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AN INVESTIGATION INTO THE CHALLENGES OF ACHIEVING FUTURE LEGISLATIVE LIMITS OVER EURO III AND WMTC DRIVE CYCLES FOR CURRENT STATE-OF-THE-ART MOTORCYCLE TECHNOLOGIES

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ABSTRACT

Motorcycle technologies will face increased challenges in the future, not only in terms of the emissions levels at Euro III which are much lower (at between a half to one third) than current levels, but also from the demands of future emission test cycles themselves which will be more severe, especially in respect to the ambient start requirements and the high speed elements of both the Euro III cycle and World Motorcycle Test Cycle (WMTC).

A representative selection of five larger capacity (>600cc) 'state of the art' Euro II level motorcycles were tested over future Euro III and World Motorcycle Test Cycles. The tests highlighted that NOx control will be critical for future motorcycle technologies; the WMTC especially produces high NOx in relation to the higher rates of acceleration, higher maximum speed and more transient nature of the cycle than current cycles. HC and CO emissions were also significantly influenced by the ambient start requirements of future cycles.

A further phase of work evaluated the performance of three state-of-the-art catalyst technologies as a replacement for the production system on one of the motorcycles. Initial tests showed that catalyst performance for NOx control was not as expected, and therefore an investigation into varying air-fuel ratio (AFR) was undertaken. Relatively small changes in AFR were shown to have a significant effect on NOx conversion. A final optimised AFR and catalyst build was defined which allowed Euro III emissions levels to be achieved.

INTRODUCTION

Directive 97/24/EC was issued by the European Parliament and the Council of the European Union in June 1997 to set emissions standards for two- and three-wheeled vehicles. Proposals have subsequently been submitted for tightening of the legislation in 2003 ("Euro II"), which led to the issue of directive 2002/51/EC [1], with a second stage for introduction from 2006. The 2006 requirements include the adoption of the urban (ECE, UDC) and extra urban drive cycle (EUDC), which has an ambient temperature start. This "Euro III" cycle, compared with the area over which Euro II measurements are taken, is shown in Figure 1 below.

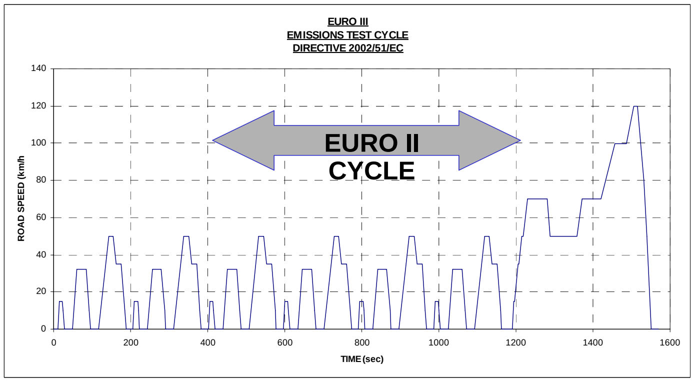

Figure 1: Euro III Emissions Test Cycle

There is a trend in many areas of the world for increased focus on motorcycle emissions and a general tightening of emissions [2]. The World Motorcycle Test Cycle (WMTC) (Figure 2), which is a three phase transient cycle (and is also an ambient temperature start), is meant to be more representative of actual on road driving conditions, and is under discussion to be introduced from 2006.

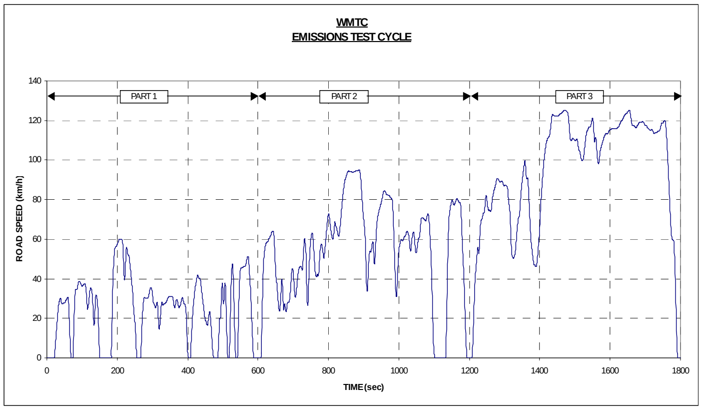

Figure 2: World Motorcycle Test Cycle (WMTC)

The limits for current and future emissions levels are shown in Table 1 below:

Introduction Date	Level	CO g/km	HC g/km	NOx g/km
1 June 2004 (all vehicles) >150cc	Euro II	5.5	1.0	0.30
1 January 2007 (all vehicles) >150cc *	Euro III *	2.0	0.3	0.15

* Equivalent values for WMTC are to be defined

Table 1: Current and Future Emissions Levels

Motorcycle technologies will therefore face increased challenges in the future, not only in terms of the emissions levels at Euro III which are much lower (at between a half to one third) than current levels, but also from the demands of future test cycles themselves which will be more severe, especially in respect of the ambient start requirements and the high speed elements of both the Euro III cycle and WMTC. Although some work has been undertaken recently to investigate AFR and cold-start effects on emissions [3,4], relatively little data have been published to date which assess the extent of the challenge faced by current motorcycle technologies [5,6].

OBJECTIVES

This programme aimed to evaluate the emissions performance of current state-of-the-art motorcycle technologies with respect to future emissions cycles and limit levels.

A further stage of the programme evaluated the potential benefit of replacing the production catalyst with three candidate novel catalysts to one motorcycle chosen from the initial phase of the programme.

TEST MOTORCYCLES AND TEST PROTOCOL

Five motorcycles were procured for the programme. The 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. The specifications of the motorcycles tested are summarised in Table 2:

Bike No.	Engine Size (cc)	EFI	Open/Closed Loop Control	SAI	Catalyst
1	600	Y	Closed	Y	Y (starter + main)
2	1150	Y	Closed	N	Y
3	800	Y	Closed	Y	Y(2)
4	1300	Y	Closed	N	Y(2)
5	1800	Y	Closed	Y	Y

Table 2: Test Motorcycle Specifications

Note: EFI = Electronic Fuel Injection SAI = Secondary Air Injection

The motorcycles were instrumented for exhaust emissions (raw and dilute), air/fuel ratio (AFR) (2 cylinders), sump oil temperature and exhaust system temperatures (engine out and pre/ post each catalyst).

Prior to testing, each motorcycle was run-in on marketplace 95 RON gasoline (<50ppm Sulphur) for 500 miles of on-road driving. The fuel was then changed to RF-02-03 (<10 ppm Sulfur) reference fuel for emissions testing.

The test protocol used was carefully controlled and ensured identical pre-conditioning and soaking periods for each vehicle. Each pre-condition and emissions test was conducted in a temperature controlled facility housing an electrical DC type single roller chassis dynamometer. The test protocol can be summarised as follows:

- Day 1 – Fuel change and pre-condition all motorcycles over Euro III test cycle
- Day 2 to Day 4 – Conduct Euro III emissions tests for all bikes (one test per bike per day)
- Day 5 – Condition all bikes over WMTC cycle
- Day 6 to Day 8 – Conduct WMTC tests for all bikes (one test per bike per day)

Thus, each bike was tested over triplicate Euro III and WMTC cycles.

Analysis of Regulated Emissions

Dilute exhaust emissions were sampled continuously in accordance with EC directive Chapter 5 Annex II 97/24/EC from the Constant Volume Sampler (CVS) and fed into the gas analysers as well as being sampled and collected into bags for analysis after the test. It is the emission results from the bag analyses that are produced as the test results and used for the subsequent comparisons. Results from continuous sampling are used by way of illustration of specific emissions results and the characteristics of particular technologies over the drive cycle.

Hydrocarbon (HC) emissions were analysed by flame ionization detection, carbon monoxide (CO) and carbon dioxide (CO2) emissions by non-dispersive infra red. NOx emissions were measured via a Thermo Electron chemiluminescence Series 10 analyser. No heating or cooling of the gas was undertaken before admission to the analyser .

Within this paper all data are converted from volume concentration to mass per km units. Data captured over the Euro III cycle was manipulated to exclude the first two ECE and the EUDC phases of the cycle, thereby providing additional “Euro II cycle” data for each bike for comparative purposes.

The bikes tested within this programme are all designated as Class 3, and results from the WMTC cycle have therefore been weighted according to current proposals as follows: Parts 1 and 3 contribute 25% each to the sum weighted mass result for each pollutant and Part 2 contributes 50%.

PHASE 1 - FUTURE DRIVE CYCLE RESULTS

The numerical data for the gaseous emissions presented in this section can be found in Appendix 1.

Repeatability – Repeatability of results was generally good over all cycles for all bikes. Bike 5 showed the highest level of variability with respect to CO emissions. Figure 3 below illustrates the three CO emissions results over the Euro III cycle for each bike.

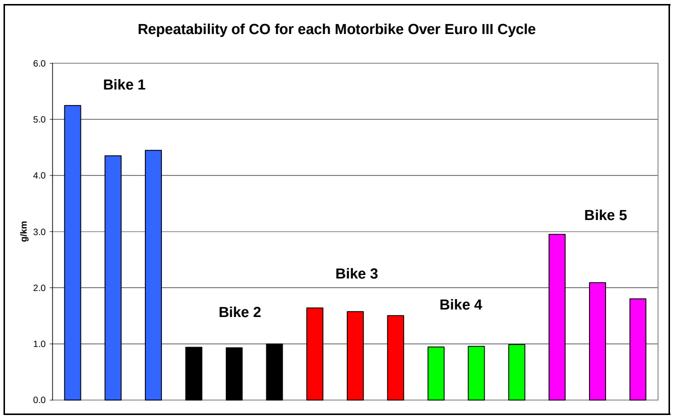

Figure 3: CO Emissions Repeatability, Euro III cycle

Hydrocarbon Emissions – Average hydrocarbon emissions are shown in Figure 4 below for all bikes for Euro II, Euro III and WMTC cycles respectively.

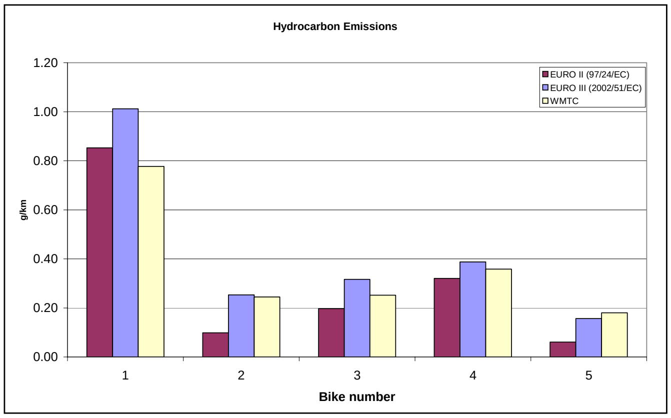

Figure 4: Average Hydrocarbon Emissions, Comparison of Cycles, All Bikes

All bikes met the Euro II regulated level of 1.0g/km. All bikes except bike 1 produced HC levels of <0.4g/km on all cycles, although only two bikes were comfortably within the Euro III limit of 0.3g/km.

It can be seen that the Euro III cycle produced highest HC emissions for most bikes. HC emissions are primarily associated with the early part of the cycle before the catalyst becomes effective, hence the Euro II cycle has an advantage for HC emissions due to the warm start.

Bike 1 produced the highest overall levels of HC; this bike tended to have the lowest exhaust temperatures of all bikes: temperatures in excess of 250°C are not reached until >350 secs into the cycle (Figure 5). Indeed, further examination of raw data showed the starter catalyst on this bike to be largely ineffective.

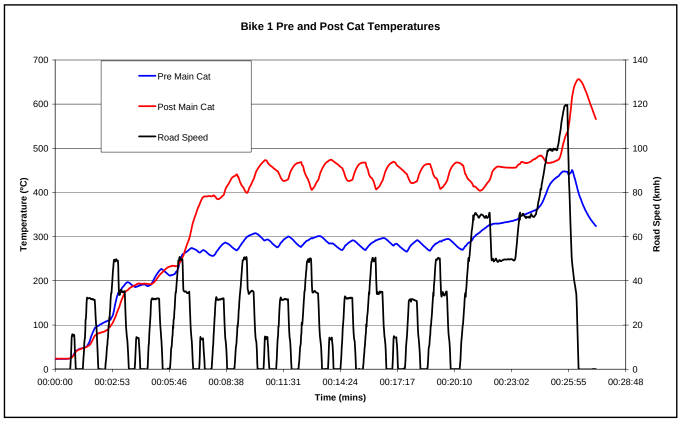

Figure 5: Pre and Post catalyst Temperatures, Bike 1

HC levels are also associated with fuel overrun on decelerations; again Bike 1 showed excessive HC overrun levels (Figure 6) and generally showed the poorest AFR control of all the bikes.

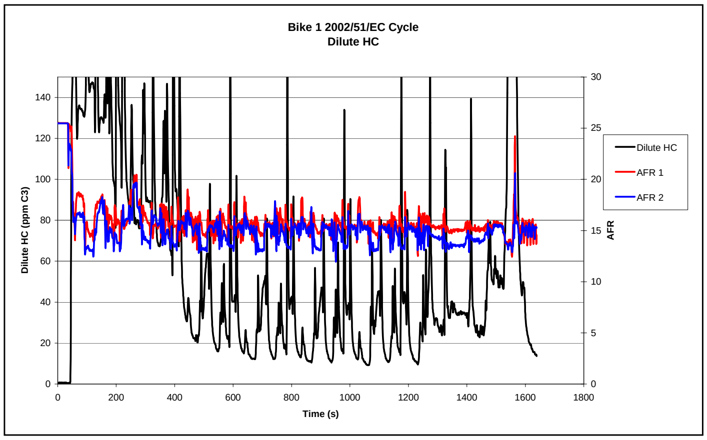

Figure 6: AFR (from 2 Cylinders) and dilute HC emissions, Bike 1, Euro III Cycle

CO Emissions – Carbon Monoxide (CO) emissions are shown in Figure 7 for all bikes. All bikes met the Euro II emissions level of 5.5g/km. However, the Euro III level of 2.0g/km is exceeded over future cycles by two of the bikes. Generally similar CO emissions were seen from Euro III and WMTC cycles.

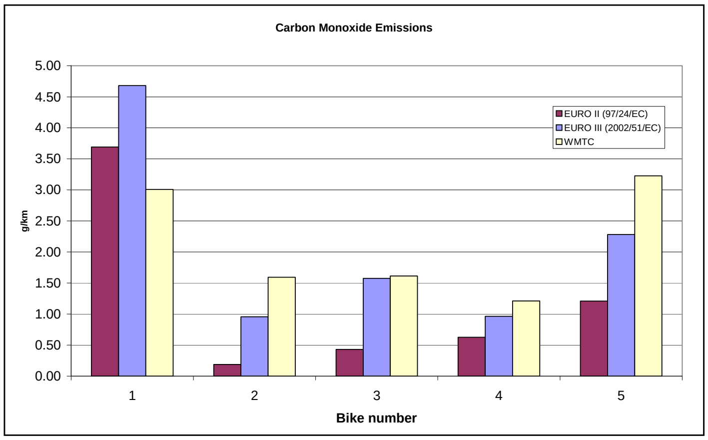

Figure 7: Average Carbon Monoxide Emissions, Comparison of Cycles, All Bikes

CO emissions can be highly dependent on fuelling calibration and engine size and power [5]. Further comments on the specific fuelling calibration of each machine are difficult, particularly for machines fitted with secondary air injection, as the precise control strategy employed for fuelling/SAI is not known. However, it is clear that generally transient fuel enrichment is used on these machines for good driveability. This is illustrated by the AFR trace for Bike 5 over the WMTC cycle, shown below in Figure 8.

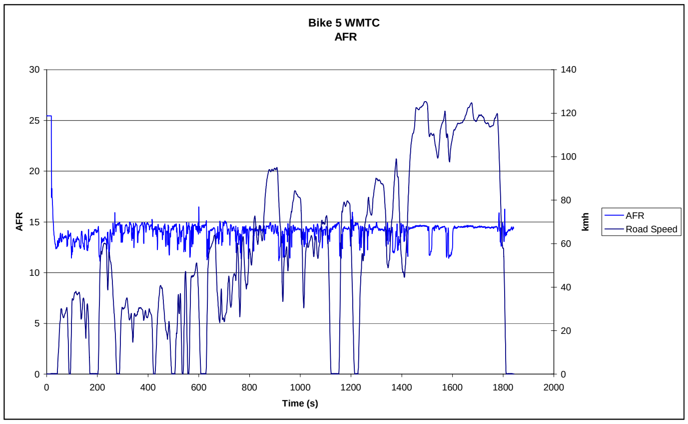

Figure 8: AFR over WMTC, Bike 5

NOx Emissions – The data for NOx emissions (Figure 9) show clear trends for different drive cycles but little differentiation between most bike technologies.

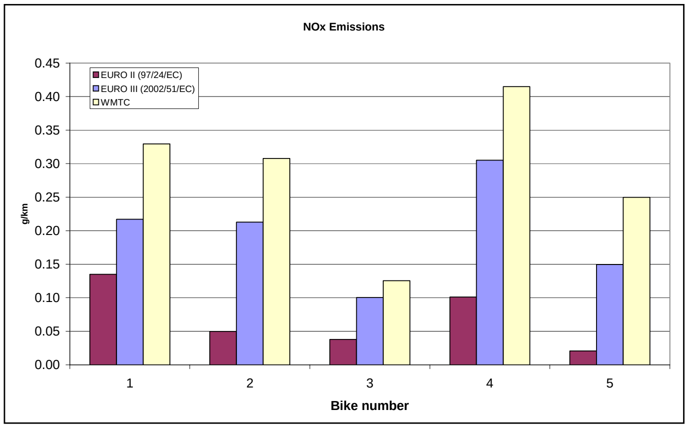

Figure 9: Average NOx Emissions, Comparison of Cycles, All Bikes

NOx emissions are clearly increased by the higher maximum speed, higher rates of acceleration and more transient nature of the WMTC cycle compared to Euro III cycle. The third phase of the WMTC cycle in particular is a challenge for emission control systems, producing up to 90% of total cycle NOx. For Bike 4, a greater than fourfold increase was seen over the WMTC compared to Euro II NOx levels (~0.1g/km vs >0.4g/km). With the Euro III NOx level set at 0.15g/km, clearly current Euro II level calibrations and emission control systems will require some significant development to meet the future NOx challenge.

The results obtained in Phase 1 indicated that there was scope for improvement of emissions, especially for NOx.

PHASE 2– FURTHER CATALYST INVESTIGATIONS

From the Phase 1 drive cycle screening results, Bike 2 was chosen as a suitable candidate for further investigations.

The production catalyst system was replaced by novel candidate catalyst technologies using a catalytic formulation similar to those used for Euro 4 passenger cars. Three catalysts were evaluated, the specifications of which are shown in Table 3 below. The physical size of the catalysts was constrained by the existing location and arrangement of the system. All three candidate catalysts were of the same external dimensions as the Original Equipment (OE) and fitted in the same location. The catalyst volume is approximately 40% of engine swept volume in each case.

Catalyst	Cell Density	Wall Thickness
Production	200cpsi	0.065mm
Cat 1A	200cpsi	0.065mm
Cat 2A	400cpsi	0.05mm
Cat 3A	600cpsi	0.04mm

Table 3: Catalyst Specifications

Catalyst performance was screened initially over the WMTC cycle. Three, or in some cases four, WMTC cycles were conducted for each catalyst.

Results for NOx and CO emissions for all WMTC tests are shown in Figures 10 and 11 respectively.

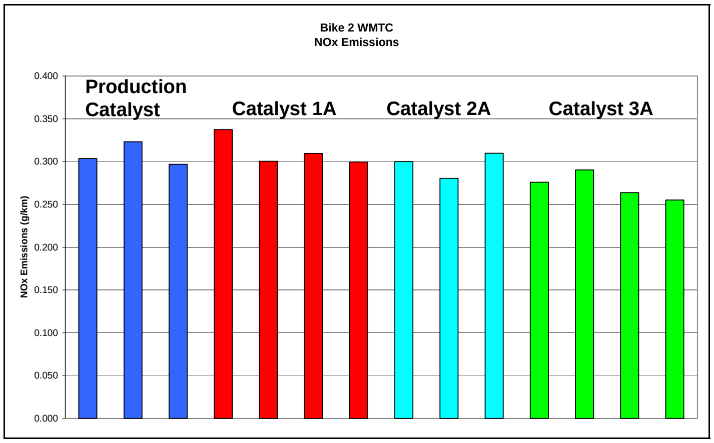

Figure 10: NOx Emissions, Comparison of Catalysts

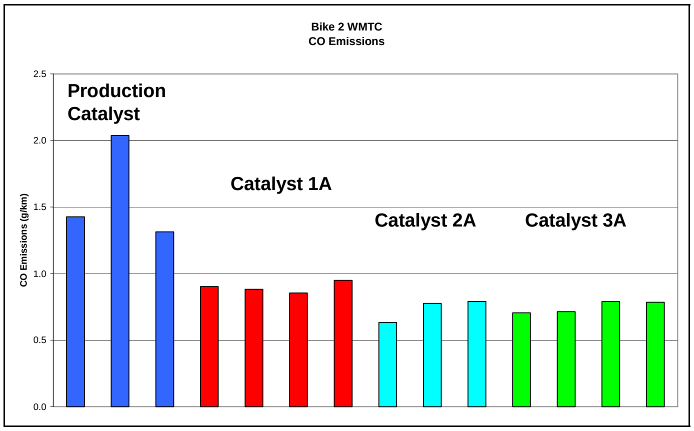

Figure 11: CO Emissions, Comparison of Catalysts

It can be seen that the NOx performance on the novel catalyst formulations was still not adequate to achieve the Euro III limit of 0.15g/km. Overall, Catalyst 3A gave the best NOx performance with average emissions of 0.27g/km. CO performance was comparable between Catalysts 2A and 3A, giving an average of ~0.74g/km compared to Catalyst 1A which achieved 0.90g/km.

MODIFIED AFR INVESTIGATION

Since NOx performance on the novel catalysts was poorer than expected, the results suggested that calibration, rather than factors such as space velocity, might be the critical factor. Therefore a further investigation was conducted to evaluate the potential NOx performance of an optimised system with a modified AFR setting.

Variable AFR was achieved using a fuel slew box fitted in-line between the electronic control unit (ECU) and the lambda sensor. This device uses a variable input potentiometer to control the speed of rich to lean fuel swings of the lambda sensor allowing both rich and lean conditions to be achieved. Several steady state tests and WMTC cycles were investigated in order to define a suitable AFR for optimum emissions conversion. All AFR measurements were recorded using the pre-cat AFR sensor (AFR 1). The various AFRs achieved are shown in Table 4 below:

CALIBRATION	SLEWBOX SETTING	TEST	AVERAGE AFR
Cal_01	NOT FITTED	100 km/h steady state, top gear	14.33
Cal_02	0	100 km/h steady state, top gear	14.34
Cal_03	153	100 km/h steady state, top gear	15.39
Cal_04	-160	100 km/h steady state, top gear	13.88
Cal_05	-80	100 km/h steady state, top gear	13.90
Cal_06	-80	100 km/h steady state, top gear	13.90
Cal_07	153	WMTC TEST CYCLE	15.25
Cal_08	0	WMTC TEST CYCLE	14.48
Cal_09	-80	WMTC TEST CYCLE	14.17
Cal_10	-40	WMTC TEST CYCLE	14.25

Table 4: Test Conditions and Different AFRs Investigated

NOx concentrations at over the WMTC cycle corresponding to different AFR conditions can be seen in Figure 12 below:

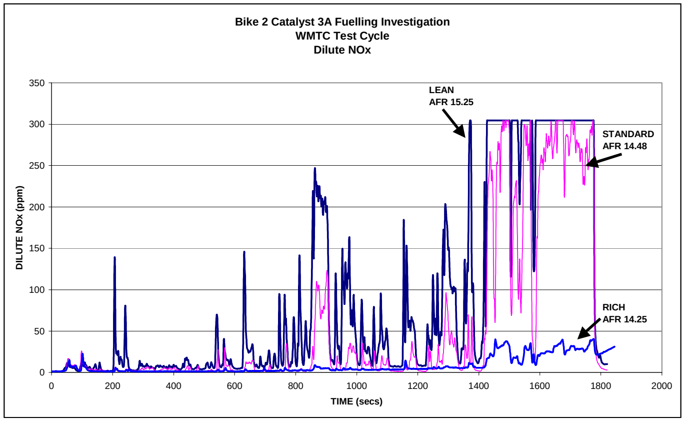

Figure 12: Dilute NOx at Different AFR; WMTC cycle

Control of NOx was far more effective at rich settings, especially over the final high speed portion of the WMTC cycle. Table 4 shows that the rich shifts made were relatively small compared to the standard setting.

Based on findings from the AFR investigations, a final build was defined of Catalyst 3A with an AFR shift of approximately 0.9% from the set point of 14.33 recorded during the 100km/h top gear steady state test.

Cumulative emissions data for the new build over the WMTC cycle is shown in Figure 13 below.

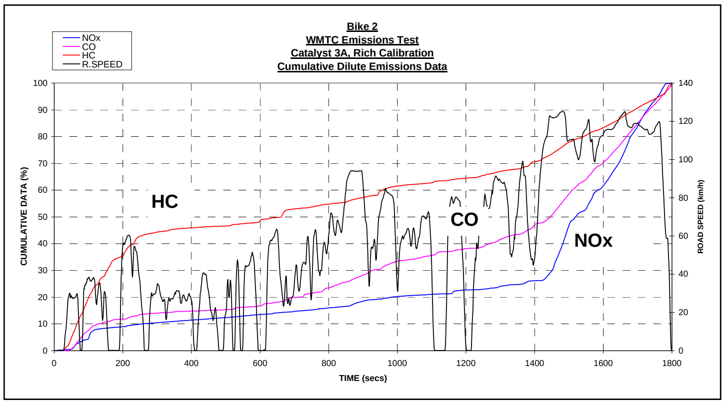

Figure 13: Cumulative Emissions Data, WMTC cycle

Emissions results for the new build are shown in Table 5 below. NOx was drastically reduced compared to the standard build and is well within the Euro III limit of 0.15g/km. CO emissions were increased with the new build over the WMTC (~2.2g/km compared to ~1.1g/km on the standard build), to just over the Euro III level of 2.0g/km.

Test Cycle	HC g/km	NOx g/km	CO g/km	CO2 g/km	F/Con l/100km
WMTC	0.229	0.030	2.373	134.0	5.762
WMTC	0.207	0.024	2.069	131.9	5.672
WMTC	0.213	0.027	2.240	133.1	5.722
Average	0.216	0.027	2.228	133.0	5.719
2002/51/EC	0.218	0.014	1.098	149.4	6.480
2002/51/EC	0.203	0.015	1.058	145.4	6.305
2002/51/EC	0.220	0.016	1.096	144.2	6.258
Average	0.214	0.015	1.084	146.3	6.348
97/24/EC	0.063	0.001	0.351	185.5	7.417
97/24/EC	0.058	0.001	0.288	172.9	7.405
97/24/EC	0.070	0.001	0.257	173.1	7.948
Average	0.064	0.001	0.299	177.2	7.590

Table 5: Emissions Results for Catalyst 3A, Rich Build

Figure 14 shows how the slight rich shift gives large reductions in NOx, especially over the third phase of the WMTC, compared to the standard build.

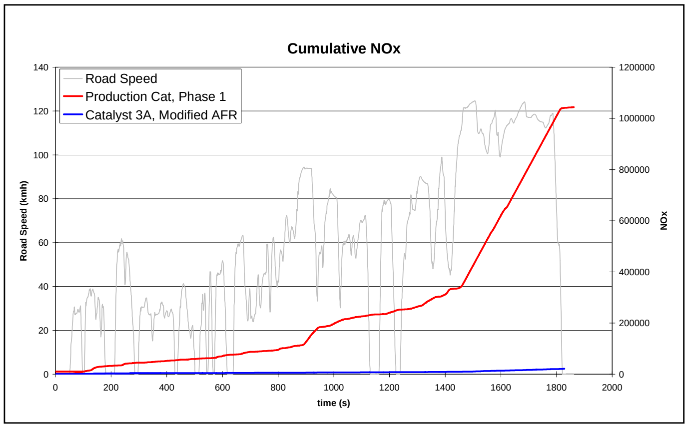

Figure 14: Cumulative NOx, Comparison of Standard versus Rich Build

CONCLUSIONS

The program investigated the effects of future drive cycle requirements on current state-of-the art motorcycle technologies. A further phase of work identified the effects of novel catalyst formulations and AFR, specifically on the control of NOx over future drive cycles.

The main conclusions of the program are as follows:

Demands of future cycles will provide challenges for NOx control, associated primarily with the higher maximum speed and more transient nature of these cycles compared to the current Euro II cycle.

HC and CO emissions were also significantly influenced by the ambient start requirements of future cycles.

Novel catalyst formulations showed good potential for improved control of NOx, CO and HC over future cycles.

An optimised build was identified utilising Catalyst 3A and an AFR rich shift of ~0.9% compared to standard build. This relatively modest shift in lambda, combined with the most promising candidate catalyst, enabled very low levels of NOx emissions which were well within the Euro III limit of 0.15g/km.

The modified AFR setting gave a CO emissions penalty over the WMTC cycle, increasing the levels to just over the Euro III limits of 2.0g/km.

ACKNOWLEDGMENTS

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APPENDIX 1 – EURO III and WMTC EMISSIONS RESULTS, ALL BIKES

	HC	NOX	CO	CO2	F/Con
Test Cycle	g/km	g/km	g/km	g/km	l/100km
Bike 1					
2002/51/EC	1.012	0.217	4.682	159.6	7.264
97/24/EC	0.853	0.135	3.692	205.9	9.152
WMTC	0.777	0.329	3.010	134.9	6.063
Bike 2					
2002/51/EC	0.253	0.213	0.956	159.4	6.902
97/24/EC	0.099	0.050	0.188	200.8	8.598
WMTC	0.244	0.308	1.592	138.9	6.067
Bike 3					
2002/51/EC	0.317	0.100	1.575	152.2	6.646
97/24/EC	0.197	0.038	0.430	198.3	8.519
WMTC	0.252	0.125	1.614	139.4	6.094
Bike 4					
2002/51/EC	0.388	0.305	0.963	158.4	6.875
97/24/EC	0.320	0.101	0.626	205.8	8.867
WMTC	0.359	0.415	1.210	137.1	5.978
Bike 5					
2002/51/EC	0.157	0.150	2.282	156.3	6.845
97/24/EC	0.061	0.021	1.207	199.5	8.606
WMTC	0.180	0.250	3.227	137.2	6.098

APPENDIX 2 – CATALYST SCREENING AND RICH CALIBRATION EMISSION TEST RESULTS

SUM MASS EMISSIONS

TEST	TEST NO.	CAT I.D.	WEIGHTED	HC	NOX	CO	CO2	F/Con
CYCLE				g/km	g/km	g/km	g/km	l/100km
WMTC	ph2_w_12	CAT 3A	Y	0.229	0.030	2.373	134.0	5.762
WMTC	ph2_w_13	CAT 3A	Y	0.207	0.024	2.069	131.9	5.672
WMTC	ph2_w_14	CAT 3A	Y	0.213	0.027	2.240	133.1	5.722
WMTC	Average	CAT 3A	Y	0.216	0.027	2.228	133.0	5.719
2002/51/EC	ph2_e_01	CAT 3A	N	0.218	0.014	1.098	149.4	6.480
2002/51/EC	ph2_e_02	CAT 3A	N	0.203	0.015	1.058	145.4	6.305
2002/51/EC	ph2_e_03	CAT 3A	N	0.220	0.016	1.096	144.2	6.258
2002/51/EC	Average	CAT 3A	N	0.214	0.015	1.084	146.3	6.348
97/24/EC	ph2_e_01	CAT 3A	N	0.063	0.001	0.351	185.5	7.417
97/24/EC	ph2_e_02	CAT 3A	N	0.058	0.001	0.288	172.9	7.405
97/24/EC	ph2_e_03	CAT 3A	N	0.070	0.001	0.257	173.1	7.948
97/24/EC	Average	CAT 3A	N	0.064	0.001	0.299	177.2	7.590

WMTC

WEIGHTED SUM MASS EMISSIONS

TEST NO.	CAT I.D.	HC	NOX	CO	CO2	F/Con
		g/km	g/km	g/km	g/km	l/100km
ph2_w_01	CAT 1A	0.186	0.337	0.903	134.2	5.677
ph2_w_02	CAT 1A	0.165	0.300	0.882	134.0	5.671
ph2_w_03	CAT 1A	0.188	0.309	0.855	134.4	5.667
ph2_w_11	CAT 1A	0.205	0.300	0.950	135.2	5.729
Average	CAT 1A	0.186	0.312	0.898	134.4	5.686
ph2_w_04	CAT 2A	0.143	0.300	0.633	136.6	5.741
ph2_w_05	CAT 2A	0.166	0.280	0.777	137.1	5.782
ph2_w_06	CAT 2A	0.157	0.310	0.791	147.2	5.800
Average	CAT 2A	0.155	0.297	0.734	140.3	5.774
ph2_w_07	CAT 3A	0.134	0.276	0.706	137.8	5.812
ph2_w_08	CAT 3A	0.131	0.290	0.715	135.6	5.722
ph2_w_09	CAT 3A	0.137	0.264	0.789	136.9	5.765
ph2_w_10	CAT 3A	0.145	0.255	0.785	135.7	5.726
Average	CAT 3A	0.137	0.271	0.749	136.5	5.756