ABSTRACT: To continue efforts towards improving air quality and achieving Read World Driving emissions targets, it is accepted that Light Duty Diesel powertrains have to maximize the NOx reduction performance of exhaust aftertreatment systems. Therefore Ricardo have continued to study the optimum configurations and thermal management techniques to improve conversion efficiency across all driving styles. The paper will consider what aftertreatment types, positions, and heating methods can achieve these goals towards post Euro 6 emissions levels, by assessing conversion efficiency profiles over WLTP and RDE cycles.

KEY WORDS: heat engine, diesel, RDE, passenger car, emissions control, aftertreatment, exhaust, thermal management [A1]

1. Introduction

As we look towards ever lower tailpipe emissions to improve air quality associated with transport, a clearer perspective of the challenges and potential solutions are being developed. With roadside NOx in the urban environment being significantly affected by road transport, we can see a clear need to improve the performance of NOx aftertreatment devices across a wide spectrum of conditions. In this paper we will focus on aftertreatment application for diesel passenger cars, but the same challenges of wide range NOx control are increasingly cross compatible to lean gasoline and heavy-duty diesel applications.

In previous papers, Ricardo have presented a simulation based methodology\(^{(1)}\) for assessing the performance of different engine and aftertreatment system over Real Driving Emissions (RDE) cycles. This highlighted the need for exhaust temperature management to increase the aftertreatment effectiveness, particularly during low speed urban phases. Further study was conducted to compare different heating strategies\(^{(2)}\) and the impact on NOx reduction against the fuel consumption penalty over a particularly challenging cycle scenario – the Ricardo ‘RC130’. This indicated the need for further refinement of the engine and aftertreatment specification to ensure the performance was improved and also the heating requirements are minimized to reduce the fuel consumption penalty.

In this paper both the cold urban and high temperature motorway challenges will be reviewed, using a combination of simulation and vehicle testing analysis. A chassis-dyno based RDE short cycle will also be presented that has been used to combine the difficult aspects of selected full RDE cycles over the course of a forty-five minute development test.

2. The Challenges

Diesel engines are under increasing pressure and scrutiny to deliver both further improved fuel economy performance that customers have come to expect along with reliable and robust real-world emissions control. In Europe particularly the diesel engine is favored in the larger car segment, and also currently features widely in medium sized C-segment cars and cross-over Sports Utility Vehicles (SUV). Across most markets the diesel engine is also the prevailing choice for Light Commercial Vehicles.

2.1. Increasing Complexity and Commonality

With a wide range of potential vehicle platforms, along with the need for modular powertrain families, the importance of correctly assessing and selecting the optimum solutions at system level, is critical to minimize cost and time for development.

Fig.1 Ricardo combine virtual and real testing

For the smaller vehicles, the absolute NOx levels are lower, but the cost sensitivity is often higher, whereas larger vehicles can potentially absorb more cost but the technical challenge can be higher due to increased NOx flow rates, aftertreatment temperature and space velocity ranges. Future diesel powertrains must consider a large selection of technology options for the engine, transmission, aftertreatment and hybridisation to meet the targets.

All these cases also need to consider and meet the requirements for NOx control in the real world, meaning a wide variety of road conditions, driving profiles and ambient conditions. Therefore a combination of virtual development and real-world testing can be used as depicted in Figure 1 to rapidly improve the assessment and performance of complex systems and support decision making during concept design as well as reducing development time and costs.
2.2. Wide Range Aftertreatment Effectiveness

To achieve the future emissions control requirements, an effective NOx exhaust aftertreatment system has become essential. Current catalyst chemistries deliver optimum performance in specific temperature windows, and with the wide range of real world conditions, the challenge of achieving NOx reduction across a wide range of temperatures and space velocities must be realised.

The catalyst specification for this study is based on reference properties for passenger car applications. The LNT considered a PGM loading around 120 g/ft³ on a cordierite substrate and the SCRf and SCR are copper zeolite type on silicon carbide substrates. The size and position of the bricks was optimised using a thermal model for the exhaust system, along with T4 exhaust temperature profile and space velocity conditions to achieve the target system performance.

In addition, the trends towards more electrified, efficient and downsized engines can move the temperature profile to further extremes. For example the drive towards lower CO₂ can translate into lower waste heat energy, and therefore contributes to lower temperatures in the exhaust system, extending the time taken for catalysts to activate. An impact of downsizing is an increase in the operating BMEP encountered during transients and motorway driving, leading to higher temperatures and space velocity conditions which can also challenge catalyst performance.

3. System Improvement Approach

3.1. Powertrain Interaction

With an ever increasing range of engine, aftertreatment, transmission and electrification combinations to consider it is critical to consider the performance of the system as a whole. For Light Duty Diesel applications the effectiveness of the aftertreatment system becomes critical, and cycle NOx conversion efficiencies need in general terms to be in the region of 80% and above.

From the analysis previously reported, we can see that two distinct challenges exist – the extremes of cold and hot operation. The cold challenge can be a combination of a warm-up phase, ambient conditions, or extended low load operation. For hot temperatures it is predominantly the impact of running high loads due to high speed motorway driving, steep gradients or DPF regeneration modes.

Therefore to achieve substantial gains in NOx control a range of system interactions, trade-offs and improvements have to be considered, and in this analysis the effectiveness of an engine with combined HP and LP EGR capability is assessed alongside different aftertreatment layouts.

3.2. Integrated Model Based Development

Before hardware assessment, Ricardo utilise an Integrated Model Based Development (IMBD) approach as shown in Figure 2 that can combine each element of a vehicle in a virtual environment to assess and optimise a system architecture and the detailed interactions of each sub-system. This toolset and methodology enables right first time hardware specification, along with reduced development time and hardware costs.

The ultimate target is to define a system capable of achieving a wide map tailpipe NOx level below the target, such that any type of operation achieves the required emissions control.

3.3. RDE Cycle Assessment

A range of RDE cycles can be used to understand the impact and performance of various technology options. In the virtual environment it is possible to run multiple cases over full cycles which can be up to two hours in length quicker than real time and without any significant costs. This allows specific profiles to be defined that challenge the engine and aftertreatment performance for a selected real-world scenario.

From previous studies the congested city cycle (reference RC130) has been utilised which includes a low speed stop-start urban phase that results in extended low temperature operation.

At the other extreme of high temperatures, travelling at the high motorway speeds up to 160 km/h creates the biggest challenge for the aftertreatment system. The previously documented and reported RA-140+ includes this profile in the motorway phase.

Hardware testing in vehicle can use a combination of on-road RDE testing with PEMS, along with chassis-dyno replication cycles. To accelerate the evaluation phase, Ricardo have developed a dyno based ‘short-cycle’ that combines the most challenging elements of selected RDE cycles in a forty-five minute test with urban, rural and motorway segments. The urban phase is thirty of the forty-five minutes to ensure that the cold NOx storage and conversion profile can be assessed considering the potentially slow rate of accumulation. The motorway segment includes travelling at speeds between 130 and 140 km/h with a period up to 160km/h to capture the high temperature and high space velocity characteristics for aftertreatment. The gradient is a key aspect for real-world driving, and this is mapped onto the cycles and controlled on the chassis-dyno as shown in Figure 3.
The cycle can be used during vehicle development to capture a wide range of driving dynamics that allow the system performance to be reviewed and developed. The shorter time compared with a ‘standard’ RDE test also improves throughput and can be used on facilities with climatic and altitude capability to widen the boundaries across the full breadth of RDE. Further validation can then follow once the expected performance is achieved.

4. System Assessment

The assessment in this paper is a combination of simulation and vehicle testing, with a reference NOx target based on Euro 6d levels (WTLC = 80 mg/km) and RDE with a Conformity Factor of 1.5 (=120 mg/km) for total cycle and urban phases.

4.1. Simulation Baseline

A downsized 1.5L engine in C-segment SUV / D-segment vehicle with HP EGR and DOC plus SCR on Filter aftertreatment as illustrated in Figure 4 has been assessed over a standard moderate cycle the RS115 and more challenging RC130.

The results show that over the standard RDE RS115 cycle, the NOx targets can be achieved with this system specification. For the RC130 cycle with low temperature urban phase, the urban conformity factor target cannot be achieved even with consideration of additional heating modes as shown in Figure 5.

This confirms the need to consider a more capable engine and aftertreatment system against these targets.

4.2. Vehicle Testing

In parallel to the simulation, Ricardo have undertaken a range of vehicle tests with different vehicle hardware to assess performance over a range of cycles. This has included WLTP testing, short RDE representative chassis-dyno cycles and validated RDE on-road testing with PEMS measurement. The results are intended to provide an indicative performance capability for the system, as full system optimization has not yet been completed.

4.2.1. Hybrid EGR with SCRF

The results from previous analysis have clearly shown the need for wide-range engine NOx control in combination with improved aftertreatment effectiveness to achieve the increasingly stringent emissions control. The use of hybrid EGR – the combination of HP and LP EGR systems can enable an improved balance of EGR and fuel consumption across a Light Duty Diesel operating range. A D-segment vehicle with a 1.6L engine similar to the simulated set-up incorporating hybrid EGR with DOC plus SCRF aftertreatment has been tested to measure cycle performance.

Over a WLTP this hardware is capable of the target 80mg/km NOx emissions at Test Mass High (TMH) and Low (TML) inertias, providing a good starting point for RDE testing. The initial RDE testing was conducted on road with PEMS equipment. A route local to Shoreham Technical Centre was used and the national speed limits observed. The results in Figure 6 show that the Conformity Factor target was achieved for both the whole cycle and the urban phase.
The vehicle was subsequently tested over the short RDE chassis cycle, where a significant increase in emissions was recorded. This is due to the combination of extended low temperature operation during the urban phase, along with higher loads and temperatures during the high speed motorway phase as shown in Figure 7.

The impact of the temperature distribution during the short cycle on SCR conversion efficiency can be seen more clearly on Figure 8 with a phase based breakdown. Here the urban section is split into Phase 1 and Phase 2, where Phase 1 represents the first three hundred seconds. Phase 3 covers the rural driving and Phase 4 is the motorway section.

There is a clear correlation between the temperature of the SCR and NOx conversion efficiency achieved. The initial Phase 1 records a very low temperature, with the small NOx conversion indicated likely to include an amount of temporary NOx storage. The motorway Phase 4 records the highest average temperature as expected, and as this is in an optimum range for the catalyst the highest conversion efficiency is recorded. Overall however the system performance remains below the target at this stage.

4.2.2. Hybrid EGR with LNT and SCR

Based on the results in the previous section, a number of options exist to improve the performance over the short dyno RDE cycle. A more capable aftertreatment system has been considered to address the wide range temperature profile. The addition of a Lean NOx Trap (LNT) as illustrated in Figure 9 enables the low temperature region to be improved through storage and careful purge management. This also allows more flexibility for the SCR positioning due to the reduced importance of close-coupling for the low temperature performance now addressed by the LNT.

In this study the results for a separate DPF plus SCR used in place of the SCRF are presented. Achieving good low temperature NOx control can remain a challenge with an LNT due to the difficulty for efficient low temperature purges, but the improvement in urban phase and cycle NOx control can be seen in Figure 10.
lower temperature for the lowest test inertia case is evident for the urban phase as shown in Figure 11.

This combines worst cases and shows the need for further mitigating measures such as heating mode or lower engine-out NOx.

4.3. Future System Specification

To further increase the effectiveness of the aftertreatment system a combined LNT plus SCRF plus underfloor SCR layout as illustrated in Figure 12 could be considered the optimum configuration to provide low, mid and high temperature capability.

This capability for NOx control must however be considered alongside potential future legislation for N2O emissions which are a function of the conversion quantities across both LNT and SCR catalysts. Formulations and chemistries may need to be selected to minimize the N2O selectivity.

The use of hybridisation is also showing it can offer significant advantages for reducing the requirement for NOx reduction. In particular for diesel engines, the use of 48V mild hybridisation can offer flexibility in engine operating modes to reduce the NOx generation at the low and high temperature extremes that cause the most challenge for aftertreatment systems. From Ricardo assessment this is best achieved using an architecture that enables the E-machine to be used while the engine is de-clutched, such as a so called P2 layout. The E-machine can then be used to its maximum effectiveness during the low speed and load operation where aftertreatment temperatures are low. There is also the potential to reduce the high load engine operation through torque assist. The additional benefit of such a mild-hybrid system is the potential for significant CO2 reduction, leading to a cost-benefit trade-off that becomes increasingly attractive as the mHEV system costs, specifically the battery, continue to reduce.

With this increasing complexity for technical solutions, and modelling requirements for real-world operation, comes the need to apply statistical analysis of the system. Ricardo continue to work on an RDE Monte Carlo Cycle Simulation technique that can run thousands of potential real-world scenarios to assess the emissions and CO2 profile. The outcome is a range for the system performance covering emissions and fuel economy and allows the impact of combined factors to be judged, as shown by the example charts of temperature distribution through an exhaust system in Figure 13.

Fig.11 Impact of vehicle mass over the short RDE cycle

Fig.12 LNT plus SCRF plus SCR multi brick layout

Fig.13 Example Monte Carlo RDE cycle distribution

5. Conclusions

Wide range emissions control for Light Duty Diesel passenger cars requires a system level approach to specification and development. A key part of the NOx control is the aftertreatment, and several options exist that will always need to be considered on an application specific basis. Simulation is a powerful tool within the development process, but with the new processes and procedures required within legislation it is also critical to gather real test data and experience to support the decision making process. With a means identified for assessment and development utilising short chassis dyno cycles, the key objective is to confirm the robustness of the selected solution, along with ensuring the capability is achieved for the best cost and fuel consumption trade-off. The requirement for wide-range NOx control leads to the conclusion that multi-brick aftertreatment systems offer an effective route to achieve these goals. The combination of LNT and SCRF / SCR systems requires a case-by-case evaluation, in combination with the other powertrain attributes. Adoption of these measures is key to ensure that the diesel engine delivers on its
potential, and continues to be a viable option for customers who desire the attributes they have become accustomed to.

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