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ABSTRACT

This paper discusses the development of a new approach to achieving EURO 4 emission standards with a simplified exhaust after-treatment system in combination with an air-assisted lean stratified Direct Injection system.

The results presented demonstrate the ability of the air-assist DI system to operate in highly stratified conditions at very lean A/F ratios, with excellent control of the raw HC and NOx emissions. In most cases the authors illustrate that with good stratified combustion control, the HC emissions can be lower than the baseline port injected stoichiometric engine. Further, the high tolerance to EGR and accurate A/F control at the spark plug enable the raw NOx emissions to be reduced by up to 85% over the European drive cycle in comparison to the baseline port injected engine with EGR.

The vehicle calibration strategy is discussed in detail, with particular attention being paid to the catalyst light-off strategy developed for the air-assist system, which enables feed exhaust gas temperatures to reach 600ºC during the first 10 second idle period, while also maintaining good control of raw emissions. Also highlighted is the development of the ability to control canister vapour purge throughout both lean stratified and stoichiometric operation. This further enables good control of HC emissions while maintaining a high purge flow through the catalyst, independent of any specific catalyst regeneration requirements.

The low raw emissions of the vehicle are then applied to a single underbody catalytic converter located 1.3m from the cylinder head face. This was fitted with a combination of three-way and lean NOx traps, which had been aged under lean hydrothermal conditions. The authors discuss the systematic approach applied to the catalyst choice, in combination with the understanding of the air-assist DI modal raw HC and NOx emissions. In particular, the very low raw NOx emission burden during stratified operation is discussed, which enabled a reduced reliance on the Lean NOx trap (hereinafter LNT) storage function. Euro 4 emissions compliance is demonstrated with aged catalysts where the degradation of NOx emissions is considered to be very low, due to reduced reliance on the NOx catalyst efficiency.

The results show how, with a systematic approach, the combined ability of the underbody TWC/LNT catalyst and air-assist DI combustion system can meet future emissions standards.

1. INTRODUCTION

The application of gasoline direct injection is being increased steadily with the aim of reducing fuel consumption. However, this has to occur hand in hand with increasingly stringent requirements for both gaseous and evaporative emissions. The problem is that many current direct injection systems suffer from increased raw engine emissions levels, which leads to a high dependence on the exhaust after-treatment system. Not only are raw emissions higher, but exhaust gas temperatures are typically lower when running lean which is not conducive to high catalyst conversion efficiency. Added to this is the fact that when running lean, NOx reduction becomes difficult in comparison to conventional port injected engine after-treatment systems.

The challenge is to achieve reduced fuel consumption while achieving the emissions requirement, but with a simplified cost effective after-treatment system. The Orbital Combustion Process (OCP) using a combination of air-assisted direct injection with a spray guided or jet combustion system makes it possible to achieve large reductions in fuel consumption while concomitantly having low raw engine emissions levels. In earlier work (1) a TWC-only type solution was investigated with some success. In this case EURO 3 emissions levels could be achieved with a margin down to EURO 4 emissions levels. The after-treatment strategy applied was to provide low NOx levels during light load operation so as not to need large amounts of post treatment and at high loads to use conventional TWC reduction. In this case the NOx reduction occurred by three mechanisms, selective reduction at low temperatures, some level of NOx storage and conventional TWC reduction at lambda 1 conditions. However, in order to meet EURO 4 emissions levels, more NOx storage/reduction capability was required.

In the following paper the after-treatment system chosen was a storage and release type catalyst combined with either a conventional TWC catalyst or oxidation only catalyst, all mounted in the same catalytic converter. One of the specific requirements of storage and release type catalysts is to operate the catalyst in a relatively low temperature band for high storage efficiency (3-10). This provides the need to mount the storage part of the catalyst some distance from the engine. This requirement has an adverse effect on catalyst light off during cold start. However, using the Orbital catalyst light off strategy, it is possible to mount the catalyst in a typical underbody position (1300mm from cylinder head) and achieve high catalyst temperatures quickly.

Storage and release type catalyst typically put a high demand on the engine management system requiring sophisticated algorithms to allow switching from a lean to rich conditions with constant torque when purging the catalyst; this process is commonly termed regeneration. The negative effect of regeneration is increased fuel consumption. This provides the incentive, if possible, to avoid specific regeneration.

Another issue facing lean burn applications is the ability to purge the evaporative emission system sufficiently during lean operation due to reduced manifold vacuum. If conventional purge techniques are applied during lean/stratified running, then increased raw HC emissions will occur. If insufficient vacuum is available, it may be necessary to revert to a more homogeneous type of operation to purge the canister, with the net effect of increased fuel consumption.

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1.1 ENGINE CONTROL

1.1.1 CATALYST LIGHT-OFF

In order to achieve the EURO 4 emissions levels with an underfloor catalyst, it is necessary to have fast catalyst light-off and hence improved conversion efficiency. Figure 1a shows the principle of operation of the engine during light off control. In summary, the fuel is injected early, and ignition occurs after TDC. Ignition timing is used to control the engine speed by the PID controller, and the fuelling level and AFR are nominally independent of this speed control. Figure 1(b) is similar to Figure 1(a) except a second nominally air-only injection event is used to assist in oxidation. Engine speed control is similar to Figure 1(a), and the advantage of this is that the second air injection reduces engine out HC emission during post oxidation. Figure 2 shows the reduction of engine out HC with and without the usage of post oxidation.

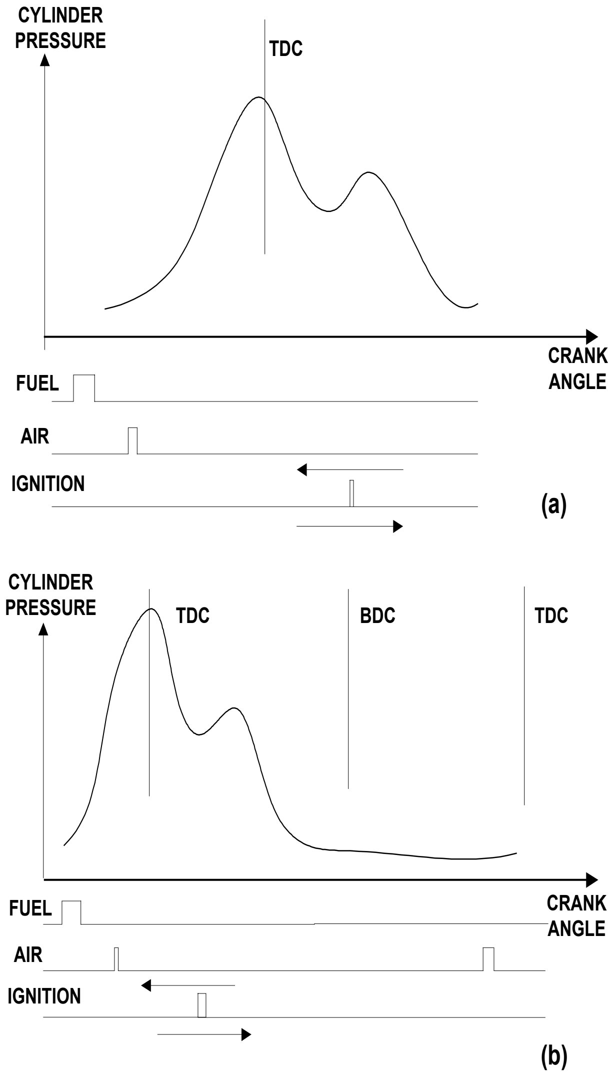

Figure 1 Fast catalyst light off strategy (a) without post oxidation (b) with post oxidation.

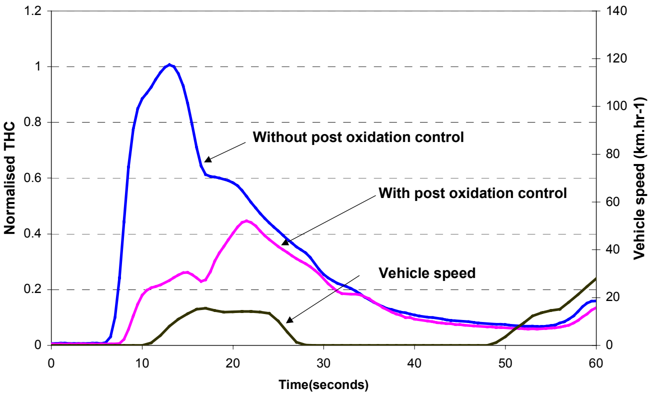

Figure 2 Engine out HC emission comparison with post oxidation during light-off mode.

1.1.2 EVAPORATIVE EMISSIONS CONTROL

The problem, which is prevalent in engines running in a nearly unthrottled condition, is to generate enough intake vacuum to draw the evaporative vapour through the carbon canister. The second problem is how to introduce the vapour into the combustion system while maintaining good HC emission control, especially during periods of stratified operation. The OCP system overcomes the first problem by using the vacuum generated in the air compressor. The vapour is then carried into the combustion system entrained in the air, which is also used to carry in the metered fuel. By using this concept, it is possible to purge in all combustion modes, such as stratified, lean homogenous and homogenous without any impact on the engine out HC. Figure 3 shows the effect of purging through the intake manifold in a conventional manner compared to the OCP technique of purging through the air compressor and air system. At a typical stratified running point (2000rpm, 2bar), the engine out HC increased by 86% and at idle by 50% when purging through the intake manifold, while the OCP technique resulted in lower overall HC.

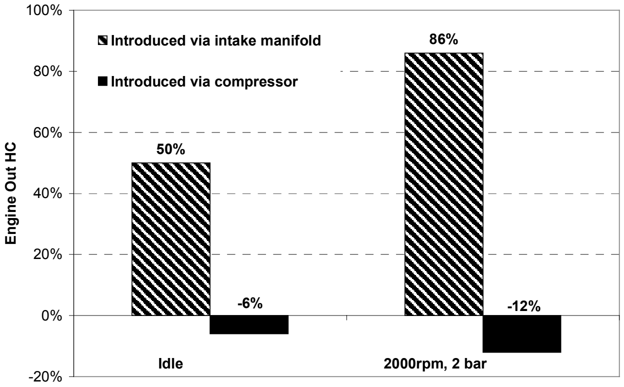

Figure 3 Variation of HC as purged via intake manifold against that purged via the OCP air compressor method.

In the next section we describe the design of the catalyst system for use with the OCP engine and control strategy.

2. EXPERIMENTAL

2.1 CATALYST PREPARATION AND AFTER-TREATMENT DESCRIPTION

For the following tests, the catalysts were prepared on ceramic monolith substrates of extruded corderite. The substrate has a diameter of 10.2 cm (4”) and was 15.2cm (6”) in length with a cell density of 62 cell cm^{-2} (400 cpsi). All catalysts and catalyst systems were placed 1.3m from the engine in the underfloor position.

2.2 CATALYST DESCRIPTION

Initially three catalyst formulations were tested on the Euro-III drive cycle. Catalyst A is a palladium-based three-way catalyst that contains barium, with a precious metal loading of $93.3gft^{-3}$ palladium and $6.66gft^{-3}$ rhodium. Catalyst B is a platinum-based three-way catalyst that does not contain any barium, with a precious metal loading of $93.3gft^{-3}$ platinum and $6.66gft^{-3}$ rhodium. Catalyst C is an advanced NOx trap formulation, with precious metal loading of $100gft^{-3}$ platinum and $20gft^{-3}$ rhodium, that has been developed for use on High Pressure Direct Injection (HPDI) vehicles. The total volume of the converter used in all cases was 100% engine swept volume (ESV).

3. RESULTS

3.1 ENGINE OUT EMISSIONS FROM ORBITAL VEHICLE

Figure 4 shows the engine out emissions of the Orbital vehicle in comparison to an HPDI vehicle currently sold in Europe (Vehicle A) and a stoichiometric running vehicle of the same engine volume (Vehicle B). Figure 5 shows the cumulative engine out emissions from the OCP Orbital Engine mounted in a development vehicle.

The raw HC emissions from the Orbital vehicle are lower than both the HPDI and the stoichiometric vehicles. More striking is the large difference in raw NOx emissions with the Orbital vehicle, emitting only $0.25g.km^{-1}$ in comparison with $0.95gkm^{-1}$ for the HPDI vehicle and $1.10gkm^{-1}$ for the stoichiometric port injection vehicle. It is the combination of low engine out NOx and HC and a fast light-off strategy that enables an underfloor-only solution on the Orbital vehicle.

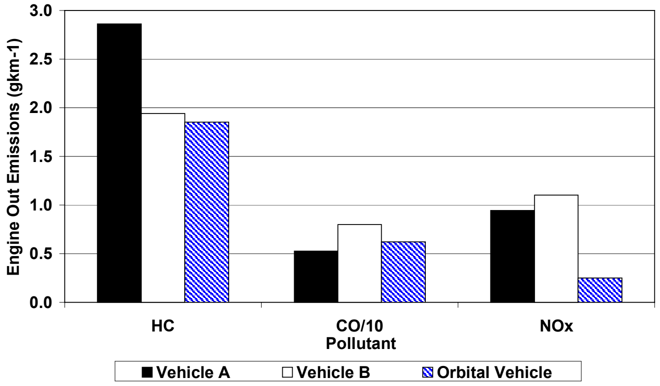

Figure 4 Engine out emissions over Euro III drive cycle.

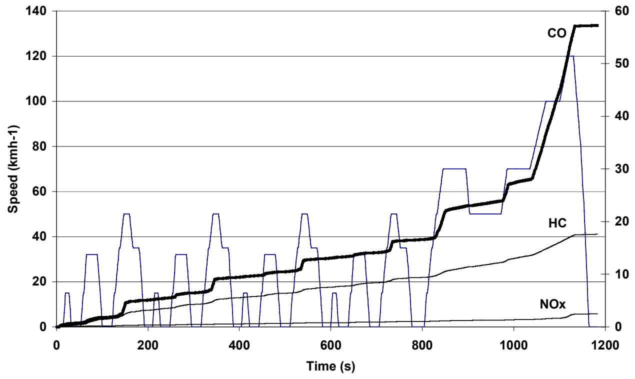

Figure 5 Cumulative engine out emissions from OCP Orbital vehicle.

3.2 EURO IV TEST RESULTS ON FRESH CATALYST FORMULATIONS

Table 1 summarises the fresh results obtained for the three formulations described above, and Figures 6, 7 and 8 show the cumulative tailpipe emissions for catalysts A, B and C, respectively. Catalyst A, at 100% ESV, met Stage IV legislation for CO but failed the standard on HC and NOx control. During 0 to 150 seconds, it was observed that catalyst A had the poorest HC efficiency of the three formulations, Figure 6.

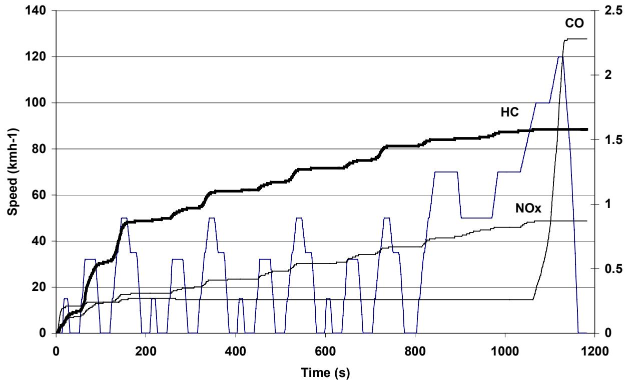

Figure 6 Cumulative tailpipe emissions from Catalyst A on OCP Orbital vehicle.

In contrast, the platinum three way catalyst, B, met Stage IV legislation for HC and CO but failed on NOx emission. The major breakthroughs of NOx emissions are seen during the ECE cycle where the vehicle runs in the lean mode, Figure 7. Considering that this catalyst does not contain a component that will adsorb NOx, it is not surprising that this formulation exhibits poor NOx efficiency on the cycle.

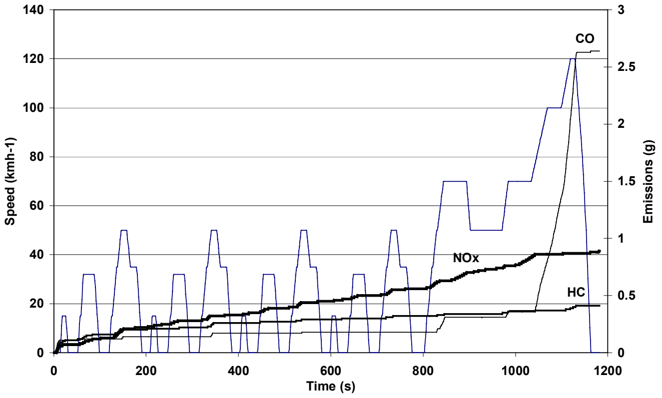

Figure 7 Cumulative tailpipe emissions from Catalyst B on OCP Orbital vehicle.

In contrast, the NOx trap formulation, catalyst C, met Stage IV legislation for NOx and CO but failed on HC, Figure 8. HC conversion efficiency between 200 and 300 ºC under lean AFR was less than the Pt based three-way catalyst, Figure 7. It is evident from Figures 7 and 8 that the light off temperature for HC activity is somewhat higher for the NOx trap than for the Pt-based three-way catalyst. This difference in light off temperature mostly accounts for the difference in tailpipe HC emissions on this vehicle between catalysts B and C.

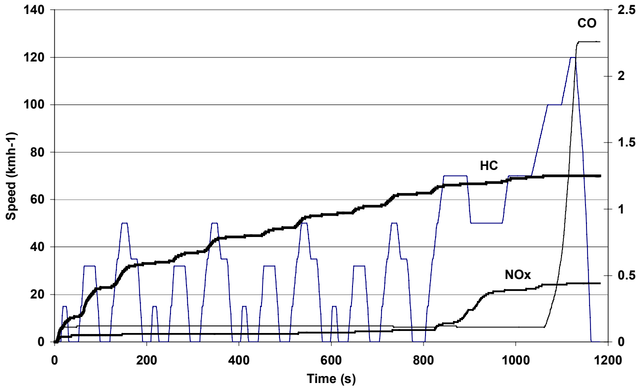

Figure 8 Cumulative tailpipe emissions from Catalyst C on OCP Orbital vehicle.

In summary the platinum-based three-way catalyst formulation was very good at lean hydrocarbon conversion, but some NOx adsorption component is also needed to improve the NOx conversion.

Formulation	HC(gkm^{-1})	CO(gkm^{-1})	NOx(gkm^{-1})
A	0.151	0.253	0.088
B	0.041	0.254	0.096
C	0.115	0.235	0.045
Stage IV	**0.1**	**1.0**	**0.08**

Table 1: Summary of fresh results for catalysts A, B and C over Euro III drive cycle.

3.3 MIXED FORMULATION CATALYST SYSTEM

3.3.1 CATALYST SYSTEM DESCRIPTION

The results obtained suggested a combination of catalyst formulations was required. Two systems were tested, which are illustrated in Figure 9. System 1 comprises 40% ESV catalyst B, the platinum-based three-way catalyst, and 60% ESV catalyst C, the advanced NOx trap formulation. A second system comprises 40% ESV of an advanced oxidation formulation, catalyst D, and 60% ESV catalyst C. The precious metal loading of catalyst D is 100gft^{-3} platinum.

System	Catalyst 1	Catalyst 2
1	Catalyst B	Catalyst C
2	Catalyst D	Catalyst C

Figure 9 System design for exhaust after-treatment.

3.3.2 EURO IV TEST RESULTS ON FRESH AND HYDROTHERMALLY AGED CATALYSTS SYSTEMS

Catalysts B, C and D were tested fresh in the combinations shown in Figure 9. The two catalyst systems were then tested following hydrothermal ageing at a range of temperatures, summarised in Table 2. Each catalyst system was evaluated on the vehicle after ageing at 750, 800 and 850ºC, resulting in a total ageing time of 14 h.

Ageing temperature (ºC)	Atmosphere	Duration (h)
750	10% H_2O, 10% O_2, 80% N_2	5
800	10%H_2O, 10% O_2, 80% N_2	5
850	10%H_2O, 2% O_2, 88% N_2	4

Table 2: Hydrothermal ageing conditions.

The catalysts on this vehicle have not undergone a road mileage accumulation exercise, so no direct comparison between hydrothermal ageing and road mileage can be made. However, lean ageing at 850ºC is considered to be a harsh ageing condition for an underfloor catalyst, with the catalyst not expected to see this condition for more than 2% of the life of the vehicle.

Table 3 summarises the test results obtained for these two catalyst systems in the fresh condition.

System	HC (gkm^{-1})	CO (gkm^{-1})	NOx (gkm^{-1})
1	0.049	0.23	0.027
2	0.028	0.18	0.035
Stage IV	**0.1**	**1.0**	**0.08**

Table 3: Summary of results for fresh catalyst systems 1 and 2 over the Euro III drive cycle.

It is apparent that both systems achieve Stage IV legislation easily in the fresh condition. It is also observed that the advanced oxidation catalyst has enhanced HC activity over the cycle while the NOx efficiency is slightly poorer.

Catalyst system 1 was then hydrothermally aged and re-tested. Stage IV legislation for HC, CO and NOx was achieved after being subjected to hydrothermal ageing at 750 and 800ºC, Figure 10. However, after ageing at 850ºC system 1 exceeded the Euro IV standard for HC, but still maintained sufficient CO and NOx conversions.

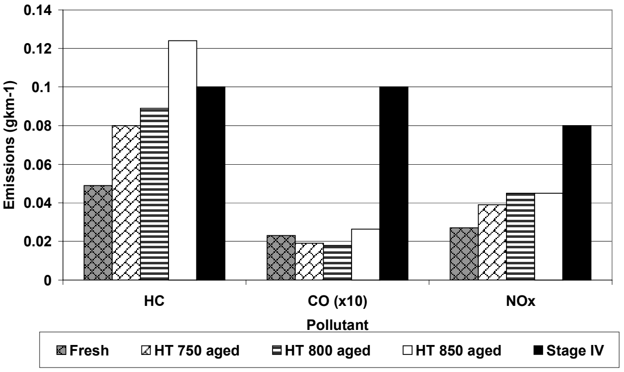

Figure 10 System 1 tested fresh and hydrothermally aged on Euro III test.

System 2 was then hydrothermally aged and re-tested. The results for system 2 show an improvement in HC emissions compared to system 1 due to the advanced oxidation catalyst (catalyst D), with Stage IV legislation being achieved for CO and NOx after ageing at 850ºC, but again failing on HC emissions, Figure 11.

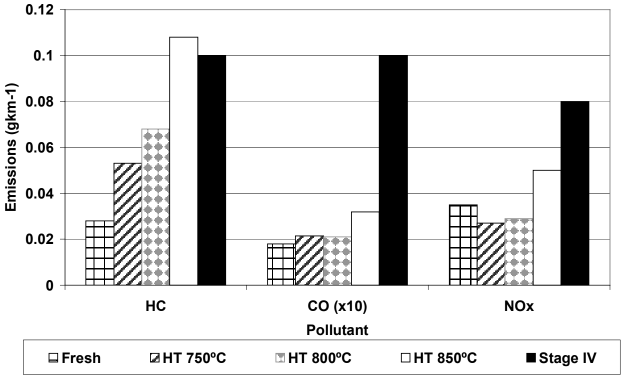

Figure 11 System 2 tested fresh and hydrothermally aged on Euro III test.

3.3.3 CHANGE IN ENGINE CALIBRATION

The results on system 2, after hydrothermal ageing at 850ºC were very close to achieving the stage IV requirement. A new calibration was entered into the engine control unit, which allowed the vehicle to run lean over a larger portion of the drive cycle. System 2, having been aged at 850ºC, was then re-tested. Figure 12 summarises the results.

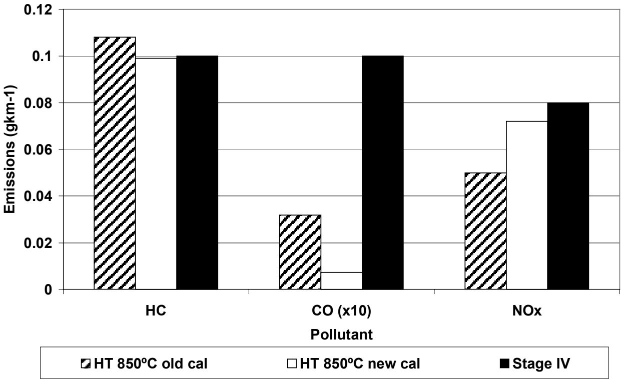

Figure 12 Effect of improved calibration on system 2 performance.

By changing to the new calibration, the NOx emissions have risen, but the vehicle now meets Stage IV legislation for CO and HC as well.

4. INVESTIGATION OF CATALYST SYSTEM BEHAVIOUR

4.1 STEADY STATE TESTING OF SYSTEM

The objective of this study was to ascertain whether Stage IV legislation could be achieved on the Orbital direct injection vehicle by the use of a three way catalyst in the underfloor position. The results have suggested that the three-way catalyst alone, even at the very low engine out NOx numbers, is insufficient to meet the NOx requirement for stage IV. It is also evident that addition of a NOx trap formulation greatly improves the NOx efficiency over the cycle. At the time of testing, there was no specific strategy on the vehicle calibration with rich excursions to release and reduce NOx emitted from a NOx trap. Therefore it was expected that the trap would adsorb NOx up to a time of saturation under lean conditions. Figure 13 shows the air-to-fuel ratio of the vehicle on the European test cycle. At certain conditions, for example at the end of each 3rd gear acceleration during the ECE phase, the vehicle returns to homogeneous rich-biased lambda 1.0 operation.

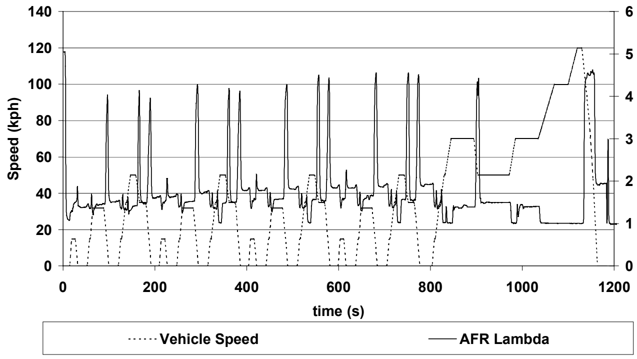

Figure 13 AFR trace over Euro III drive cycle.

Since reductant mass flow rate is high under these conditions, it is possible that there is sufficient reductant in the exhaust gas to regenerate NOx adsorbed in the trap. A number of tests were carried out using system 1, aged hydrothermally at 750ºC, on the vehicle to investigate NOx trap behaviour. These are described below.

Figure 14 shows engine out and tailpipe NOx emissions from the vehicle running at 60kph under stratified operation, having an air-to-fuel ratio of 22:1. The initial 50s of the chart shows a warm-up phase. It is apparent that the NOx efficiency of the system at the onset of lean operation was very high, in excess of 95%.

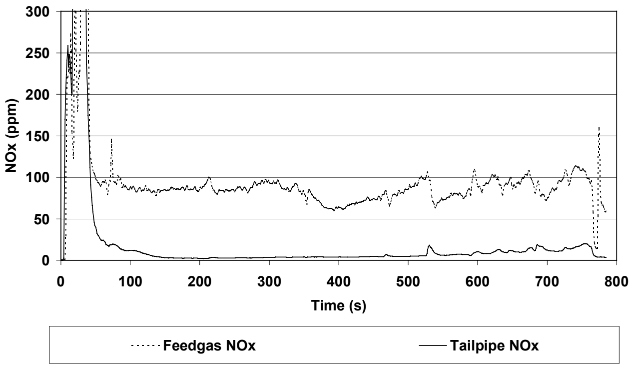

Figure 14 NOx emissions during 60kph steady state cruise of system 1.

After 500s the tailpipe NOx begins to increase and at the end of the steady state condition, around 760s, the tailpipe NOx reaches approximately 25ppm. This behaviour is entirely consistent with adsorption of NOx under lean conditions, showing that saturation of some of the adsorption sites leads to a steady increase in tailpipe NOx emissions.

4.2 REPEATED TESTING OVER ECE AND ECE + EUDC

As stated above, this vehicle does not use a specific regeneration mode based on a NOx model during the NEDC drive cycle. The vehicle controls to rich-biased lambda 1.0 homogeneous operation based on engine speed and load only. The control of rich-biased lambda 1.0 was enabled 3 times at each 3rd gear acceleration mode during the ECE cycle and was enabled from 100 km.hr^{-1} during the EUDC cycle, Figure 13. The NOx trap used was designed to regenerate quickly at rich-biased lambda 1.0 calibration.

In order to determine whether the NOx trap could store and regenerate on cycle, the ECE portion of the European test was repeated five times on system 1. Repeating the cycle allowed us to observe whether the tailpipe NOx numbers gradually increase or whether these excursions to rich-biased lambda 1.0 are sufficient to release and reduce the stored NOx on the NOx trap. Figure 15 shows how the tailpipe NOx increases over time.

Over the first ECE cycle, lasting 800s, the NOx efficiency was very high. Towards the end of the second cycle, and thereafter, a steady increase in tailpipe NOx emissions was observed. This indicated that the trap reached saturation, with fewer and fewer sites available for NOx adsorption as the test proceeds, resulting in higher tailpipe NOx emissions.

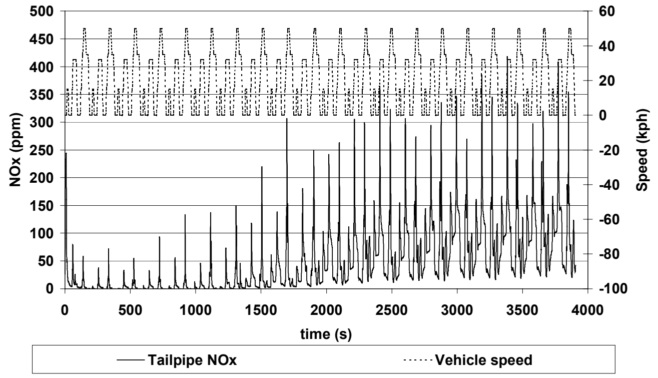

Figure 15 System 1 tested 5 times over ECE portion of European test.

Figure 16 shows the tailpipe NOx emissions from the vehicle on a third test where the complete ECE + EUDC cycle is repeated 5 times. In this test the tailpipe NOx emission is more or less repeatable from cycle to cycle. This is suggesting that the rich-biased lambda 1.0 excursions on the EUDC part of the cycle are sufficient to regenerate the trap whilst those during the ECE cycle, which give a lower mass of reductant species, are not.

Furthermore, optimisation of the calibration to adjust these rich-biased lambda 1.0 excursions to be slightly richer biased may allow the trap to be regenerated at lower load points on the cycle.

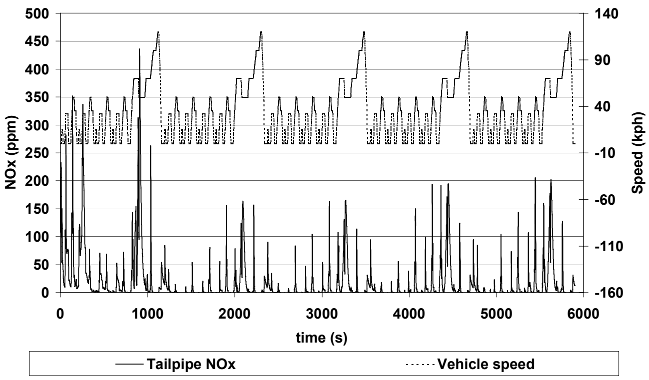

Figure 16 System 1 tested over 5 cycles of the ECE + EUDC portions of the European test.

5. CONCLUSIONS

The engine out NOx is extremely low with the Orbital engine in comparison to both conventional high-pressure DI engines and engines with port fuel injection running at lambda 1.0. The engine out hydrocarbon emission is lower with the Orbital engine than for current production, high pressure DI engines. The Orbital engine concept also allows a rapid light off strategy, which removes the necessity for a close-coupled catalyst to supplement the underfloor converter.

Stage IV emission targets have been attained by use of an underfloor-only converter having an engine swept volume of only 100 %, after hydrothermal ageing at 850ºC. This converter contained an advanced oxidation catalyst and a lean NOx trap with 3-way catalyst functionality.

By use of a novel lean NOx trap formulation, it is evident that excursion to a slightly rich-biased lambda=1.0 homogeneous operation under high gas flow rate on this vehicle is sufficient to regenerate the NOx trap.

Moreover, the low engine out NOx emission from the vehicle means that much fewer forced excursions to rich conditions will be necessary to regenerate the NOx trap function of the emissions system, resulting in improved fuel economy over a vehicle with higher engine out NOx level.

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