FlexValve: CVVA System for Diesel Engines

Optimisation of air-path systems and EATS thermal management

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Abstract

The forthcoming introduction of RDE and ever tightening global regulations mean that vehicle manufacturers will need to upgrade their diesel engine families with new combinations of technology to meet stringent emissions targets.

FlexValve is a CVVA system for optimising the gas exchange of IC engines with the flexibility to control both the main and additional valve events. The system can also be implemented without any valvetrain friction penalty and a minimal impact on the engine architecture. This paper focuses on a diesel FlexValve application generating a variable secondary exhaust valve opening during the intake stroke.

Unlike 2-step systems currently in production, FlexValve offers continuously variable secondary event lift and duration, enabling optimisation across the engine operating range to benefit both the warm-up phase and normal operation.

Test results presented indicate that a continuously variable exhaust second event can utilise Internal-EGR to increase the exhaust gas temperature and deliver a BSFC reduction by reducing reliance on post injection. Additional benefits demonstrated are a significantly shorter warm up and catalyst light-off time for reduced drive cycle and real world emissions together with the capability for LNT regeneration over more of the engine operating map. In combination with a LP-EGR system, results also indicate that Internal-EGR could eliminate the requirement for a HP-EGR system.

Background

In order to meet the demands of the WLTP and RDE testing being introduced from September 2017, new diesel engines will need to demonstrate both tighter control of engine-out emissions and the ability to maintain optimum performance of the exhaust after treatment system (EATS) under real driving conditions. In particular, minimising the warm up time of the EATS and maintaining tight control of emissions during the highly transient operation that will occur in the WLTC and RDE testing present a significant challenge.

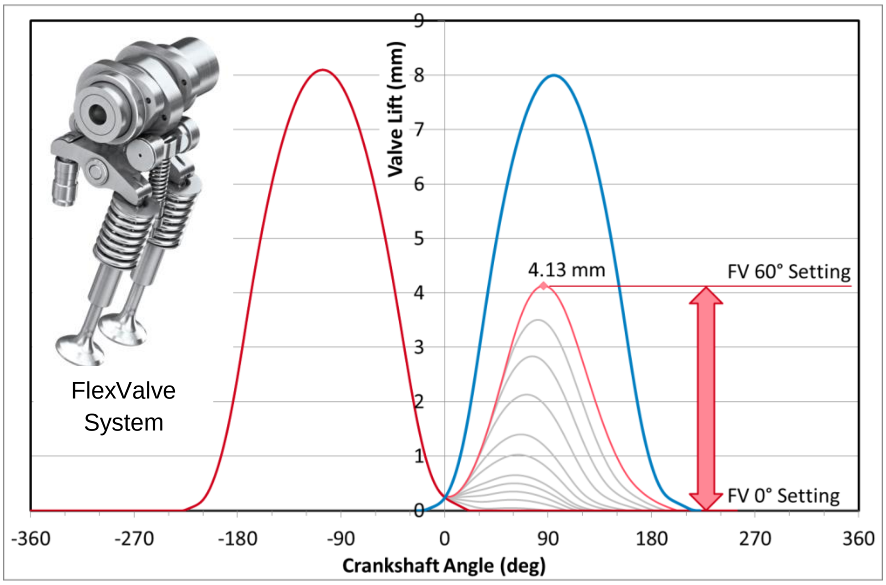
External EGR systems (eEGR) are already essential to control the NOx emissions of diesel engines and light duty applications are increasingly supplementing High Pressure EGR (HP-EGR) with Low Pressure EGR (LP-EGR) for medium to high load operation. Internal EGR (iEGR), in the form of residuals, is always present in any IC engine to some extent as a natural consequence of the gas exchange process, but in most cases iEGR is minimised in the interests of volumetric efficiency. Variable Valve Actuation (VVA) systems offer the opportunity to directly control the level of iEGR throughout the operating range of the engine, either by trapping exhaust gas in the cylinder during the exhaust stroke, or by drawing exhaust gas back into the cylinder during the intake stroke.

A variety of different VVA strategies have previously been proposed and tested that are able to control the level of iEGR that is generated [1] and production diesel engines incorporating VVA systems are now available in some vehicles. Comparison of these different strategies has concluded that secondary exhaust lift is the most effective method for increasing exhaust gas temperature (EGT) using VVA technology [2] and testing of a switchable exhaust secondary lift has demonstrated an in-cylinder and exhaust gas temperature increase of up to 40°C with a reduction of HC and CO emissions of 20% over the whole FTP cycle and 50% over first 200 seconds [3].

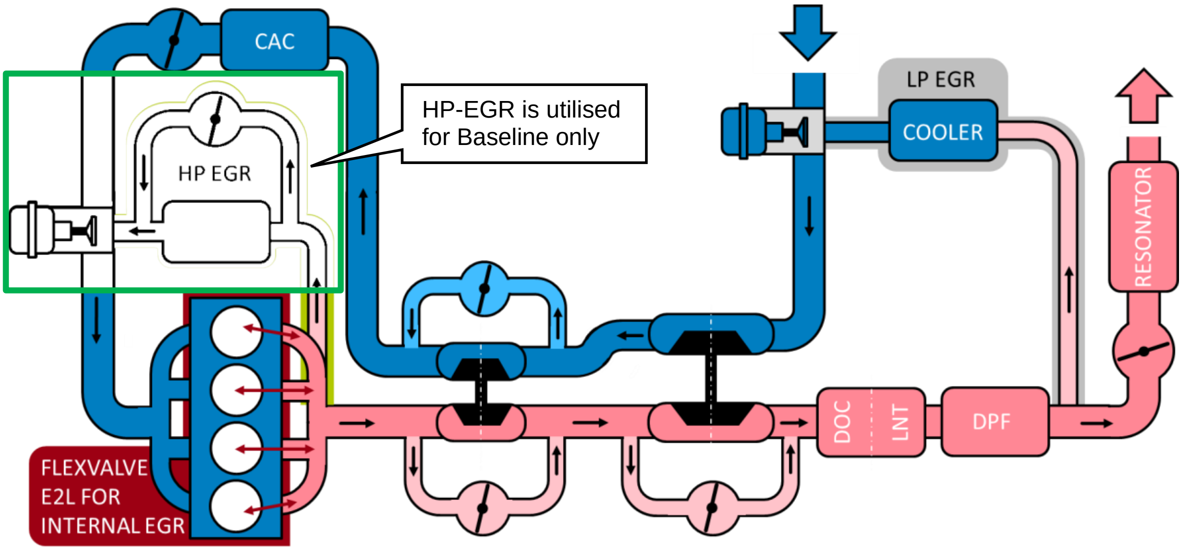
Continuously variable VVA (CVVA) systems such as FlexValve, offer a number of potential advantages over switched VVA systems because they can provide rapid and precise control of the volume of iEGR in response to transient demands. The benefits of using iEGR to increase exhaust gas temperature and reduce cold emissions has previously been demonstrated [4], as well as the potential to reduce EATS warm-up time with a lower BSFC penalty than Post Injection (PoI) [2]. There is also evidence to suggest that iEGR can reduce BSFC by up to 4% at part load after the engine warm-up phase is complete due to the reduction in intake pumping work [4].

Test Engine Configuration

Fired engine testing has been carried out using a 4-cylinder diesel engine equipped with a FlexValve system configured to generate a fully variable secondary exhaust valve event during the intake stroke. The layout of the engine with turbochargers, external EGR systems and EATS is shown in Figure 1, together with the family of valve lift curves utilized for the testing.



CAN Request	Exhaust 2nd Lift (mm)
FV 0°	0 (Parked)
FV 2°	0.05
FV 4°	0.2
FV 6°	0.35
FV 8°	0.50
FV 10°	0.65
FV 15°	1.03
FV 20°	1.40
FV 30°	2.13
FV 40°	2.84
FV 50°	3.50
FV 60°	4.13 (Max)



Summary of Engine Specification			
Displacement	1968cc	**Injection System**	CR 2500bar
Cylinders	DOHC - I4	**Turbocharging**	2-Stage WG
Bore	82	**EGR Systems**	HP-EGR, LP-EGR + FlexValve iEGR
Stroke	93.2	**Emission Standard**	Euro 6a

Figure 1: - Fired test engine configuration diagram showing FlexValve lift control & CAN request

As shown in Figure 1, the FlexValve system utilises a unique rocker mechanism to combine two different cam profiles in order to generate valve lift. The rocker system is operated by a concentric camshaft, mounted in a conventional position, which enables relative phasing of the two cam profiles. The relative phasing of the cam profiles dictates the way that the profiles are combined by the FlexValve rocker system and consequently determines the valve lift characteristic. The 2nd event lift of the test engine was controlled directly via a CAN request specifying the relative cam profile phase angle, as detailed in the table of Figure 1.

Whilst in this case the FlexValve system has been configured to generate a variable secondary exhaust valve event, the system is able to produce a wide range of other valve lift families having a variable main event, second event or both. The valve lift characteristics generated by the FlexValve system are defined by the cam profile forms, rather than the geometry of the rocker system and so the concept can easily be adapted to both diesel and gasoline engine applications. A particular advantage of the FlexValve system in diesel applications is that it naturally generates families of valve lift curves with fixed valve opening or fixed valve closing timing, maintaining valve to piston clearance.

Investigation Objectives

This investigation explores the potential for using a CVVA system generating a fully variable secondary exhaust valve lift as part of the emissions control system for a modern light duty diesel engine. In particular, different strategies for using VVA in coordination with existing engine systems such as post injection (PoI) and throttling in order to increase exhaust gas temperature are investigated and the potential to reduce the warm-up time of the after-treatment system is assessed.

As an integrated part of the emissions control system some other potential benefits of using an advanced VVA system are assessed, such as the potential for extending the areas of the operating map where LNT regeneration can take place and evaluating the combined effect of VVA with variations in geometric compression ratio.

Five different groups of tests have been carried out as part of this investigation as follows: -

- Steady state optimisation of EGR, throttling and injection strategies
- Engine warm up characterisation at specific speed / load sites
- Engine warm up over a simulated NEDC test cycle
- Investigation of EGR switching strategy
- Effect of iEGR on LNT regeneration

Steady State Optimisation Results

Two different iEGR strategies have been evaluated against the HP-EGR strategy of the base engine at four cycle representative operating points. Strategy 1 (S1) replaces HP-EGR with LP-EGR and assesses a range of iEGR settings both with and without post injection. Strategy 2 (S2) replaces all eEGR with a combination of iEGR and increased intake throttling. The engine operating points used for this investigation were as follows: -

1) 1500 rpm, 3 bar BMEP; 2) 1250 rpm, 1 bar BMEP; 3) 1000 rpm, 3 bar BMEP; 4) 2000 rpm, 4 bar

For each iEGR setting, intake throttle, rail pressure and injection timing were optimised for maximum exhaust temperature at a coolant temperature of 40°C. For Strategy 1, LP-EGR rate was then set to match the NOx output to the base engine setting, whilst keeping the centre of heat release, BSFC and particulate matter within acceptable limits. For strategy 2, the iEGR rate was increased in steps until the NOx level of the base engine was matched. To give a valid comparison between compression ratios for both iEGR strategies, equivalent crank angle timing for 50% heat-release was maintained.

It can be seen from Figure 2 that both strategies can deliver significant EGT increases measured before the DOC, and that similar levels are reached with both original and reduced CR, despite differences in Pmax. As expected, higher levels of iEGR result in higher EGT with both strategies, with S2 having up to 7% stronger heat-up behaviour compared with S1, for a given iEGR setting. This is due to the absence of cooling LP-EGR and lower mass airflow due to the reduced intake throttle opening. The results for S1 generally shows that more exhaust heating is achieved with iEGR than using just PoI (FV 0° setting). At operating point 1 a heating benefit of up to 16% at 1500rpm, 3 bar BMEP is indicated by the red arrows on the temperature graphs.

In addition to the higher heating potential of iEGR, the combination of iEGR + LP-EGR used in S1 demonstrates a generally lower BSFC penalty over the base setting than PoI + LP-EGR. The results using iEGR without PoI have a lower BSFC penalty than those using PoI without iEGR (FV 0°), and at operating point 1 the green arrows in Figure 2 indicate a BSFC penalty that is 4% lower. A BSFC benefit of up to 15% was observed at the other operating points investigated.

At all operating points S1 shows a small BSFC penalty over the baseline due to the increased throttling losses of the intake air and the higher eEGR rate caused by switching from HP-EGR to LP-EGR, which requires a corresponding retard of the main injection timing. The BSFC penalty for S2 is higher than S1 due to the increased throttling required to support a higher iEGR rate which generates increased pumping work.

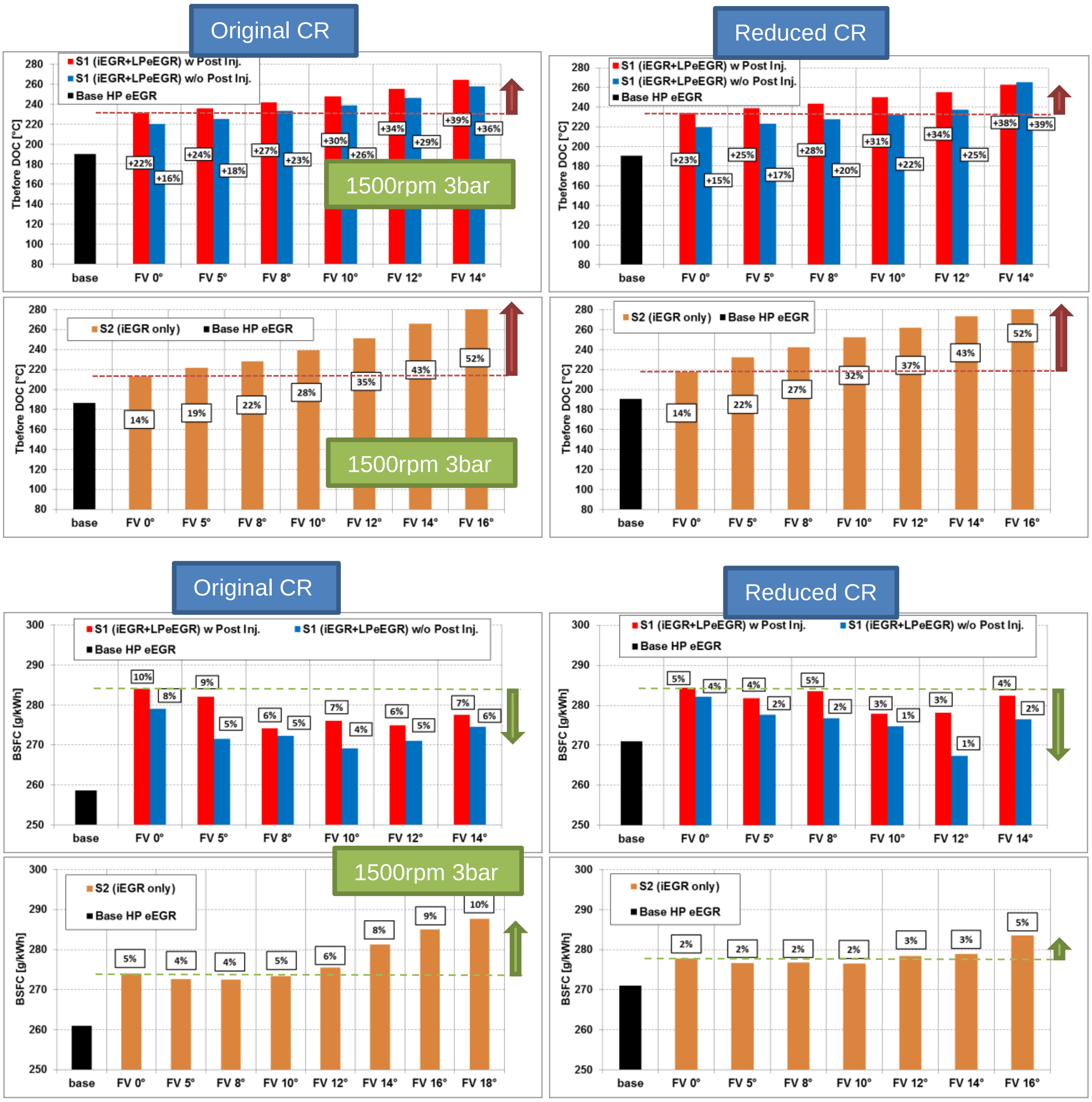


Figure 2: - Steady State Optimisation Results @ 1500rpm, 3bar BMEP (Operating Point 1)

A decrease in HC emissions with increasing rates of iEGR was measured for both S1 and S2 at all operating points, the benefits being sufficient to reduce the higher HC levels generated by the reduced CR configuration to the level of the original CR baseline. The significant HC increase associated with PoI could also be largely counteracted by using iEGR. CO levels also decreased with increasing iEGR for S1, and equivalent levels could be reached for both original and reduced CR, despite a large baseline increase with a reduced CR. PoI has a negligible effect on CO at the original CR and offers a decrease of around 2-3% in combination with the reduced CR. When using S2, CO levels drop initially but begin to rise back towards the baseline at higher levels of iEGR.

At an equivalent NOx level, PM emissions increase in proportion to iEGR at any given operating point due to the corresponding decrease in the lambda value, which reduces the O_2 available to oxidise carbon in the exhaust gas. In general S2 data shows a higher level of PM than S1 for equivalent NOx, due to a further lambda decrease caused by the increased throttling of the intake air.

In the steady state operation investigation, Strategy S1 shows good potential for extended periods of operation due to better control of BSFC and PM, but for shorter periods, the higher heating potential of strategy S2 could be beneficial. Increasing PM levels place a general constraint on the maximum iEGR level that can be used for heat-up although a significant increase over the low PM level of the base specification could be tolerated by the DPF, but nonetheless PM generation must remain within reasonable limits. Optimum iEGR settings for subsequent heat-up tests have been selected based on OEM guidelines for acceptable DPF regeneration frequency.

Cold Start Heat-Up Testing

Exhaust Gas Temperature (EGT) heat-up performance, before and after the DOC, was measured on a time base at two operating points; 3bar BMEP at 1000 and 1500rpm, each with a starting coolant temperature of 25°C. Higher EGT before the DOC enables faster control of CO and HC, but higher temperatures after the DOC reduce the time required for the NOx after treatment system to reach peak absorption/conversion efficiency.

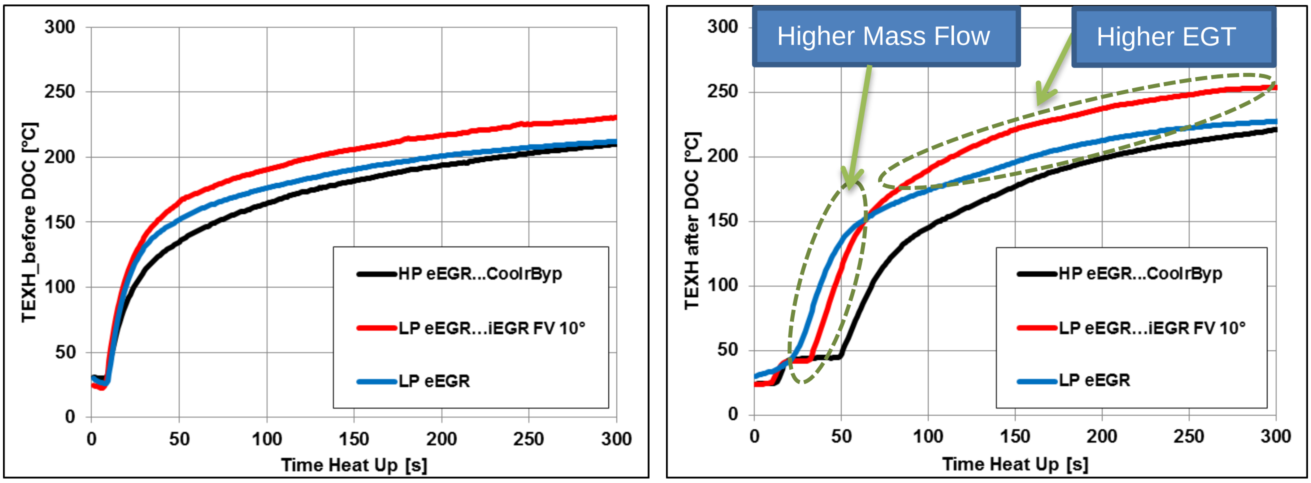


Figure 3: - S1 Heat up Curves – 1500rpm 3bar

Temperature before the catalyst is a product of exhaust gas temperature only and therefore performs as expected from the steady state testing, however temperature after the DOC vs time is more complex, as shown in Figure 3. The warm up performance using LP-EGR exceeds that of the standard HP-EGR with cooler bypass, but in the first 70s heating without using iEGR is faster due to a higher exhaust gas mass flow. After 70s a more rapid heating of the DOC is achieved with iEGR, here exhaust gas temperature dominates despite a lower mass flow. A time advantage of 88 s, over HP-EGR, with a cooler bypass, for heating up to 200°C, is demonstrated using LP-EGR + iEGR. The addition of PoI would lead to a further reduction in Time to Temperature (T2T); however the steady state testing has shown that this would bring disadvantages in terms of HC and BSFC.

Heat-up testing with reduced CR produced similar results to the original CR, however it was necessary to change the iEGR setting to FV 15° (from FV 10°) to give the best compromise between exhaust gas temperature and combustion stability. A lower operation point was also investigated at 1250rpm, 1bar BMEP where the reduced CR could not reach the same level of EGT using S1. For comparison, S2 was implemented using the reduced CR and a significantly faster heat-up was demonstrated. A summary of T2T benefits achieved with iEGR at different speed/load points, against a baseline using LP-EGR only, is shown in Table 1.

N (rpm)	BMEP (bar)	Compression Ratio	FV Position S1 [S2]	T2T Reduction (s)*	T2T Reduction (%)*
1000	3	Original	8°	124	**31%**
1250	1	Original	15°	86	**20%**
1250	1	Reduced	15°	270	**45%**
1250	1	Reduced	[10°]	345	**58%**
1500	3	Original	10°	130	**44%**

Table 1 – Heat up iEGR settings

The T2T reduction shown in Table 1 compares the time taken using iEGR to achieve a set temperature with that of a baseline using LP-EGR. The value is determined by taking 80% of highest temperature reached without iEGR (LP-EGR only) and comparing to the time taken to reach this temperature using iEGR.

The range of iEGR settings shown in Table 1 for the different operating points demonstrates that a 2-Step VVA system represents a very significant compromise. The optimum iEGR setting varies with operating point to give a balance between EGT, NOx, PM, BSFC, HC and CO and a fully variable iEGR system is therefore required to ensure optimum emission performance over the widest possible area of operation.

NEDC with iEGR 2-position switching

For a cycle heat-up evaluation, the FlexValve iEGR was configured to behave as a switching system (iEGR on or off) to check the effect over a complete test cycle. Strategy 2 (no eEGR or PoI) was used because of its lower testing time requirements for calibrating to a full transient cycle, and a comparison was then made between the base engine and in the following two settings:

1) Throttle closed without iEGR (FV 0°)
2) Throttle closed with iEGR (on/off – FV 10°/FV 0°)

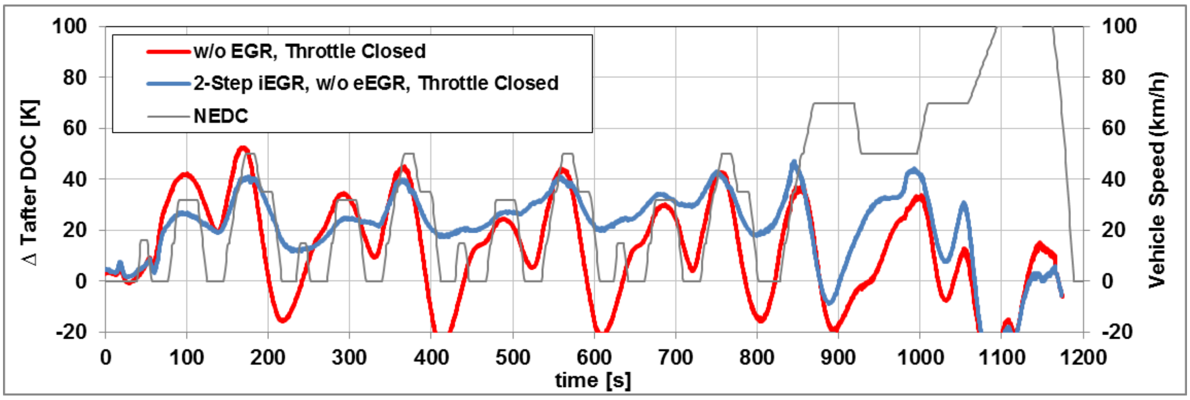


Figure 4: - Heat up Characteristic for Simulated NEDC Cycle

Figure 4 compares the difference from the HP-EGR baseline of the other two strategies and shows that 20-40k higher EGTs after the DOC are possible, with iEGR maintaining a more consistent temperature increase during low load and stationary periods. Some periods with high NOx were found at higher loads due to the limitation of the 2-step iEGR test configuration. PM peaks are within manageable limits of the DPF; but again further reduction should be possible, based on evidence from the steady state tests, using continuously variable iEGR and a more detailed calibration effort. Further investigations are therefore required to assess the true cycle potential of iEGR and a full calibration study over WLTP and RDE conditions is required to enable this.

The after-treatment system has to be kept warm during stop-go traffic or long periods of engine overrun and iEGR shows good potential to manage EGT in this area of operation. Early LP-EGR activation offers an improved BSFC/DeNOx balance over HP-EGR, however it can also lead to lower exhaust gas temperatures during normal running which could be counteracted by the use of iEGR.

Switching Strategy

LP-EGR offers the reduction of engine-out NOx at a lower BSFC compared to HP-EGR. However the introduction of exhaust gas upstream of the turbocharger also has the danger of forming condensation which could cause damage to the compressor wheel. The EGT after the DPF is an important indicator to manage the water droplet risk, and increasing EGT enables an earlier switch to the more efficient LP-EGR. A short investigation was therefore made to consider the scenario where no HP-EGR is available and high EGT is reached with iEGR only and intake throttling.

LP-EGR switching was tested at a steady state operating point of 1500rpm 3bar BMEP, to check the effect on combustion stability and exhaust gas emissions. Due to restricted ECU functionality it was not possible to use LP-EGR with slowly increasing rate, so a direct switch from iEGR + throttle to LP-EGR was investigated.

Despite the step change in LP-EGR, no unacceptable spikes in emission values are seen in the time-base data and 50% heat release timing and peak cylinder pressure indicate that combustion remains stable for a constant accelerator position. Combustion noise level was also continuous, indicating that no customer-detectable issues occur during the switching of modes.

LNT Regeneration

Regular regeneration of the LNT is needed during operation because as the quantity of NOx stored in the LNT increases, its storage efficiency decreases. Over the full duration of the WLTC it is likely that between 4 and 10 LNT regenerations will be required to maintain efficiency, each lasting between 3 and 10 seconds [5]. Regeneration of the LNT can only take place under rich operation, with an associated BSFC penalty, and this requirement restricts regeneration to a limited area of the engine operating map.

An LNT regeneration investigation has been carried out to determine if it is possible to achieve the deNOx rich combustion mode at lower injection quantities and at lighter engine loads using iEGR. Three operating points were selected: 1) 1500 rpm, 2.2 bar BMEP; 2) 1500 rpm, 1.7 bar BMEP; 3) 1250 rpm, 1.7 bar BMEP.

At each operating point, two different strategies were compared at a coolant temperature of 80°C:

a. Original engine setting (Pilot/Main/After/Post1)

b. iEGR @ FV 10° setting (Inactive eEGR and pilot 3)

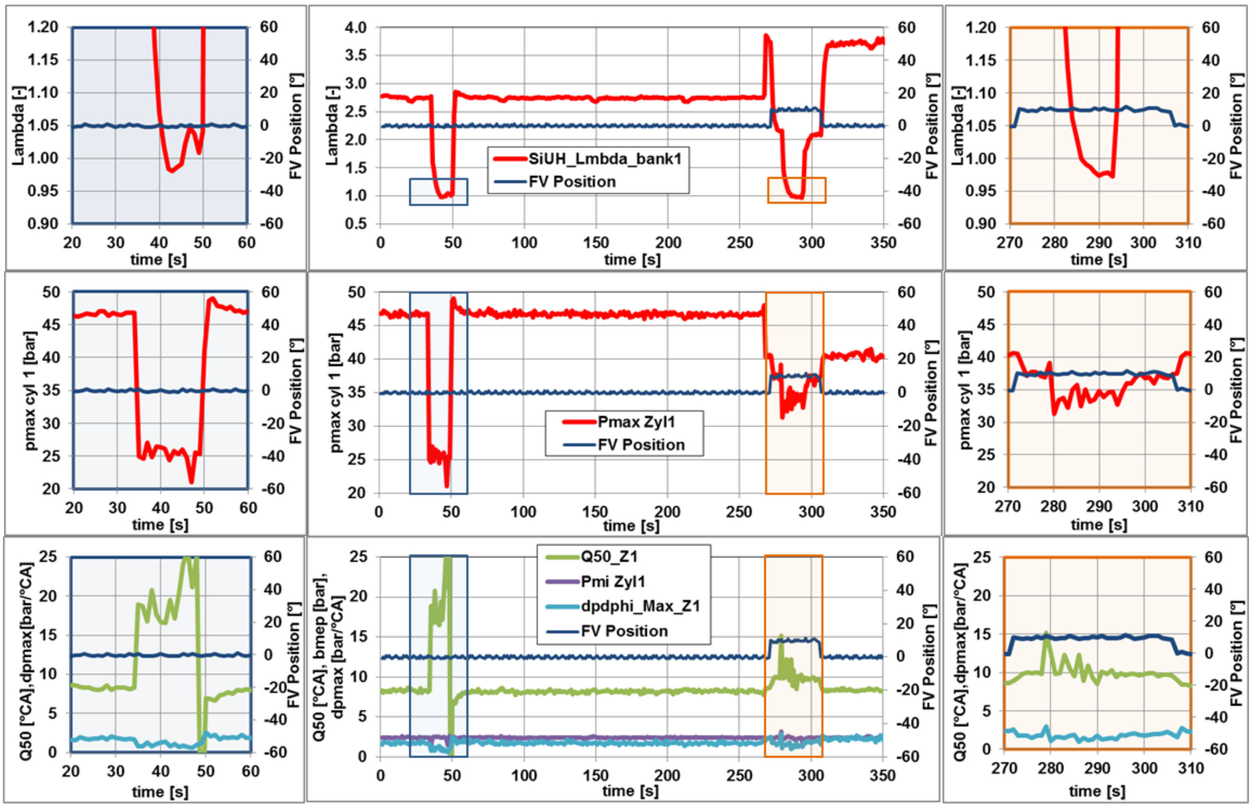


Figure 5: - LNT Regeneration Strategy a vs. Strategy b

Figure 5 shows the results at operating point 3, but these are also indicative of the results at operating points 1 and 2. The figure shows the regeneration strategy ‘a’, detailed in the blue area followed by strategy ‘b’ detailed in the orange area. It can be seen from the graph of lambda values that without iEGR it is not possible to reach a rich combustion mode completely. The second event with iEGR active shows a sustained lambda value below 1, demonstrating a successful rich combustion mode for the complete LNT regeneration event even at this very low load. The maximum cylinder pressure indicates a significant drop for the first LNT regeneration (without iEGR) from 47 to 25 bar, but using iEGR, the pressure drop reduces by 40% to 34 bar. This indicates a higher efficiency due to earlier combustion, which is also demonstrated by the position of the 50% rate-of-heat-release (Q50) shown in Figure 5. In conventional operation the Q50-position occurs at 8-9° crank angle ATDC, which is quite near the optimum in terms of efficiency. At the first LNT regeneration using HP-EGR, the Q50-postion switches from 8° to around 20° degrees ATDC. In contrast, using iEGR only causes a Q50-shift from 8° to around 10° ATDC.

Conclusions and Future Work

FlexValve iEGR has demonstrated significant potential for improving the effectiveness of diesel exhaust after-treatment system. The generation of iEGR, via a fully variable exhaust valve 2nd event in the intake stroke, reduces engine-out HC emissions and enables increased exhaust gas temperatures for earlier activation of catalyst systems and the use of a LP-EGR circuit - potentially without the need to use HP-EGR. Testing has shown that the heat up benefits are consistent when evaluated with two different compression ratios, reduced compression ratio also tending to deliver a further HC and a PM reduction.

Equivalent NOx levels to the HP-EGR baseline are reached at 4 cycle representative steady points by a combination of iEGR and LP-EGR for both reduced and original compression ratio variants. In combination with improved heat-up at a reduced fuel penalty compared to PoI, the results indicate the potential to delete the HP-EGR system, reducing cost, weight and cooling requirements, whilst increasing available packaging space close to the engine. In order to verify this potential, basic tests have been carried out which confirm the ability to make a smooth transition between an iEGR with intake throttling operating regime to a LP-EGR regime.

A further benefit of iEGR is the ability to extend the area of the operating map where LNT regeneration through rich operation can take place. This is demonstrated at lower loads where effective regeneration has been achieved at lower injection quantities with iEGR compared to HP-EGR.

Whilst transient investigations have not been the focus of this investigation, the use of iEGR in an on/off configuration for a simulated NEDC cycle has revealed some further potential. The ability for iEGR to maintain exhaust temperature more effectively during the stationary periods of the cycle has been demonstrated, as well as highlighting the difficulty of using iEGR in an on/off configuration due to the fast response rate of the system in comparison to the surrounding systems. This indicates that the FlexValve system has potential to work well as a continuously variable iEGR control in a model based NOx control system [6].

Building on the potential demonstrated by this paper, further work is required to evaluate a fully calibrated iEGR + LP-EGR concept against Euro 6d test conditions. Low Temperature behaviour and transient operation are particular areas of focus. Shorter reaction times to eliminate NOx-peaks when using a NOx-calculation model in the ECU, show potential benefits over HP-EGR systems.

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