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# 118 Air Assist Direct Injection - Fuel Economy with Global Emission solutions

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Air assist direct injection system offers the potential for significant reduction in fuel consumption and engine out emissions. This paper presents the approach taken to achieving the fuel economy goal whilst meeting the various emissions standards posted globally. The results presented demonstrate that the one air assisted direct injection system can fulfil customer requirements for both US (ULEV-II) and European (EURO-IV) standards by changing only the aftertreatment system, engine calibration and control strategies. In addition data for the European standard will show that it is possible to trade between vehicle fuel economy and aftertreatment system cost. The data will demonstrate the ability to achieve the EURO-IV emissions standards with significant fuel economy benefits whilst constrained with high sulphur fuel similar to that in the market today.

*Key words:* **Engines/Gasoline Direct Injection/Spray Guided**

## 1. INTRODUCTION

The development of the gasoline direct injection engine has been pursued with rigour over the last decade with the aim of achieving significant improvements in vehicle fuel economy. These improvements have been primarily gained from reduced pumping losses (lean/stratified operation), the ability to run higher compression ratios and the ability to run higher EGR rates. Nonetheless the uptake of direct injection technology in mass production has not met the forecasts in both timing and volumes. There are many commercial reasons why this might have happened. From a technical standpoint the main issues are system robustness (combustion system, injection system) and high-untreated emissions. These issues are combined with the need to run non-conventional aftertreatment systems in the form of LNC or LNT (lean NOx converters or Lean NOx traps) to achieve the legislated tailpipe NOx levels. The use of this type of aftertreatment leads to further issues such as maximum temperature stability, sulphur resistance and NOx regeneration capability. The above prognosis is based on meeting today's emissions standards, with the future standards, ULEVII, Euro IV and Euro V likely to magnify the problems.

Despite these challenges, Orbital's air assisted (spray guided) direct injection technology OCP (Orbital Combustion Process) (1,2), has demonstrated successfully the ability meet Euro-IV initially on one vehicle platform in 2000 and subsequently on several other engines and vehicle platforms. The combustion process demonstrated the capability to have lower untreated THC emissions when compared to a wall guided DI system combined with very low levels of NOx emission. Typically NOx levels are 20-25% of a comparative single fluid high-pressure direct injected engine. Leveraging this advantage it has been possible to achieve Euro IV emissions with severely aged catalysts both with TWC aftertreatment technology and LNT technology. One LNT system tested required an average conversion efficiency from the NOx trap of only 75-80% compared with the typical 85-95% (3) required from a single fluid high pressure DI systems to achieve Euro IV. The LNT system was further developed to increase NOx conversion efficiency and thereby to optimise fuel economy benefits. Catalyst light off is critical to achieving any of the current and future emissions standards. The stability of the OCP combustion system makes it possible to retard the combustion event immediately after starting the engine and maximise the exhaust temperature (4).

This paper focuses on presenting the various options to achieve Euro IV and beyond plus data showing the same basic system has the capability to meet ULEV-II standards.

## 2. TEST ENGINE AND VEHICLE, EURO-IV

A Ford Zetec 2.0l engine was modified to suit the OCP combustion system and installed in a Mondeo vehicle. The OCP DI engine and vehicle specifications relative to the original PFI systems are summarised in Table 1

| | PFI | Orbital DI |
|---|---|---|
| Vehicle model | Ford Mondeo GLX | |
| Engine model | 2.0 Litre Zetec DOHC | |
| Inertia weight | 1360kg | |
| Comp. Ratio | 9.8 | 10.8 |
| Fuel system | MPI | OCP DI |
| Camshaft | Standard | Retard on EVC |
| EGR system | Ford system | High flow rate (Max. 35%) |
| Aftertreatment | TWC | Co-developed system with Johnson Matthey |
| Transmission | 5 speed manual (FDR=3.84) | |
| EMS | Ford system | Orbital system |

Table 1 Engine and vehicle comparison

## 3. EURO-IV SYSTEM

### 3-1 System compatible with high sulphur levels, #1

Current sulphur level in fuel today makes the use of present LNT technology more difficult in some regions and markets. In order to keep the NOx conversion efficiency of these catalysts favourable, sulphur levels of <10pmm are required and some form of desulphation strategy will be necessary. By comparison to LNT's, conventional TWC (Three Way Catalyst) technology is relatively insensitive to sulphur poisoning. Moreover, this type of catalyst technology is relatively robust from thermal degradation but offers little in the way of NOx storage capability or conversion in lean AFR operation.

In conjunction with Johnson Matthey a TWC (Pt/Rh) was designed having an ESV of 85%. This was mounted close coupled approximately 0.35m from cylinder head. The catalyst was hydro thermally aged in a lean environment at 1050 $^{o}$ C to represent the close-coupled nature of the catalyst. Fig. 1 illustrates this aftertreatment system.

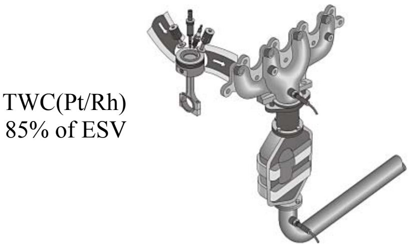

Fig.1 TWC system #1 for high sulphur fuel

To use this type of aftertreatment system and meet Euro-IV emissions levels, it was necessary to reduce the engine out NOx emissions during stratified combustion mode and maximise the NOx conversion efficiency during homogeneous combustion mode, $\lambda$=1.0. During the calibration process the maximum NOx reduction was attained at approximately an AFR of 19 combined with high levels of EGR during stratified running.

In order to maintain high NOx conversion efficiency during $\lambda$=1.0 operation a rear oxygen sensor was installed at the outlet of catalytic converter and the OSC (Oxygen Storage Capability) was monitored from the feedback of rear oxygen sensor. By analysing OSC, the fuelling could be controlled to achieve the best NOx conversion efficiency. Fig 2 shows that the tailpipe emissions are below Euro-IV limits and fuel economy improvement over PFI vehicle is 12.5%. Test fuel had a 200ppm sulphur level

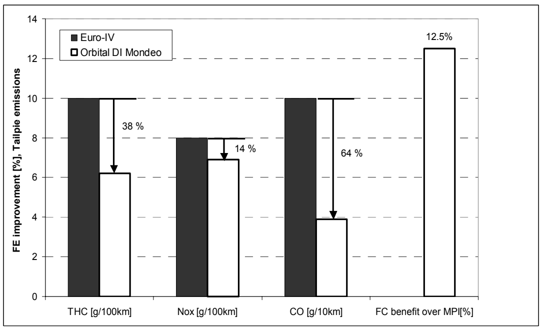

Fig.2 Tailpipe emissions and FE with TWC system#1

### 3-2 Low cost system LNT system #2

By working closely with Johnson Matthey a single underbody catalyst system comprising of an oxidation catalyst and LNT in the same container was developed for use on the Mondeo vehicle (See Fig.3). A previous paper$^{(4)}$ covered much of this development work. In this earlier work the aging up to 850deg C hydro thermally had caused the tailpipe HC emissions to exceed Euro IV standards. Subsequent to this, it was possible to significantly lower the HC emissions by calibrating at leaner AFR with the concomitant effect of increasing the NOx. This was combated by changing the catalyst diameter from 102mm to 118mm whilst maintaining the same catalyst volume. The effect was to lower the exhaust backpressure as well as to change the space velocity and residency time. This in turn reduced the exothermic energy from the oxidation catalyst on to the NOx trap (See Fig.4) thus increasing the NOx conversion efficiency as the trap was now operating in a more favourable window. This is clearly seen from the acceleration to 50km/hr during the ECE 15/04, where a 50 deg C difference in the oxidation catalyst temperature is observed and is reflected in the reduced peak trap temperature. This resulted in an increase in NOx conversion efficiency of 9 % over the ECE 15/04 cycles.

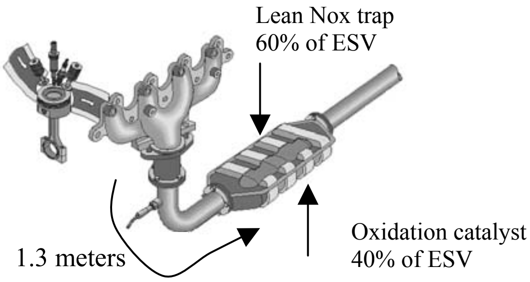

Fig 3 Low Cost aftertreatment system #2

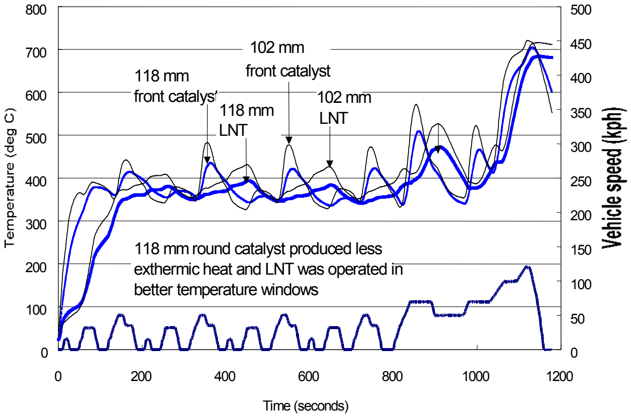

Fig 4 Comparison of exhaust temperature for 102mm to 118mm

For NOx regeneration, AFR was switched to $\lambda$=0.98 during acceleration and 100-120 km/hour. Test fuel was low sulphur fuel (<50ppmS). Fig.5 shows tailpipe emission data and fuel economy improvement relative to Mondeo PFI Vehicle.

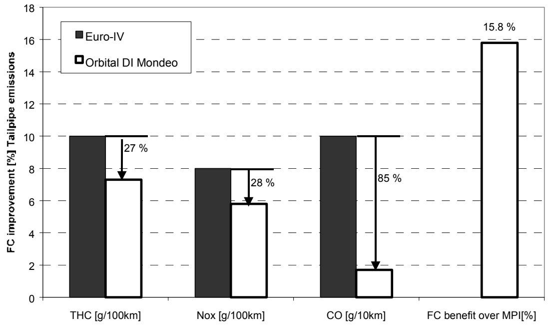

Fig 5. Tailpipe emissions & FE with system #2

The calibration applied to LNT is nominally to increase AFR in the low load, lower speed region. These regions dominate the ECE15/04 phase of the European drive cycle. This resulted in a reduction of fuel consumption by approximately 3.5% over the TWC calibration. Fig-6 indicates the % shift in AFR across the drive cycle between the LNT calibration and TWC calibration

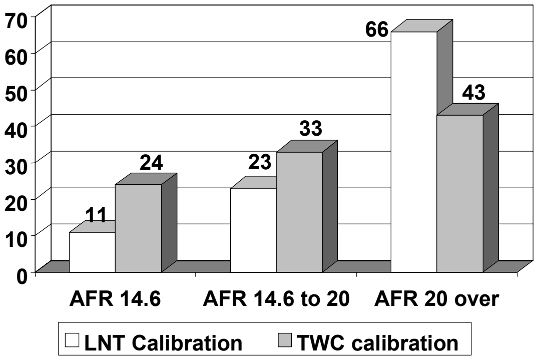

Fig.6 The comparison of AFR distribution for TWC calibration and the LNT calibration.

The calibration strategy applied to the TWC was to reduce the engine out NOx emissions during stratified operation. Fig 7 shows the accumulated engine out NOx mass for the PFI engine and the two calibrations for the TWC and LNT systems.

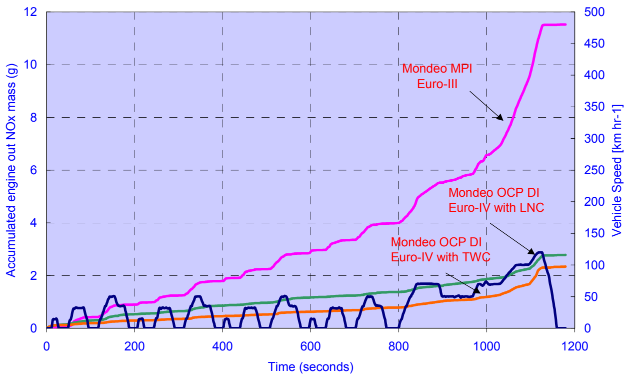

Fig.7 The comparison of accumulated engine out NOx mass (PFI vs. system#1 vs. system#2)

At the end of the ECE cycle the accumulated NOx mass with LNT system is approximately 40% of the PFI system and the accumulated NOx mass with the TWC calibration is approximately 20% of the PFI system.

### 3-3 Fuel economy optimised system #3

To demonstrate the maximum fuel economy potential of the DI system, the aftertreatment system must be able to efficiently treat higher levels of NOx generated in a lean environment. In order to achieve a high efficiency lean Nox aftertreatment system, two separate catalyst substrates were selected. A front oxidation catalyst was positioned at 0.95m from the cylinder head. The second substrate LNT (Lean NOx Trap) was located at 1.3m from cylinder head. Catalyst volume was increased only for LNT (100% ESV-Engine Swept Volume) (see Fig. 8).

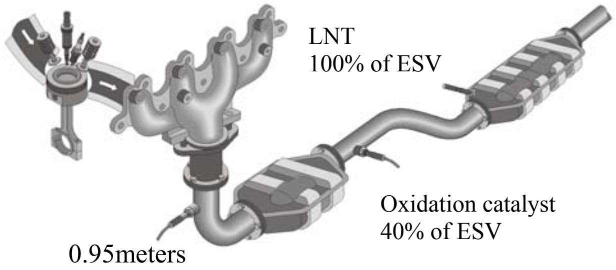

Fig 8. Optimised aftertreatment system for best FE with system #3

Both the splitting of the substrates and the increase of the NOx trap volume made it possible to extend the lean AFR capability across the cycle. The light-off calibration for heating the catalyst was optimised as the front catalytic converter was moved forward from 1.3m to 0.95m. As a result, close to 20% improvement in fuel economy was achieved whilst still falling well within the Euro-IV emissions standards Interestingly, the tailpipe emissions for this system running on the baseline calibration fall within the 50% of Euro IV standards. (See Table 2) All emissions results quoted here are measured with 850deg C hydro thermally aged catalyst systems.

| System | THC | NOx | FE (%) |
|---|---|---|---|
| Low cost system, system #2 | 0.07 | 0.06 | 15.8% |
| Low emission with system #3 | 0.04 | 0.02 | 15.8% |
| Optimised FE with system #3 | 0.04 | 0.06 | 19.8% |
| Euro-IV standards | 0.1 | 0.08 | - |

Table 2. The summary of tailpipe emissions in g/km and FE improvement

### 4. ULEV-II system

OCP technology similar to that used to demonstrate Euro IV was applied to a 2.2l 4-valve engine and demonstrated that it is possible to achieve ULEV-II emissions standards (5). The ability to achieve this result is again attributable to the low untreated emissions, which is product of air assist direct injection.

The aftertreatment system was designed for improvement of light-off performance to meet extremely low NMOG (Non Methane Organic Gas) standard. This system was similar to system #3 but LNT volume was increased to 110% of ESV. In order to reduce exhaust thermal inertia during the cold phase a single skin tubular exhaust manifold was fitted and the front catalyst moved closer to the engine. The front catalyst used was a Pt/Rh catalyst with a volume of 35% ESV. Both the front and rear catalysts were aged hydro thermally at 950 degC and 850deg C respectively.

Light off control was optimised for the closer front catalyst with the effect of achieving exhaust gas temperature of up to 500 degC within 20 seconds. The front catalyst mid brick temperature rose linearly to a similar temperature over a 40 second period

The calibration philosophy was similar to the European calibration in principle. The LNT regenerations were actively controlled by the ECU (engine control unit) with the target AFR slightly richer than stoichiometry. High NOx conversion efficiency during $\lambda$=1.0 operation was again achieved using a rear oxygen sensor down stream of the front catalyst. In this instance the rear oxygen sensors role was to better control NOx/CO ratio being presented to the LNT to improve the regeneration process.

Fig.10 shows tailpipe emissions and FE improvement that were measured. The tailpipe emission results with this demonstration vehicle fell within the ULEV-II 50K standards and fuel economy was improved by approximately 12% over the baseline PFI vehicle.

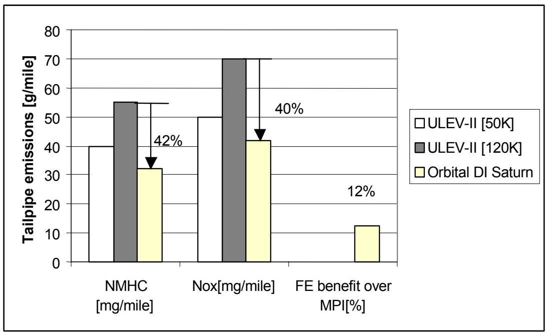

Fig. 10 Tailpipe emissions and FE, ULEV-II

## 6. Conclusions

OCP technology has clearly demonstrated the ability to satisfy present and future global emission standards with the various aftertreatment systems and calibration strategies. These achievements are summarised in view of system cost (simpler system), fuel economy improvement and gasoline (sulphur level) for European emissions in Fig.9. Orbital Air-Assist DI technology has shown that it is transferable across different engines targeting different emissions levels with only changes to the calibration and aftertreatment system.

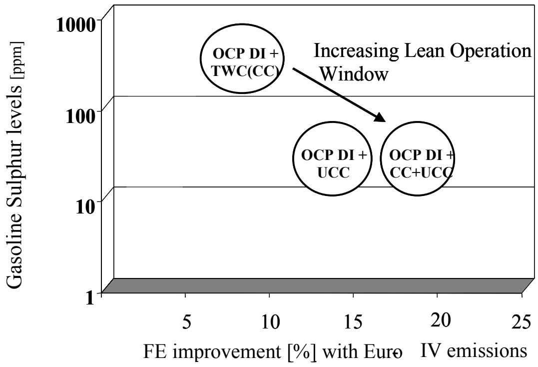

Fig. 9 OCP DI aftertreatments options

CC=close coupled UCC=underfloor catalytic converter

On the European drive cycle it has been demonstrated that its possible to meet Euro IV with 15.8% FE over a similar MPI. The same vehicle also showed that with a different calibration and modified aftertreatment system it was possible to achieve 19.8% FE improvement.

To remove the risk of the aftertreatment failing due to the sulphur levels in current pump fuel a TWC aftertreatment solution was developed whilst still maintaining an FE improvement of 12.5%.

Using the same engine and DI technology as for Europe it has been demonstrated that it's possible to meet California ULEV-II emission standards with 12 % fuel economy improvement over the MPI baseline vehicle.

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