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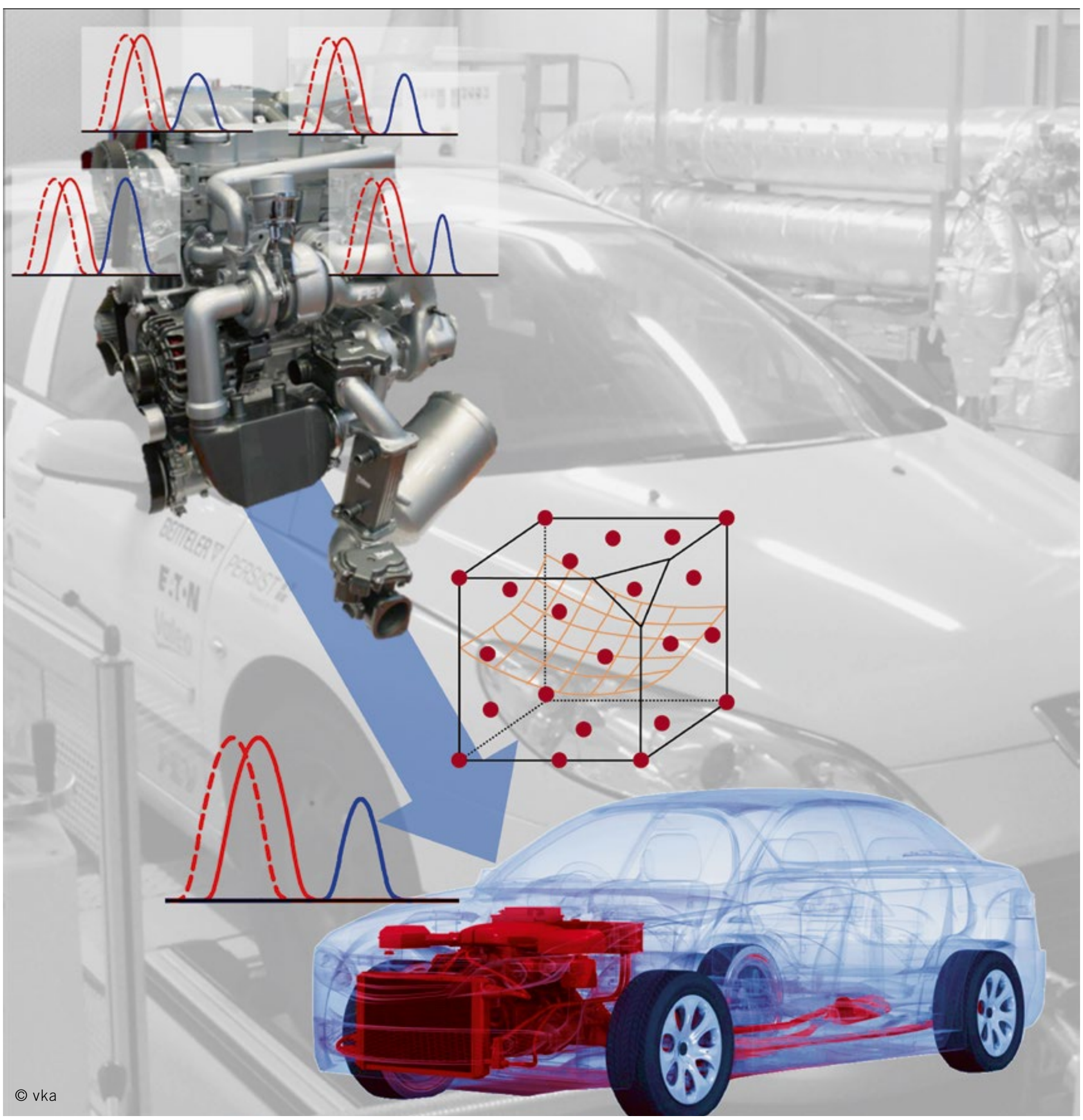
# Potential of Valve Train Variabilities on Gas Exchange of Diesel Engines II

The variable valve train delivers multiple potentials to achieve future emission legislations by a reduction of engine out emissions and control of exhaust gas temperature. These characteristics have been demonstrated by numerous research projects in the past. As part of a FVV research project, the potential of a variable valve train in passenger car diesel engine application has been analysed and then evaluated at the Institute for Combustion Engines of RWTH Aachen University with the help of extended experimental investigations on a laboratory test bench and a demonstrator vehicle. The results of the research can be used to generate operation strategies to support the engine cold start and heat-up behaviour.



## 1 MOTIVATION

The further development of passenger car diesel engines is a continuous process. Since 2015, the European Commission has decided that the $CO_2$ fleet emissions have to be limited and this upper limit will be decreased in coming years [1]. As a consequence of the efficiency improvements, more and more decreased exhaust gas temperatures result. Thus, reduced efficiencies and conversion rates of the exhaust aftertreatment components occur.

Besides that, the cold start and heating phase of passenger car diesel engines is essential to achieve today's emission legislation target. The pollutant emissions HC and CO, which are produced in this phase, support more than 70 % of the total cycle results. This is due to the very low conversion efficiency of the exhaust aftertreatment components, because of the low temperature level. The future requirements provide a further strengthening of the emission legislation, thus, these phases will become even more important. A fast heat-up of the exhaust aftertreatment is aspired without fuel consumption penalties to reduce engine out emissions efficiently. A variable valve train can be an additional technology to fulfil both requirements on a diesel engine [2].

## 2 TEST OBJECTS OF THE EXPERIMENTAL INVESTIGATIONS

The experimental full engine investigations within the research project have not only considered steady state investigations on a laboratory test bench, but also dynamic experiments on a demonstrator vehicle. Both engines are built on the same base engine and have an identical combustion system. The maximum injection pressure at the demonstrator vehicle is 2000 bar and at the laboratory test bench, it amounts to 2500 bar. However, this difference did not affect the considered engine operation ranges of this research project. In order to ensure an optimal cylinder filling and charge motion, the intake port layout considers a filling port and a tangential port. Additionally, both intake valves are equipped with seat swirl chamfers to provide an improved mixture formation at low and medium loads. The low compression ratio, high peak firing and injection pressure capability in combination with the advanced cooled EGR concept allow lowest particulate emissions and achieving Euro 6b $NO_x$ emission legislation limits in NEDC without an active $DeNO_x$ aftertreatment system. Further information about both engines can be taken from **TABLE 1** and [3 to 5].

## 3 INVESTIGATED VALVE TRAIN VARIABILITIES

The essential results of the former research project No. 1027 [6] have been considered to define productive valve train variants for the experimental investigations. The different investigated valve train variabilities are shown in **FIGURE 1**. Detailed information of the variants can be found in [2]. The exhaust cam phasing offers

| – | Unit | Laboratory | Demonstrator vehicle |
|---|---|---|---|
| **Bore × stroke** | mm | 75 × 88.2 | 75 × 88.2 |
| **Displacement** | $cm^3$ | 1560 | 1560 |
| **Valves per cylinder** | 1 | 4 | 4 |
| **Maximum valve lift** | mm | 8 | 8 |
| **Maximum cylinder peak pressure** | bar | 160 | 160 |
| **Fuel injection system** | – | Common-rail system | Common-rail system |
| **Compression ratio** | 1 | 14 | 15.1 |
| **Maximum injection pressure** | bar | 2500 | 2000 |
| **Boosting system** | – | Two-stage | Single-stage |
| **Charge air cooling** | – | Two-stage, water-cooled | Single-stage, water-cooled |
| **Glow plug** | – | Yes | Yes |
| **EGR** | – | Internal, cooled HP- and LP-EGR | Internal, cooled HP- and LP-EGR |
| **Valve train variabilities** | – | Switchable intake rocker arm<br>Exhaust cam phaser | Switchable intake rocker arm<br>Exhaust cam phaser |
| **Specific power output** | kW/l | 100 | 60 |
| **Norm** | – | Euro 6b | Euro 6b |

**TABLE 1** Specifications of the full size diesel engines (© vka)

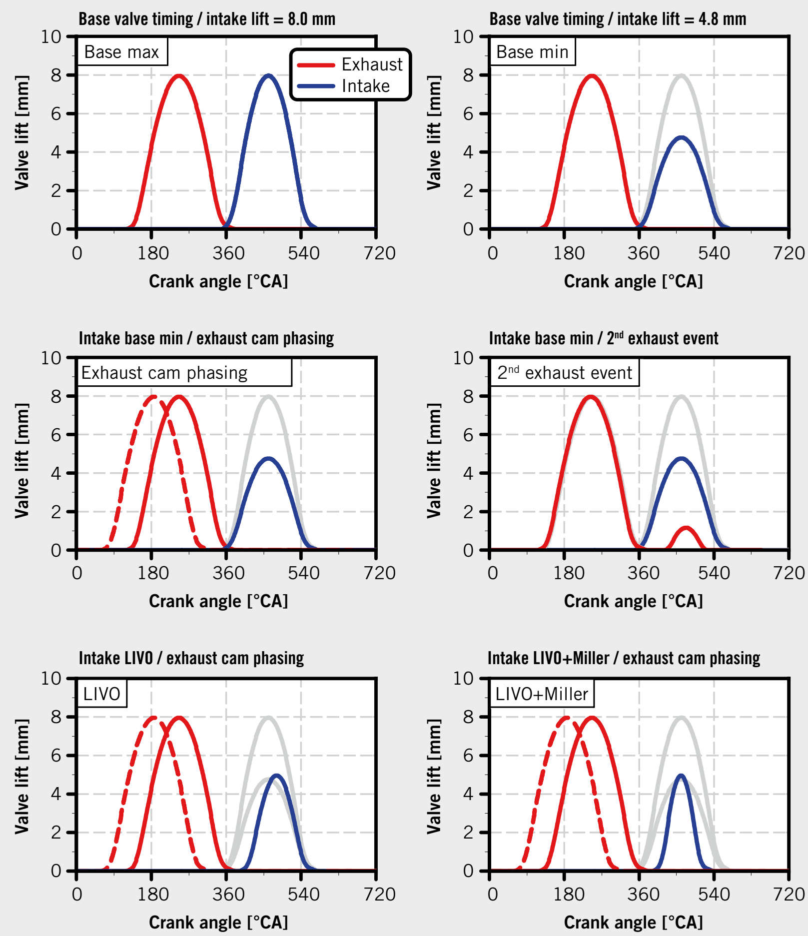



**FIGURE 1** Selected valve train configurations for the experimental investigations (© vka)

the possibility to generate internal EGR, but produces expansion and gas exchange losses and stores the internal EGR at the intake ports. The Late Intake Valve Open (LIVO) with an exhaust cam phasing keeps the internal EGR inside the combustion chamber and prevents the storage of internal at the intake ports. That leads to an improved gas exchange, due to the complete expansion of the compressed residual gas before the intake valve opens. A further reduction of the intake event delivers an early closing of the intake valves and causes a reduced cylinder filling considered at LIVO+Miller.

| Cam lobe curve | Unit | Base Max | LIVO | LIVO+Miller |
|---|---|---|---|---|
| **Maximum valve lift** | mm | 8 | 5 | 5 |
| **Intake event length at 0 mm valve lift** | °CA | 225 | 178 | 138 |
| **Engine speed** | rpm | 1000 – 2600 | | |
| **BMEP** | bar | 0.4 – 18 | 0.4 – 8 | |
| **Exhaust cam phaser** | °CA | -35 – 0 | | |
| **Desired boost pressure** | – | Scaled ± 15 % | | |
| **Desired $NO_x$ concentration level** | – | Scaled ± 20 % | | |
| **HP-/LP-EGR distribution** | – | 0 – 100 % of LP-EGR | | |
| **Coolant temperature** | °C | 90 | 30, 60, 90 | 45, 90 |
| **Injection pattern strategy** | – | Main and single pilot | | |
| **Injection timing** | – | Centre of combustion control | | |

**TABLE 2** Parameter matrix of global DoE investigations (© vka)

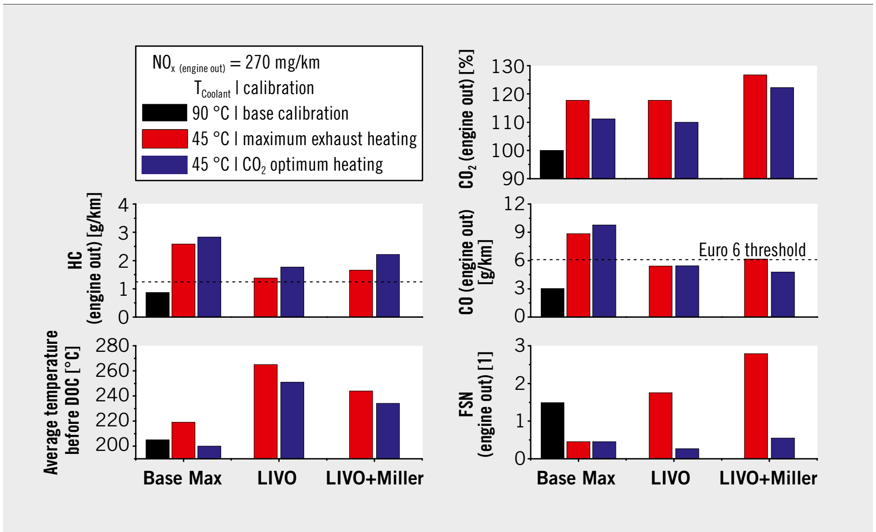



**FIGURE 2** Summary results of the global model prediction of the 1st phase of WLTC (© vka)

## 4 CYCLE PROJECTION BY MEANS OF GLOBAL DOE

The experimental investigations at the laboratory test bench concentrate on steady state measurements by a variation of different parameters. The parameter space is summarised in **TABLE 2** of these experiments. The results were used to generate global DoE models for predicting the 1st phase of the WLTC (Worldwide Harmonised Light-duty Vehicles Test Cycle), the low load phase. Afterwards, global optimisations have been carried out for the three intake lift configurations. The main focus of the analysis laid on the heating potential of the exhaust gas and the engine out emission reduction. An Euro 6 $NO_x$ engine out emission level of 270 mg/km has been defined as upper limit related to the WLTC. The results are summarised in **FIGURE 2**.

A first analysis was carried out for base valve lift variant Base Max at a coolant temperature of 90 °C. The results show that the engine out emissions of HC and CO stay below the Euro 6 threshold, while under such hot engine conditions, a variable valve train system (VVT) only provides minor fuel consumption advantages. Therefore, the coolant temperature has been decreased to simulate the cold start and heat-up phase in a second step. The evaluation considered an averaged coolant temperature of 45 °C at two different heating scenarios. On the one hand, a maximum exhaust heating in red and on the other hand, a $CO_2$ optimally moderate exhaust heating in blue. The results show for variant Base Max that the HC/CO engine out emissions have increased significantly and clearly exceeded the Euro 6 threshold. This is caused by flame quenching near the cylinder walls and a reduced post oxidation by the low combustion temperature. The $CO_2$ emissions are increased by 10 % that is manly caused by an increased friction under these cold conditions. The averaged exhaust gas temperature upstream DOC is on a similar level compared to hot engine conditions. An extended ignition delay leads to a reduction of soot emissions.

Both VVT variants LIVO and LIVO+Miller generate internal EGR through the negative valve overlap by the exhaust cam phasing. The hot internal EGR delivered an improved post oxidation of HC by 47 % and of CO by 40 %. According to this, the variant LIVO+Miller provides a strong cylinder filling reduction with a lower post oxidation potential in the entire considered range. The averaged exhaust temperature upstream DOC increases for variant LIVO by 46 to 51 K and for LIVO+Miller by 25 to 34 K. These results were achieved without any drawback in $CO_2$ emissions for variant LIVO and a drawback of 10 % for LIVO+Miller compared to the variant Base Max under cold conditions. Furthermore, the model prediction of soot emissions delivers no drawback for the $CO_2$ optimally scenario, although the internal EGR delivers an inhomogeneity of EGR in the combustion chamber, a lower air-to-fuel ratio is produced and the ignition delay is reduced. On the other hand, the reduced air mass leads to an increase in soot emissions for the red scenario of a maximum exhaust heating.

The projections have proven the potential of a VVT system to support the engine cold start and heat-up phase. Therefore, dynamic measurements on a demonstrator vehicle were carried out at a roller chassis dynamometer to verify the potentials under transient operation.

## 5 DYNAMIC INVESTIGATIONS ON THE DEMONSTRATOR VEHICLE

The vehicle investigations considered the first phase of WLTC again under standard cold start conditions (22 °C) whose are comparable to the testing conditions at the laboratory engine. The experimental program contained the intake lift configuration Base Max, Base Min and LIVO only, due to the higher expected potential based on the model prediction results. The variant Base Min is characterised by a reduced intake lift compared to Base Max. Both variants Base Min and LIVO were investigated with an exhaust cam phasing, whose calibration was taken from the model prediction of the $CO_2$ optimally scenario, and compared against Base Max without any exhaust cam phasing, **FIGURE 3**.

The demonstrator vehicle is equipped with a closed coupled DOC/DPF only, whereby the $NO_x$ engine out emissions are still evaluated instead of tailpipe emissions. The EGR calibration achieved the $NO_x$ emission target for all variants. However, the HC and CO emissions downstream the DOC exceeded the Euro 6 threshold for variant Base Max, due to the high engine out emissions at engine cold start.

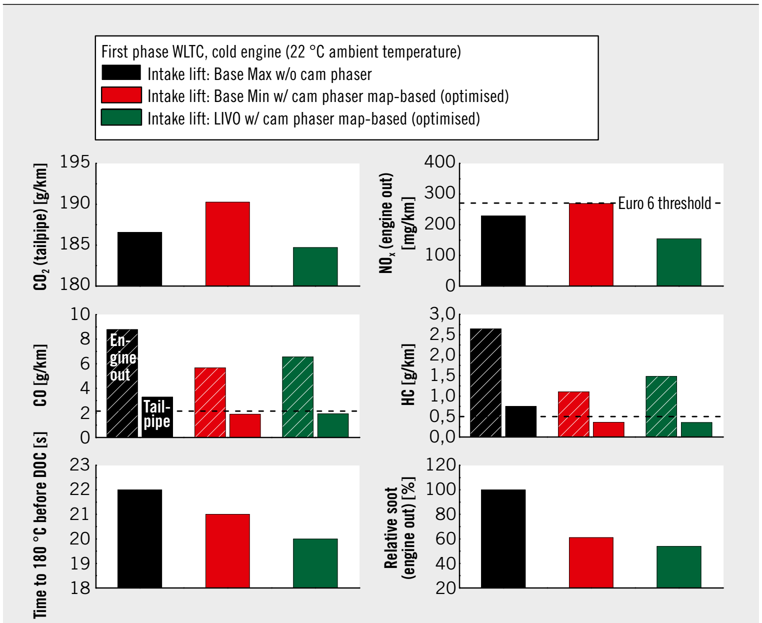



**FIGURE 3** Summary results of the transient experiments on the demonstrator vehicle of the 1st phase of WLTC (© vka)

The internal EGR, which is generated by an exhaust cam phasing for variant Base Min, also confirms the potentials of an improved HC/CO post oxidation by the vehicle investigations, whereby the tailpipe emissions are dropped below the Euro 6 threshold. Furthermore, a faster heat-up of the DOC after engine start has been detected by the usage of internal EGR, through an evaluation of the temperature upstream DOC.

The conventional opening of the intake valves at variant Base Min with an exhaust cam phasing produces increased gas exchange losses and thereby increased $CO_2$ emissions. These losses could

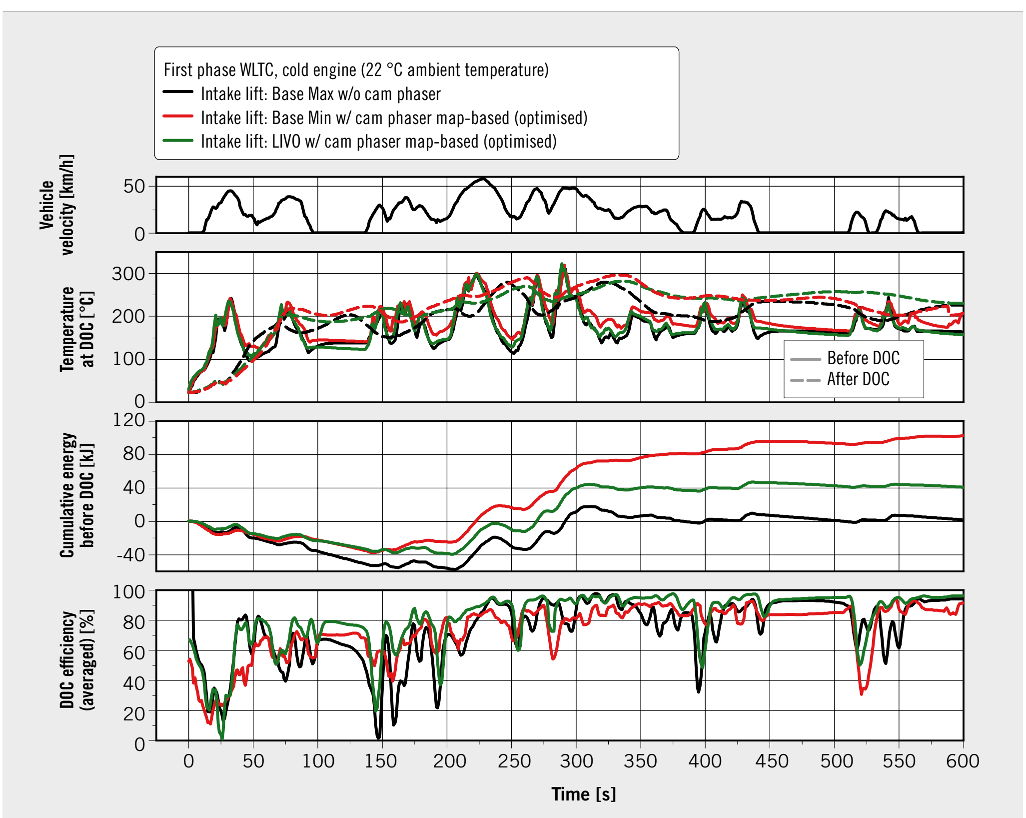



**FIGURE 4** Impact and reaction of the DOC of the first phase of WLTC (© vka)

be neglected by a retarded opening of the intake valves, wherefore the variant LIVO does not lead to a fuel consumption drawback. The reduced intake valve lift of these two variants achieved an improved mixture formation through the seat swirl chamfers and led to reduced soot emissions.

A more detailed evaluation of the exhaust temperature, the energy upstream DOC and the averaged DOC efficiency versus time are shown in **FIGURE 4**. The temperature upstream DOC shows an increase by 40 K through an exhaust cam phasing only, because of the generated expansion and gas exchange losses. A combination of variant LIVO with an exhaust cam phasing increases the exhaust temperature by 15 K and basically comes from the reservation of internal EGR inside the combustion chamber. Both variants show a gently inclined gradient for the temperature downstream DOC by the exhaust cam phasing, because the improved post oxidation lowers HC/CO engine out emissions and reduces the exothermal reaction inside the DOC. The increased temperature upstream DOC leads to a clear increase of energy into the DOC, although the exhaust cam phasing reduces the exhaust mass flow rate. This can be seen in the cumulated trend. Furthermore, this effect is not only supported by the high exhaust temperature, but also by a reduced cool down of the DOC at phases of tip out and engine idling during the cycle. In parallel an extended retention time of hot exhaust gas inside the catalytic converter is achieved within these phases. This results in an improved DOC conversion rate and increased efficiency by 15 %.

## 6 SUMMARY

This project impressively showed the potentials of a variable valve train system in a passenger car diesel application by using different approaches, like cycle projection by global DoE models and dynamic vehicle measurements. A retarded intake valve opening in combination with an exhaust cam phasing has improved the post oxidation of HC/CO engine out emissions by 47 %, increased exhaust gas temperature upstream DOC by 51 K and no drawback in $CO_2$ emissions by some model prediction based on steady state test bench measurements under cold engine conditions of 45 °C. Vehicle investigations on a roller chassis dynamometer have approved the model results. The VVT variant LIVO with an exhaust cam phasing has achieved improved engine cold start and heating and increased DOC conversion rates by the generated internal EGR. The obtained findings impressively demonstrated the potentials of a variable valve train system to support the cold start and heat-up behaviour, in terms of exhaust temperature management, engine out emission reduction as well as response, light off and regeneration behaviour. The research project was able to highlight the advantages of a VVT system for diesel engine applications.

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