

Investigation of VVA-Based Exhaust Management Strategies by Means of a HD Single Cylinder Research Engine and Rapid Prototyping Systems

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ABSTRACT

Heavy Duty (HD) Diesel engines fulfill the current NO_x limits by a sophisticated combination of in-cylinder technologies and an aftertreatment system. In the face of current testing cycles with low average load and efficiency/CO₂ demands measures for the provision of an adequate exhaust temperature become a development core.

An alternative to common exhaust management strategies could be variable valve actuation (VVA). Hence a self-developed camless valve actuation system was implemented on a single cylinder research engine to investigate potential strategies. As these investigations require an appropriate test bench setup the paper consists of two parts. The first part describes the design process of the test bench and focuses on the Rapid Prototyping Systems (RPS) that enabled its operation. The second part discusses the results of different VVA based exhaust management strategies and gives an outlook to further investigations.

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INTRODUCTION

The development of HD Diesel engines on the one hand has been dominated by the successive decrease of PM and NO_x emission limits and on the other hand by the demand for minimal fuel consumption and the reduction of CO₂ emissions respectively. On the engine side these conflicting priorities led to the implementation of technologies like high pressure direct injection, cooled external exhaust gas recirculation (EGR) or controlled turbocharging so that complex aftertreatment systems had been avoidable in the past [1, 2, 3]. Though considering the current and upcoming NO_x emission limits [4] at least a NO_x aftertreatment seems presently inevitable for all affected engines in on- and off-road applications [5]. Because of the fragmentation of the HD engine market various configurations for the overall system of the engine and the aftertreatment can be envisaged. Ideally the combination of in-cylinder technologies and aftertreatment components is tailored to every specific

application to allow the calibration of an optimal operating performance.

In [Figure 1](#) an aftertreatment system configuration typically used in long-haul trucks is shown schematically. It is given here as a representative for the numerous other possible aftertreatment setups as it contains widespread components to process all presently limited pollutants.

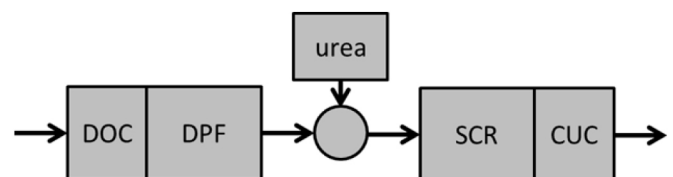


Figure 1. Schematic of a long-haul truck aftertreatment system, see e. g. [6, 7] for details

To enable the intended aftertreatment processes the physical properties of the exhaust gas flowing through this system should comply with the following requirements.

- Adequate residual oxygen content as a function of the current overall system operating status to enable the particular aftertreatment reactions [8, 9]
- Space velocity matching the aftertreatment system dimensioning range
- Rapid achievement and maintenance of a system inlet temperature between 200 and 450 °C in order to realize
 - DOC-light-off for the oxidation of HC, CO and NO
 - Passive regeneration of the DPF with NO₂
 - Urea hydrolysis
 - Optimum NO_x conversion in the SCR and CUC light-off for the reduction of slipped NH₃
- Mass-based exhaust NO_x-PM-ratio above 20 for the passive regeneration of the DPF [6]
- Controlled achievement of a temperature above 500 °C for the active regeneration of the DPF with O₂ if required

Many part load engine operating situations occurring in current engine testing scenarios or in real world situations e. g. of disposal vehicles or city busses prohibit meeting the above listed requirements. Thereby an adequate exhaust temperature often is the main challenge. Those operating conditions require active exhaust management (EM) measures to keep the aftertreatment system working. Examples for conceivable EM constituents are given in Figure 2.

air path	fuel path	misc.
EGR valve	injection	heater / burner
turbocharger control	exhaust injector	insulation
EGR cooler & air cooler	fuel / fuel additive	component arrangement
exhaust and intake flap(s)		transmission / hybridization
VVA		waste heat utilization

Figure 2. Examples of conceivable EM constituents

Ideally an ECU-implemented EM controller can adjust several EM actuating elements simultaneously to independently adapt the parameters exhaust mass flow, exhaust temperature and exhaust oxygen content [9, 10] to the current requirements of the aftertreatment system. At the same time avoiding any extra fuel consumption caused by these adjustments has top priority. However, series EM strategies often rely on engine throttling and/or fuel path

adaptations. Alternatively a VVA system could be used to gain further EM degrees of freedom.

The potential of VVA for HD Diesel engines has been mainly investigated in connection with the following fields. The references are given as examples for several other studies that can be found.

- Engine braking [11]
- BSFC optimization [12]
- Alternative combustion concepts [13]
- Variable swirl [14]
- Transient Operation [12]

Interrelated investigations focusing particularly on the potential of VVA systems as EM devices for current HD Diesel engines have not been published yet although commercial applications already have been launched, e. g. in form of an exhaust side camphaser [15]. However, promising results can be found in other VVA studies for HD Diesel engines. De Ojeda [16] examines early inlet valve closings (EIVC) that lead to an extended ignition delay with increasing pressure gradients, a notable exhaust gas temperature increase and a reduction of fuel consumption for a constant combustion phasing. Lombard and Forestier [17] observe similar effects for early and late inlet valve closings (LIVC) but discover a fuel penalty for a constant start of injection (SOI).

The aim of the present study is to investigate basic principles of various VVA-based exhaust management strategies also altering other valve timings than IVC. This allows interrelated comparisons between different approaches. Furthermore two of the main objectives were to isolate valve timing effects from other engine parameters by several closed-loop controls and to orient the investigations towards current engine operation conditions arising among other things from the above listed aftertreatment requirements. As the pursuit of these objectives needs an adequate test bench setup the paper consists of two parts. The first part summarizes the development of important test bench components like the VVA system and focuses on the rapid prototyping systems used to perform the test runs. The second part discusses the results of different VVA based exhaust management strategies in view of the stated objectives and gives an outlook to further investigations.

PART 1: TEST BENCH DESIGN

Single Cylinder Research Engine

The engine for the present study is derived from the series production engine MAN D20. The cylinder block and the cylinder head are especially designed for a single cylinder application and are mounted on the crank case of an AVL FM 520 research engine with a stroke of 140 mm.

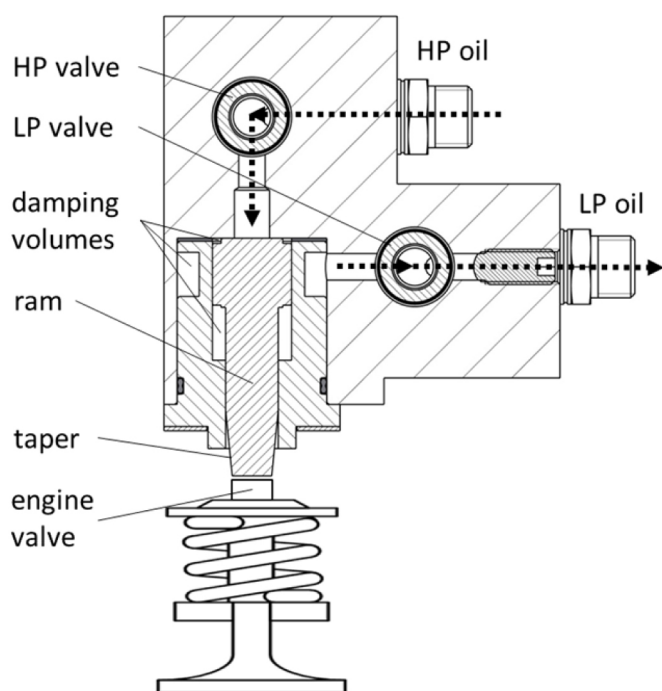
Table 1. Engine specifications

Series	MAN D20
Displaced volume	1583 cc
Stroke	140 mm
Bore	120 mm
Connecting rod length	256 mm
Compression ratio	17:1
Number of valves	4

VVA System

Overview

The VVA system used for this study is self-developed and was designed to obtain a highly flexible system for research purposes. Results of a first prototype were published in [18]. Each engine valve is actuated by a separate actuator connected to a shared hydraulic unit. In Figure 3, a schematic of one actuator is shown. When the high pressure (HP) valve is opened after the low pressure (LP) valve was closed, the ram is subjected to the HP oil of the hydraulic unit and starts to move the engine valve. Damping volumes interconnected by lift dependent throttling geometries control the motion sequence until the ram reaches its bottom stop position. When the LP valve is opened after the HP valve was closed the actuator is subjected to the tank pressure of the hydraulic unit. The energy stored in the engine valve spring moves the valve and the ram to the initial position while the oil flows back to the tank. Again the damping volumes control the motion. The upper damping volume limits the engine valve closing speed to prevent valve seat wear.

**Figure 3. Schematic of a VVA actuator**

Performance analysis

The first prototype presented in [18] proved the general functionality of the described VVA concept and its motion control mechanisms. The ensuing investigations determined the performance of different produced prototypes and led to several further developments. Here the status that was achieved before the implementation to the fired engine began is summarized.

The performance analysis was performed on a cylinder head mockup whose geometries were adapted to the geometries found at the fired engine. Single actuators as well as the whole engine ready VVA system with four actuators can be installed. One valve lift is directly measured by a laser triangulation system aiming on the combustion side of the particular valve head. As this measuring principle is sensitive to changes of the reflection conditions on the valve head e. g. caused by valve rotation and tilting, transient measurement errors can occur that have to be removed manually. The engine RPS provides an engine simulation mode so that the mounted VVA configuration can be driven continuously like on the fired engine without any changes to the system setup.

Figure 4 shows the envelope curves of respectively 200 engine simulation mode cycles obtained by the laser triangulation system at 1200 rpm. In the first case a single VVA actuator conducted the minimum possible opening angle, in the second case it conducted an opening angle extended by 100 °CA. The envelope curves were computed with the minimum and the maximum valve lifts at each sample crank angle that had been extracted from all valid cycle data. The four envelope curves vary about 1 °CA at a lift of 6 mm.

The repeatability of the developed VVA system can be compared to the repeatability of lost-motion VVA systems for HD Diesel engines [19]. Hence the implementation to the fired engine is feasible from this point of view. The system provides very steep and nearly trapezoidal valve lift curves instead of conventional parabolic ones. Therefore it enables basic studies of valve timing effects as the valve lift profile's influence on the intake flow is low and not altered by valve timing changes like it is normally done by cam driven VVA systems.

The measurements for Figure 4 were performed under constant ambient conditions. The fired engine and the neighboring actuators introduce several disturbances concerning temperature, vibration, gas forces and engine valve spring tolerances that can influence the VVA system behavior.

Further general improvements of the VVA system could be gained by closed-loop control, e. g. a short ballistic event with sufficient repeatability may then be possible. Nevertheless permanent reduced valve lifts and thus shorter opening angles can already be realized by the installation of a modified ram.

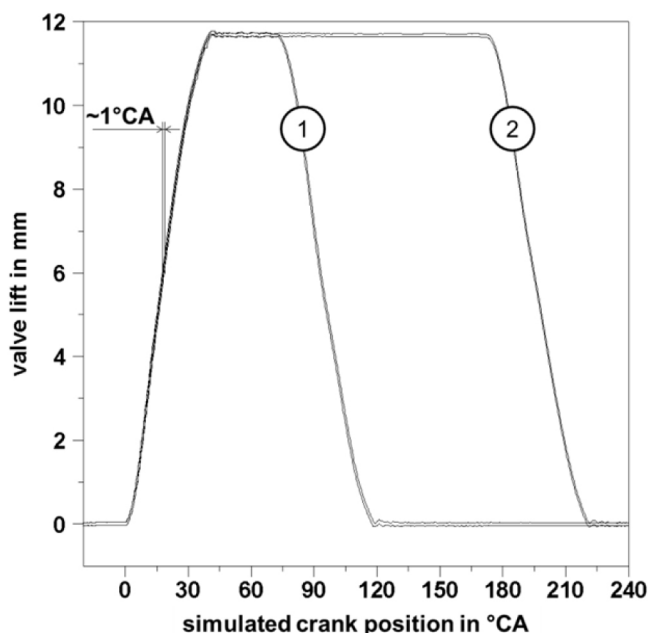


Figure 4. Envelope curves of respectively 200 engine simulation mode cycles at 1200 rpm obtained by the laser triangulation system

On-engine valve position measurements

Laser triangulation measurements are not suitable for on-engine runs so that other devices had to be implemented. The continuous valve movement is measured by Hall Effect sensors, Figure 5. They are mounted in the VVA base plate that is not shown here. The rams' ends are formed as tapers so that the magnetic flux generated by permanent magnets is altered when the rams move. A second system was chosen to provide binary information about the VVA system status. Robust switching sensors originally designed for contactless cam shaft sensing are used to detect a valve position of approx. 1 mm. They are fixed in a holder mounted on the injector, the valve retainers are used as switching targets.

The Hall Effect sensor signals are processed by the RPS, see below. The binary signals are sampled by three logic analyzers (LA), Figure 6. Because of the low data depth this data stream is recorded by LA 1 at high sampling rates during whole engine runs without data storage interruptions. Furthermore the signals of the crank angle encoder and a crank angle reference sensor are comprised to perform cycle based timing checks. LA 3 e. g. is able to identify a crank angle encoder misalignment that could lead to a VVA system damage and to report the problem to the test bench RPS.

With the data recorded by LA 1 the repeatability of the VVA system during whole engine runs is assessable. For 10000 valve actuations at 1800 rpm under fired engine operation with constant inlet valve timings the following standard deviations of the inlet valve open durations detected by the switching sensors were computed.

- Inlet valve 1: 0.0720 ms / 0.778 °CA at 1800 rpm

- Inlet valve 2: 0.0627 ms / 0.677 °CA at 1800 rpm

The recorded data and thus the standard deviations can be influenced by the possibly unsteady valve train clearances, engine vibrations and the fluctuations of the engine speed.

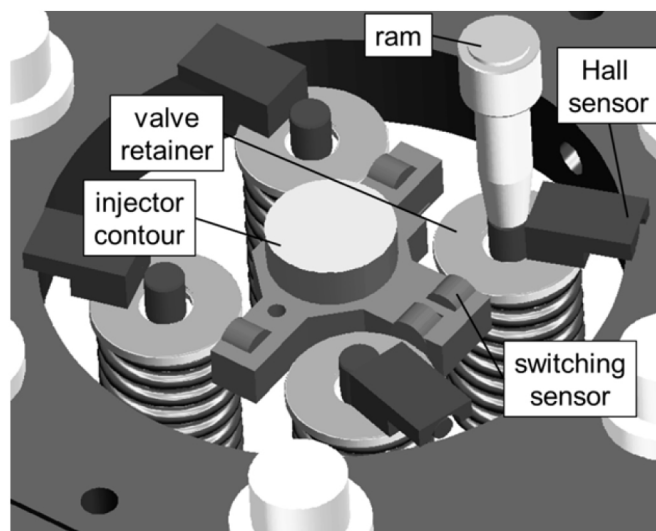


Figure 5. On-engine valve position measurements

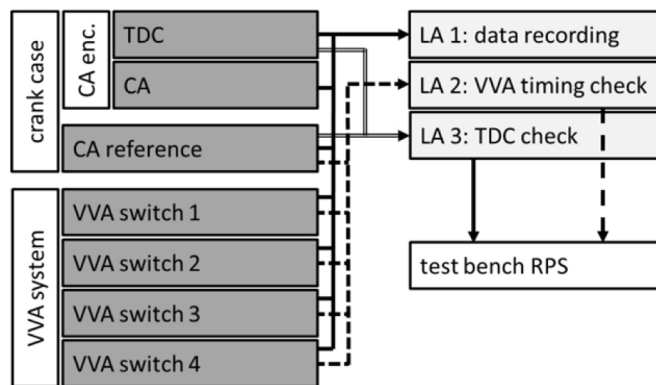


Figure 6. Logic analyzer measurements

Engine Environment

Overview

Figure 7 provides an overview of the whole test bench setup and the engine environment subsystems of which some are discussed in the following paragraphs.

Fuel system

A conventional Bosch CRIN2 injection system is applied. The high pressure pump provides an injection pressure of up to 180 MPa that is indicated via a Kistler 4067 pressure sensor. The pump inlet temperature is controlled by an industry controller via a heatable or coolable heat exchanger. The fuel mass flow is metered by a Siemens Massflo.

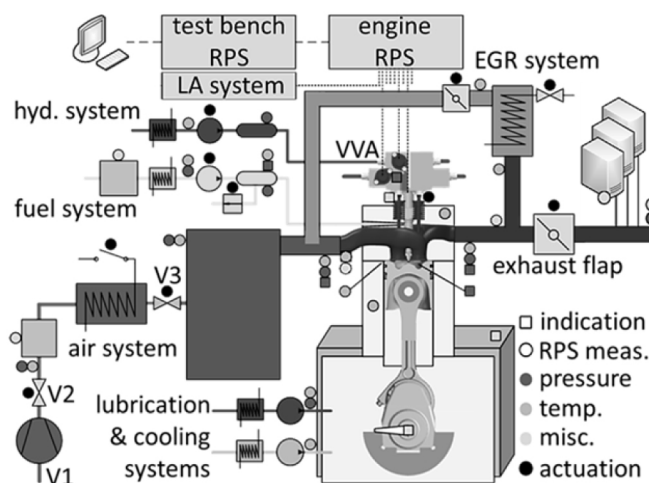


Figure 7. Test bench setup overview

Air system

The air mass flow is provided by a screw compressor and measured by an ABB Sensyflow. To realize full engine intake temperatures the air can be heated before it reaches the inlet pulsation damper. The intake pressure is indicated by a Kistler 4045 sensor. Several further pressures and temperatures of the air system are measured by the RPS.

The test bench setup was modeled among other CAE tools with the software Ricardo WAVE before its construction began. The model is shown in figure 8. One of the objectives of the modeling work was to determine an air system setup that damps the unsteady single cylinder behavior that can induce unwanted air mass flow and intake pressure oscillations at the respective measurement positions.

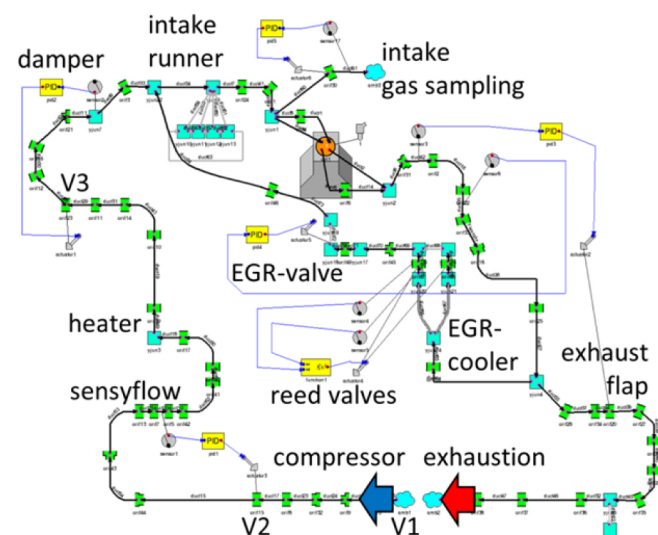


Figure 8. Test bench model

The intake pressure oscillations on the one hand could be reduced by enlarging the inlet damper to a volume of 0.250 m³. On the other hand an intake runner as short as possible but with a large diameter is beneficial what led to the runner

geometry identified by orange color in figure 11. A comparison between the pressures obtained by simulation and the pressures measured during a real engine run can be seen in Figure 9.

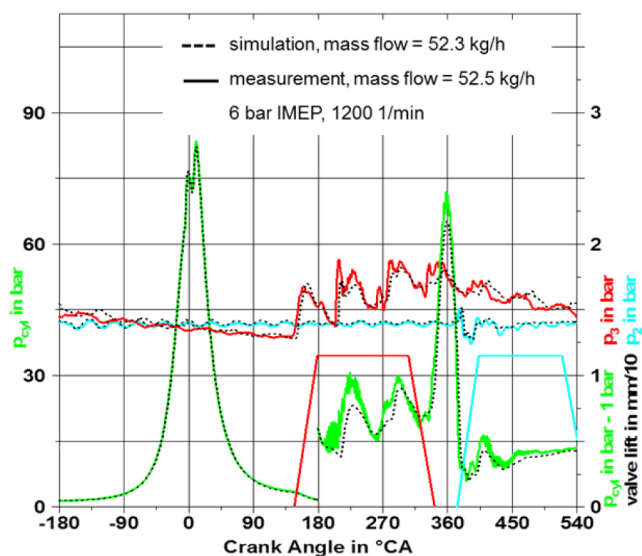


Figure 9. Model results vs. measurement

To obviate the temperature's influence on its measurement accuracy the mass flow measurement should be located upstream of the heater. The inlet pulsation damper has to be mounted as close as possible to the engine. So only the air system component order in Figure 7 and 8 remains available. The simulations show that the oscillations of the mass flow at the sensyflow position strongly depend on the pressure values in the different air system parts and thus on the set points (SP) for the pressure controllers with the valves V1, V2 and V3, Figure 10.

A pressure step between the inlet damper controlled by V3 and the mass flow measurement pressure controlled by V2 drastically reduces the mass flow oscillations at the