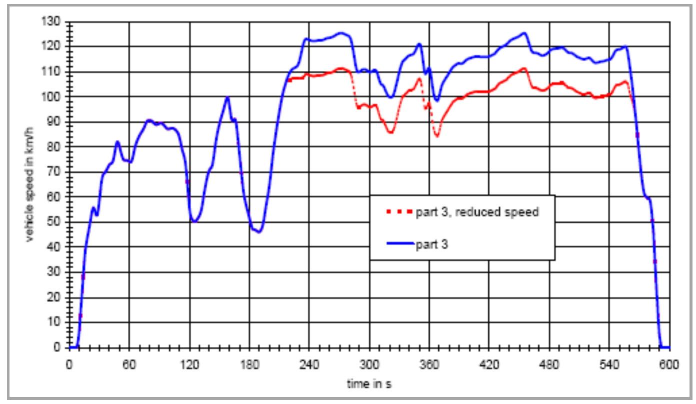

Figure 5: WMTC part 3, for vehicle class 3

The emissions limits for Euro 3 type-approvals are shown in Table 1. These limits are different but designed to be equivalent.

Test Cycle	Class	CO (g/km)	HC (g/km)	NOx (g/km)
Euro 3	≥ 150cc	2.0	0.3	0.15
WMTC	Vmax < 130km/h	2.62	0.75	0.17
	Vmax ≥ 130km/h	2.62	0.33	0.22

Table 1: Euro 3 emissions limits

OBJECTIVES

This test program was a follow-up of a previous test program run on Euro 2 motorcycles [3] and was aimed at evaluating the emission performance of current state-of-the-art motorcycle technologies with respect to Euro 3 emissions cycles and limit levels.

Emissions on both the Euro 3 and WMTC test cycles were compared to the limits set in directive 2006/72/EC and achieved in the previous AECC test program.

Passenger car NEDC equivalent emissions were calculated to allow comparison to Euro 5 gasoline passenger cars limits.

In addition to regulated emissions measurement, unregulated particulate mass and particle number measurements were carried out along the lines of the UNECE light-duty Particle Measurement Procedure (PMP) [4].

A further stage of the program evaluated the durability performance of one selected Euro 3 bike.

TEST MOTORCYCLES AND TEST PROTOCOL

In the first phase of the program, five motorcycles equipped with emissions control devices were procured. Four Euro 3 motorcycles were selected to cover a range of different manufacturers, engine and vehicle types and sizes, and to represent the current state-of-the-art with respect to emission control technology. An Indian specification motorcycle, built for fuel economy, was also included in the test program.

The specifications of the motorcycles tested are summarized in Table 2 below:

Bike	Engine	EFI	Open/ Closed Loop Control	SAI	Catalyst	Spec.
A	800cc V4	y	Closed	y	y	Euro 3
B	800cc in line 2-cyl.	y	Closed	n	y	Euro 3
C	1300cc in line 4-cyl.	y	Closed	y	y	Euro 3
D	500cc 1-cyl.	y	Closed	y	y	Euro 3
E	149cc 1-cyl.	n	N/A	y	y	Indian spec.

EFI = Electronic Fuel Injection SAI = Secondary Air Injection

Table 2: Tested motorcycles

The motorcycles were either rented or purchased new. Prior to testing, each new motorcycle was run-in for 1000 km with a mix of road and chassis dynamometer driving. Nevertheless, bike A was not new and had already run 8000 km when it was tested.

The motorcycles were fitted with non-intrusive tailpipe adaptors in order to measure exhaust emissions (raw and diluted), and air/fuel ratio (AFR).

Emissions tests were performed on a brush 120 kW, 275 km/h motorcycle chassis dynamometer equipped with a road speed proportional cooling fan, Constant Volume Sampling (CVS) system and dilution tunnel for particulate mass determination, raw and dilute exhaust emissions measurement and installed in a temperature-controlled cell.

No pre-test condition is required for the Euro 3 driving cycle, however all motorcycles were preconditioned by running a Euro 3 cycle to guarantee reproducible conditions for the test. Prior to WMTC tests, all motorcycles were pre-conditioned to the WMTC test cycle as stated in the regulation. Three repeats of Euro 3 cycle and three repeats of the WMTC were performed on each of the five motorcycles. The four Euro 3 motorcycles, all class 3.2 vehicles, were tested on the standard 3 phases of WMTC while the Indian bike was tested on reduced speed phase 1 followed by reduced speed phase 2 only, according to the gtr n°2 testing requirements for a class 2.1 vehicle. Tests were conducted with a cold start, machines being ‘soaked’ over night under test conditions according to the regulation; filter paper weighing was conducted on the day prior to testing. All three repeats were conducted using TX40 filter papers for particulate mass measurement, but for each bike, one of the tests was conducted with an additional glass fiber filter to permit particulate chemical analysis. All test fuel was taken from a single batch of pump grade 95 RON Unleaded. Continuous and bags data were recorded.

On top of regulated emissions and CO_2, particles were also measured on each test. Particle number (PN) and particulate mass (PM) were sampled from the CVS according to the light-duty and heavy-duty PMP procedures. The measurement equipment was the same as that described previously [5]. A dilution ratio of 150:1 was used for the initial two bikes as it was sufficient to keep peak PN concentrations from these lambda 1 bikes below 10 000 /cm^3. It was increased to 180:1 with latter bikes to ensure concentrations were maintained below 10 000 /cm^3. Cycle average data were measured at ~200 /cm^3. Measurements were performed according to the latest draft of R83 except that the CVS dilution tunnel did not have a HEPA filter but a coarse filter. Background particle number levels were a little high, e.g. typical background levels were measured at 10 – 20 /cm^3 compared to other work at a background level below 2 /cm^3. Prior to the testing, the CVS and transfer tube were purged of particles and low volatility HC by high temperature operation of another lambda 1 motorcycle run at 150 km/h.

In a second phase, motorcycle D, a scooter, was selected to conduct a 30 000 km mileage accumulation program. Three repeats of the Euro 3 cycle were conducted at periodic intervals. Regulated pollutants and PM were measured at each test point. Particle number was measured at the first and last test points. The scooter was driven on a chassis dynamometer following the Moto69 - ACEM durability proposal rev3 (see Annex 1) for 30 000 km. Periodic emission tests were carried out using a reference transmission belt (CVT) and front pulley roller set to eliminate any change in gear ratio due to wear during mileage accumulation.

PHASE 1 – EMISSIONS RESULTS

Table 3 below gives the average mass emissions measured on three tests for each of the five motorcycles. WMTC mass results are weighted according to gtr n°2 requirements, 25% for phase 1, 50% for phase 2 and 25% for phase 3 for the four Euro 3 models which are Class 3.2 vehicles and 30% for phase 1 and 70% for phase 2 for the Indian Class 2.1 motorcycle.

Particulate mass measurement is not a requirement for petrol-engine motorcycles emissions. Due to filter handling limitations, only one filter paper was used to sample the entire cycle. As a result, the particulate mass for WMTC is not weighted as per regulation for gaseous emissions.

Bike	Test	CO	HC	NOx	PM	CO_2	FC
		(g/km)			(mg/km)	(g/km)	(l/100km)
A	Euro 3	1.276	0.194	0.129	1.05	159	6.87
	WMTC	1.574	0.198	0.141	0.88	132	5.75
B	Euro 3	1.102	0.085	0.049	1.14	109	4.72
	WMTC	1.420	0.100	0.059	2.15	101	4.39
C	Euro 3	0.340	0.109	0.076	0.95	153	6.54
	WMTC	0.549	0.093	0.081	0.90	136	5.82
D	Euro 3	1.278	0.078	0.097	0.61	112	4.90
	WMTC	1.623	0.077	0.192	0.56	106	5.75
E	Euro 3	0.832	0.309	0.214	1.82	51	2.28
	WMTC	1.217	0.225	0.444	0.97	41	1.86

Table 3: Average mass emissions

As three repeat tests were performed on each bike, figures 6 to 10 show average emissions with error bars covering the 3 repeats.

Figure 6 shows bike A passed Euro 3 and WMTC limits on all tests. NOx emissions reached 93% of the Euro 3 limit on one test but not more than 66% of the WMTC limit for this bike at 8 000 km. Test to test repeatability was improved on the transient world-harmonized cycle. Due to restrictive availability of this bike, a test vehicle was chosen with 8 000 km. As there was no control of the operation of the motorcycle over this period, it is possible that the style or period of mileage accumulation may have had an impact on emissions performance. Although used, bike A still met the emission limits requirements.

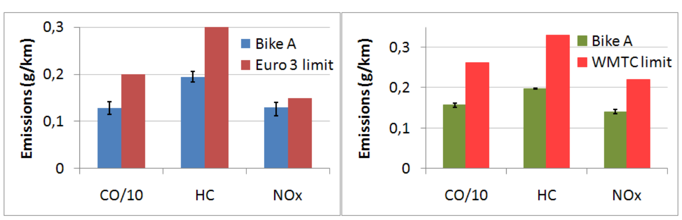

Figure 6: Bike A emissions
(left: Euro 3, right: WMTC)

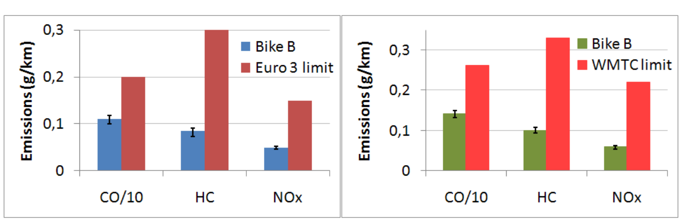

Figure 7: Bike B emissions
(left: Euro 3, right: WMTC)

Bike B had low emissions of HC and NOx (Figure 7), both on the Euro 3 and WMTC cycles.

Bike C was a very low emissions vehicle with all CO, HC and NOx limits passed easily (Figure 8). All three repeat tests also passed WMTC at less than 40% of the limit. Some test to test variability was observed on Euro 3 test cycle, especially on NOx results where the error bar is larger.

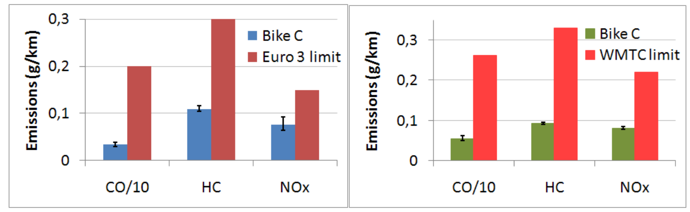

Figure 8: Bike C emissions
(left: Euro 3, right: WMTC)

Bike D exhibited some erratic behavior when tested according to the same test protocol, being extremely sensitive to small variations and to fuel composition. As a result, special preconditioning of 5 km at 120 km/h, recommended by the manufacturer, was conducted. As there is no defined provision for preconditioning in the Directive 2006/72/EC [2], this specific procedure set by the manufacturer still meets the legislative requirements. Using reference fuel and the manufacturer's prescribed preconditioning cycle, the bike showed generally good Euro 3 passes, particularly for HC (Figure 9). Similar trends between the Euro and WMTC cycles were observed, with a particularly large margin for HC.

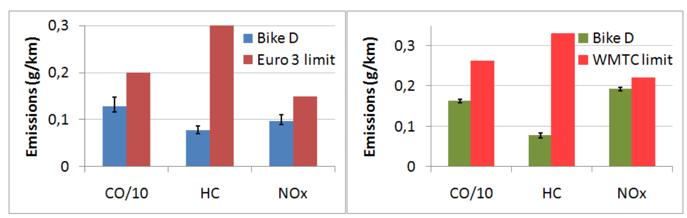

Figure 9: Bike D emissions
(left: Euro 3, right: WMTC)

Due to its top speed and engine displacement (<150 cc) the Indian bike E was not required to complete the EUDC section of the Euro 3 cycle and was also tested with the reduced speed WMTC. Nevertheless, Figure 10 shows the bike exhibited high HC and very high NOx emissions at 139% of Euro 3 and 265% of WMTC limits.

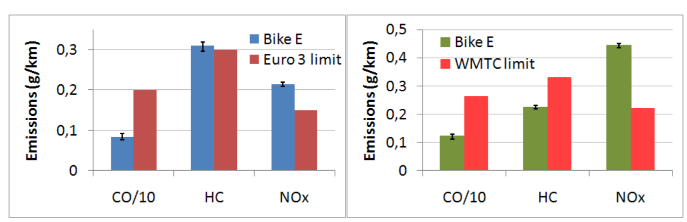

Figure 10: Bike E emissions
(left: Euro 3, right: WMTC)

The poor control of NOx emissions can be explained by the lean fuelling calibration of the Indian motorcycle which Air: Fuel Ratio (AFR) is oscillating and far from lambda 1. The AFR measured during Euro 3 test cycle on the Indian bike E was plotted against the AFR of a similar European bike of the same manufacturer (Figure 11). Both motorcycles use secondary air injection as part of the aftertreatment system but after warm-up, the Indian bike AFR oscillates between 16 and 18 to 1 while the European bike stays between lambda 1 and AFR 16 to 1 for most of the time.

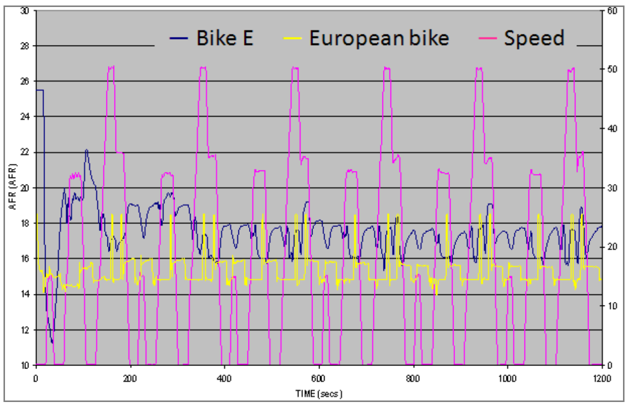

Figure 11: AFR Comparison of bike E vs. European similar bike

EURO 2 vs. EURO 3 MOTORCYCLES

In the previous test program [3], Euro 2 specification bikes A and C were tested to the Euro 3 and WMTC test cycles. Figure 12 compares the emissions of these bikes in Euro 2 and 3 specifications on the Euro 3 test cycle.

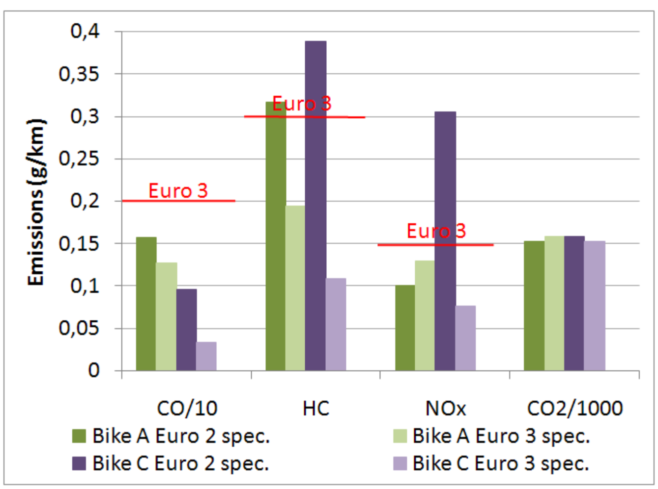

Figure 12: Euro 2 vs. Euro 3 bikes emissions on Euro 3 test cycle

Bike C shows a significant improvement in emissions between Euro 2 and 3 versions. Also, the Euro 3 specification bike C had lower emissions levels than bike A for all 3 legislated gases. Bike C showed reductions in all gases, including CO_2, indicating a potential improvement in combustion system. Comparison of the data shows that bike A had lower NOx and CO_2 emissions results in the Euro 2 specification. This could be the results of mileage accumulation of the Euro 3 motorcycle or a change in calibration or a combination of both. The NOx level increased from Euro 2 to 3 on bike A although it remained below the Euro 3 limit level.

Figure 13 shows comparative emissions of these bikes tested on the WMTC. General trends are the same as those observed on Euro 3 cycle, except that bike A displays smaller relative improvements in CO and HC on the WMTC cycle. The CO_2 trend on bike A is very different on the WMTC compared to Euro 3 cycle and reduces relative to the Euro 2 specification model.

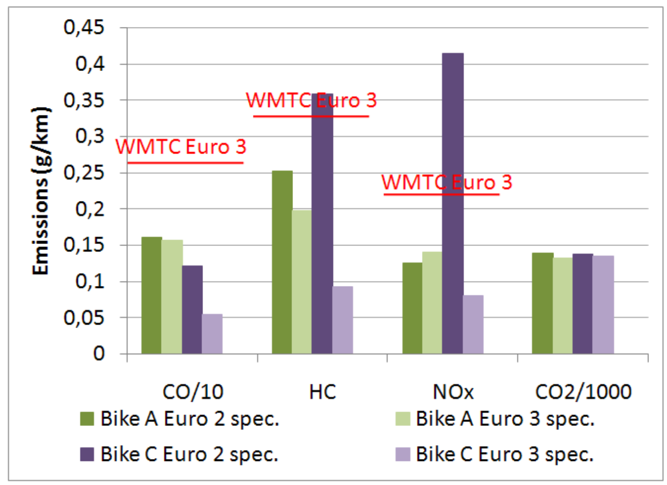

Figure 13: Euro 2 vs. Euro 3 bikes emissions on WMTC

EURO 3 TO WMTC CORRELATION

For the four Euro 3 motorcycles, the WMTC emission results are plotted against the Euro 3 measurements in Figure 14. A reasonable level of correlation was obtained, especially for HC and CO, allowing WMTC limits to be derived from Euro 3 values.

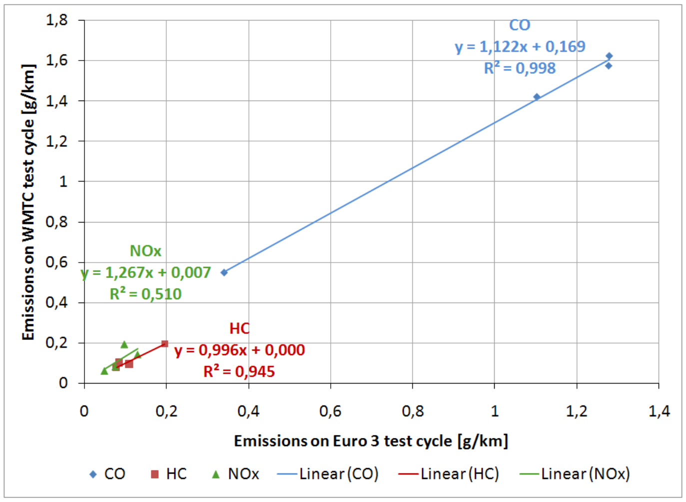

Figure 14: Correlation between Euro 3 and WMTC

Possible WMTC limits had been extrapolated from the previous test program run on Euro 2 motorcycles by multiplying Euro 3 limits by the average WMTC/Euro 3 measured emissions ratio for each pollutant. A similar extrapolation of WMTC limits based on results from the Euro 3 motorcycles are shown in Table 4 below; they confirm that WMTC limits defined by the European Union in Directive 2006/72/EC remain appropriate for Euro 3 motorcycles.

[g/km]	2004 AECC Test Program Extrapolation (5 Euro 2 bikes data set)	WMTC Limits	2008 AECC Test Program Extrapolation (4 Euro 3 bikes data set)
HC	0.256	0.33	0.299
CO	2.038	2.62	2.447
NOx	0.217	0.22	0.197

Table 4: WMTC limits and extrapolations

COMPARISON TO PASSENGER CAR EMISSIONS LIMITS

Euro 3 emission cycles results were re-calculated to give a comparison with the European passenger car emissions requirement. The NEDC test cycle for cars is slightly different from the Euro 3 motorcycle one: 4 ECE-15 (urban subcycles) followed by the EUDC (extra-urban) driving element for cars but 6 ECE-15 followed by the EUDC for motorcycles. Bag data was available for each Euro 3 test. The first bag covered ECE_1 and ECE_2, the cold start urban phase, the second bag covered $ECE_{3,4,5 \text{ and } 6}$, the hot urban phase and the third bag covered the EUDC. As the emissions during the four elements on the hot urban phase are similar the value may be divided by two to provide an equivalent to the passenger car cycle emissions when combined with the cold start and EUDC elements.

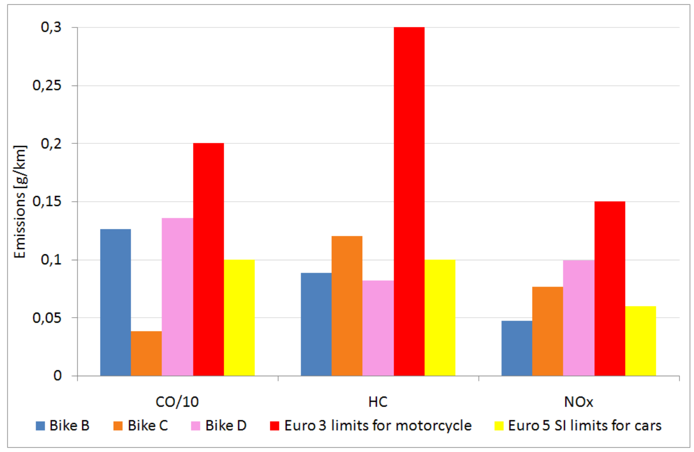

Figure 15: Recalculated equivalent NEDC emissions from Euro 3 motorcycles

Bag data was not available to recalculate NEDC-equivalent emissions for bike A. Euro 5 passenger car emission limits are significantly lower than the Euro 3 limit for motorcycles. However, when data for three of the Euro 3 motorcycles is recalculated to the NEDC equivalent, the motorcycle emissions are close to Euro 5 at the mileages they were tested (Figure 15).

PARTICLE NUMBER AND PARTICULATE MASS

Particle numbers emissions in #/km were calculated from $\#/cm^3$ concentrations across the entire cycle using CVS flow and cycle distance. Figure 16 shows particle number emissions per phase, for the total Euro 3 cycle, and a NEDC-equivalent calculation to allow comparison to the Euro 5 diesel passenger car limit of 6×10^{11} /km. Cold start generally showed highest PN emissions but all the Euro 3 motorcycles emitted fewer particles than the 6×10^{11} /km diesel passenger car Euro 5 limit on the recalculated NEDC.

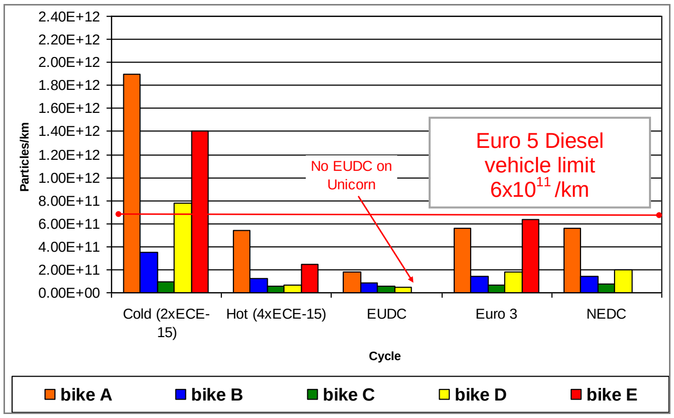

Figure 16: Particle number emissions on European cycles

Figure 17 shows particle number emissions per phase for total WMTC, unweighted and weighted. Again, cold start generally shows highest emissions. WMTC emissions did not exceed 10^{12} /km for any of the bikes.

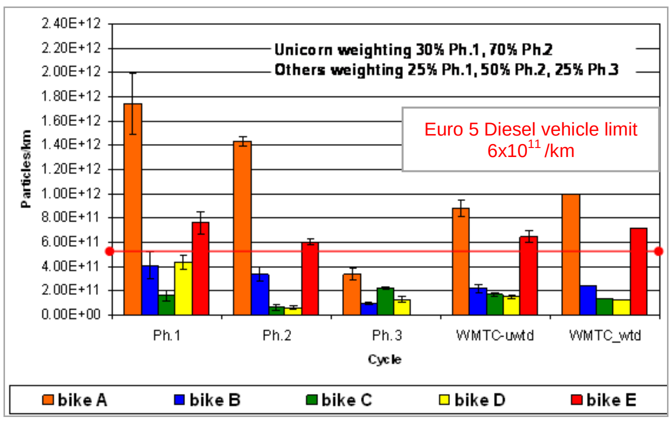

Figure 17: Particle number emissions on WMTC

The effect of rich running on bike A was determined by causing open loop operation, during urban driving phase of NEDC, through interference with the O_2 sensor signal. Figure 18 shows that rich operation leads to elevated particle numbers and to the presence of visible soot in the PM. Particle number emissions from rich tests exceeded 10^{12} /km while lambda 1 operation led to particle numbers around 5×10^{11} /km.

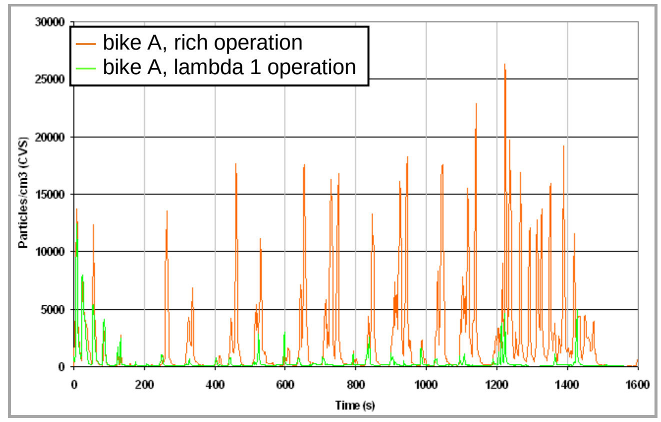

Figure 18: Bike A particle emissions under rich and lambda 1 operation

Figures 19 and 20 below show particulate mass (PM) measured on Euro 3 cycle and WMTC respectively.

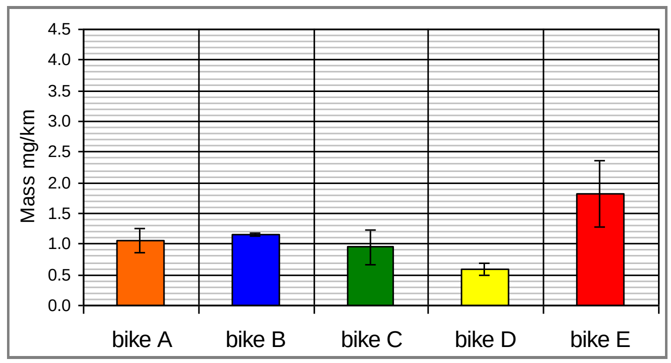

Figure 19: PM emissions on Euro 3 cycle

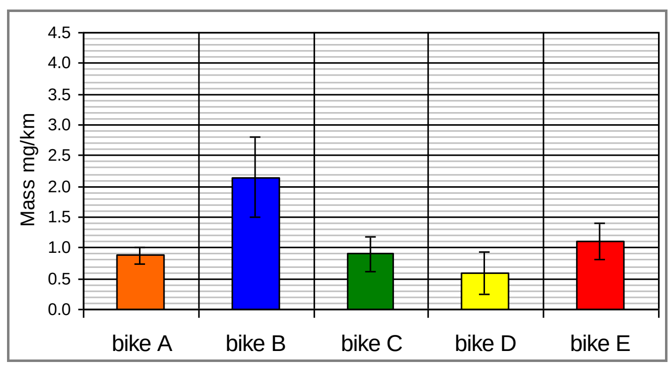

Figure 20: PM emissions on WMTC

Generally, similar mass levels were observed from all motorcycles on both WMTC and Euro 3 cycles. The particulate mass always remained below 2.5 mg/km, indicating emissions levels below the 4.5 mg/km level required for Euro 5 DPF-equipped Diesel and GDI cars.

Particulates were collected for elemental analysis on one test per motorcycle for each cycle. Elemental carbon was only present at trace levels (similar to blank) in PM from all bikes. Bikes A and D showed light grey filters on both cycles while all other filters remained white. In all cases, the absolute mass level of elemental carbon was low with fractions from 0.2 mg/km to 0.6 mg/km. Oil HC appeared to be a major contributor, sometimes up to 80% of the total PM, and may be a contributor to solid particle numbers. Trace levels of anions were detected as sulphates and nitrates.

PHASE 2 – DURABILITY RESULTS

The scooter D previously tested was selected for durability evaluation. Mileage accumulation was carried out using pump grade 95 RON gasoline and the periodic emissions tests performed with European specification reference fuel. Figures 21 to 23 show CO, HC and NOx emissions evolution throughout the mileage accumulation with Euro 3 limits two times the limits also plotted. In addition, particle and fuel consumption measurements are shown in Annex 2. The scooter's calibration proved to be not very robust and some slight fuel consumption variations were observed during the mileage accumulation. Nevertheless, it was possible to achieve 3 repeats of emissions tests at 6 consecutive steps: start, 2000 km, 5000 km, 10000 km, 15000 km and 20000 km.

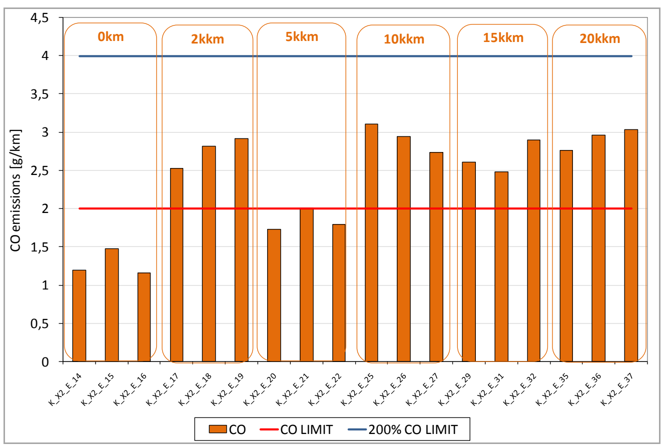

Figure 21: CO emissions measured on Euro 3 cycle

The unexpected lower CO emissions at 5000 km seems to reflect the general variability of this machine.

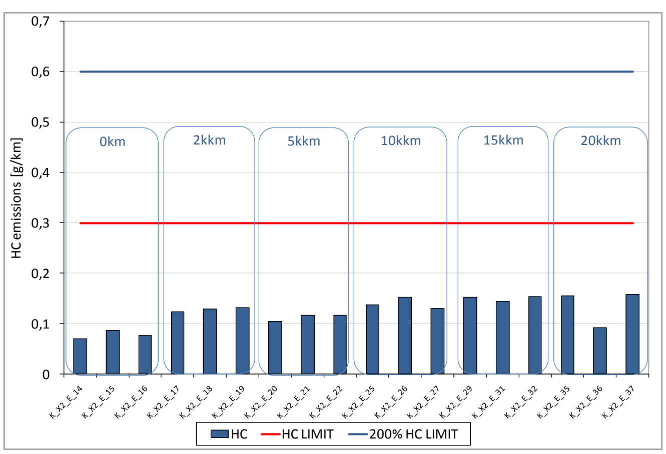

Figure 22: HC emissions measured on Euro 3 cycle

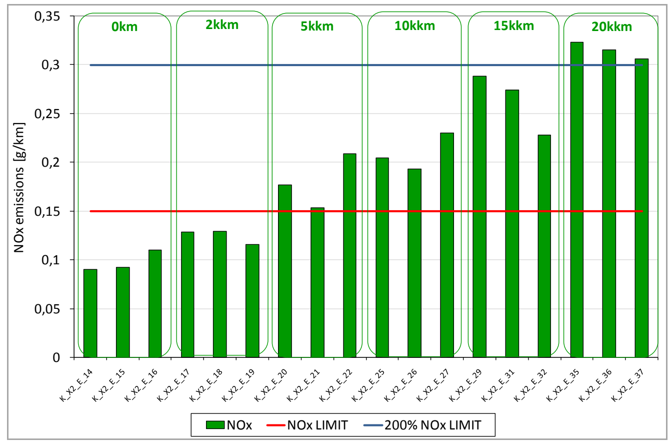

Figure 23: NOx emissions measured on Euro 3 cycle

The Euro 3 certified scooter exceeded CO emissions limit after only 2000 km and NOx emissions limit after only 5000 km. Durability was stopped at 20000 km as NOx emissions had reached twice the Euro 3 limit. Figure 24 shows that NOx emissions increased linearly across the mileage accumulation exercise. Air:fuel ratio plots did not show any significant drift in calibration throughout mileage accumulation, so NOx emissions increase is likely to be linked to rapid degradation of this particular catalyst.

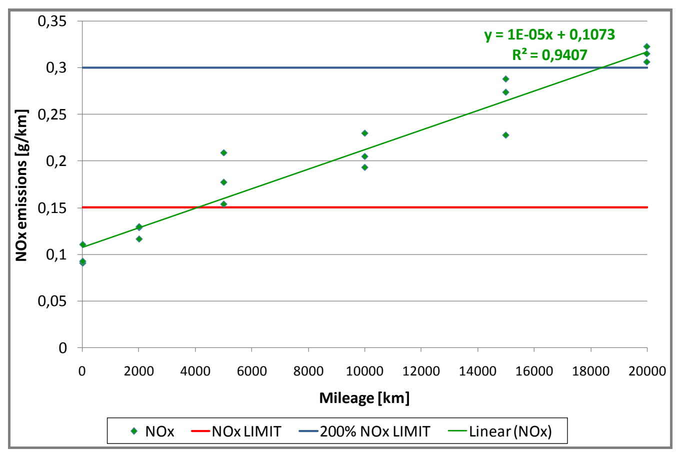

Figure 24: NOx emissions measured on Euro 3 cycle

Particulate mass and number remained stable across the durability testing. All PM mass measurements were below 4.5 mg/km and particulate numbers remained stable below $6x10^{11}$ /km, the Euro 5 diesel passenger car limit.

CONCLUSIONS

The emissions performance evaluation of five state-of-the-art motorcycles showed that all Euro 3 certified models met both Euro 3 and WMTC limits when tested in relatively new condition.

WMTC generally exhibits better repeatability when compared to Euro 3 cycle and WMTC vs. Euro 3 correlation established on four motorcycles confirms the WMTC limits.

The motorcycle emissions results were close to Euro 5 passenger car limits at the mileages tested.

Comparison to a previous test program showed that significant improvements have been made to emissions from Euro 2 to Euro 3 bikes. Particle mass levels below the Euro 5 diesel limit of 4.5 mg/km were measured on all bikes and lambda 1 bikes demonstrated similar particle number emissions to DPF equipped diesel passenger cars over the NEDC.

The durability exercise demonstrated a certified Euro 3 motorcycle could have emissions exceeding the limits after only 2 000 km, which highlights the need for improved durability requirements in future legislation.

ACKNOWLEDGEMENTS

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[1] ECE/TRANS/180/Add.2 Global technical regulation n°2 Measurement procedure for two-wheeled motorcycles equipped with a positive or compression ignition engine with regards to the emission of gaseous pollutants, CO_2 emissions and fuel consumption, 2005.

[2] Commission Directive 2006/72/EC amending for the purposes of adapting to technical progress Directive 97/24/EC of the European parliament and of the Council on certain components and characteristics of two and three-wheel motor vehicles.

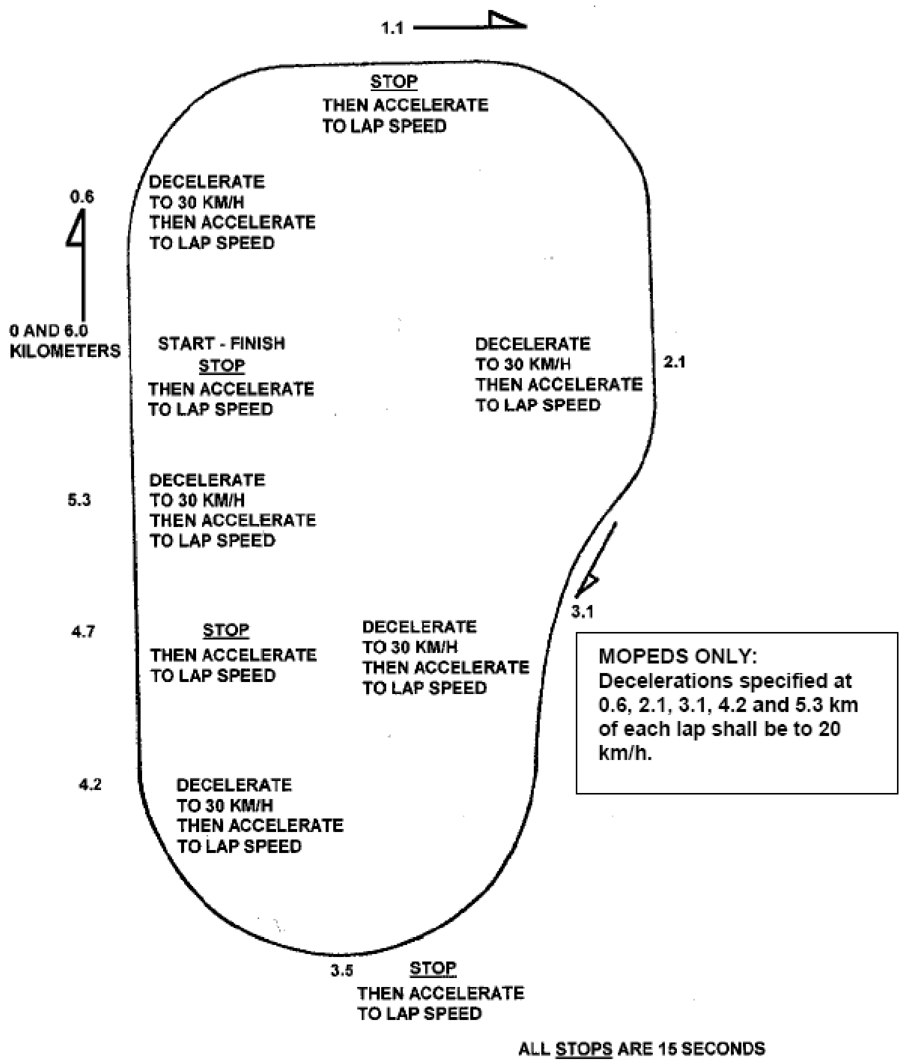
[3] Bosteels, D.; May, J.; Etheridge, P.; DeSouza, I.; Lance, D. “An investigation into the challenges of achieving future legislative limits over Euro 3 and WMTC drive cycles for current state-of-the-art motorcycle technology”; SAE 2005-01-2156.

[4] UN-GRPE PMP Phase 3 Inter-laboratory Correlation Exercise: Framework and Laboratory Guide, A Document For The UK Department for Transport. Ricardo Document RD04/80801.5 Jon Andersson and David Clarke

[5] John May; Dirk Bosteels; Chris Such; Andrew Nicol; Jon Andersson “Heavy-duty engine particulate emissions: application of PMP methodology to measure particle number and particulate mass”; SAE 2008-01-1176.

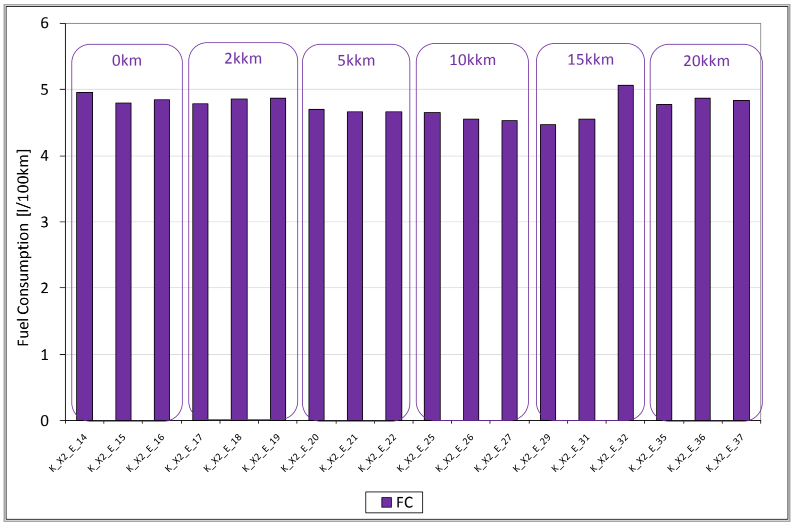
ANNEX 1

Moto69-ACEM durability proposal rev3

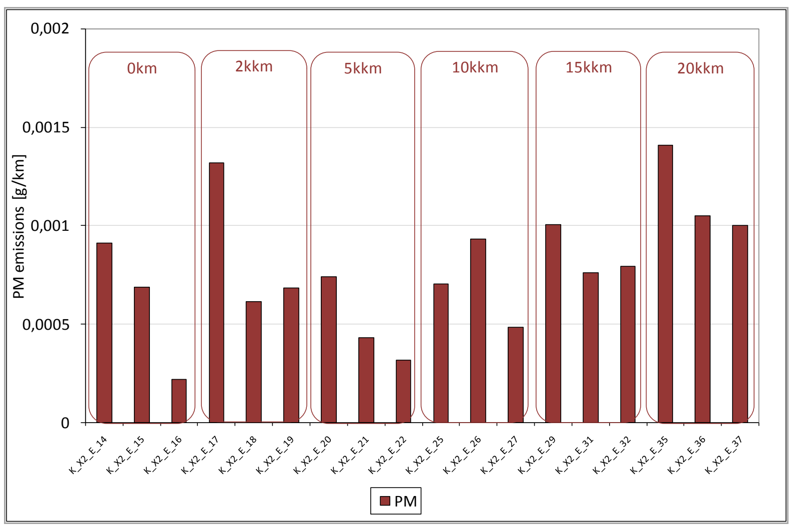


The durability cycle is composed of 11 cycles covering 6 km each.
During the first nine cycles, the vehicle is stopped four times in the middle of the cycle, with the engine idling each time for 15 s.
The 10th cycle is carried out at a steady state condition of 90 km/h.
The 11th cycle begins with maximum acceleration from stop point up to lap speed. At halfway, braking is employed normally until the vehicle stops. This is followed by an idle period of 15 s and a second maximum acceleration.

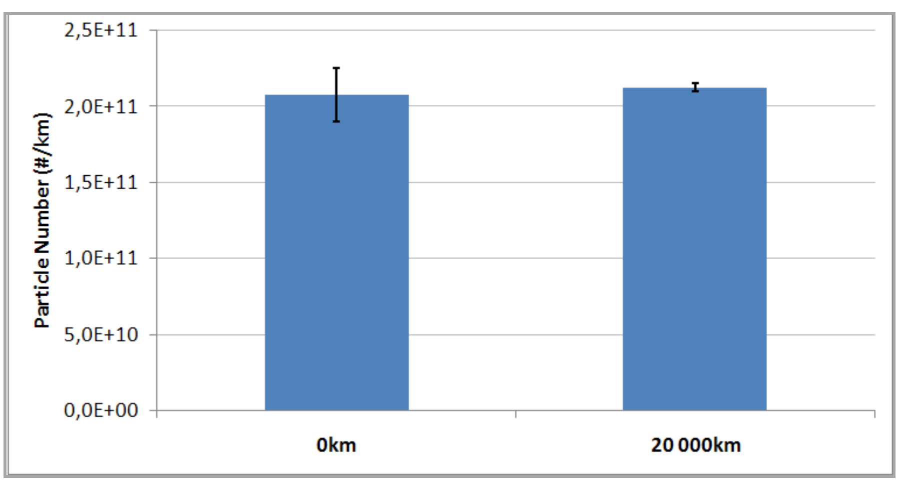
ANNEX 2



Fuel consumption measured on Euro 3 cycle with bike D during durability



Particulate mass emissions measured on Euro 3 cycle with bike D during durability



Particle number emissions measured on Euro 3 cycle with bike D during durability