Lowering Transient Emissions and improving Transient Performance of Diesel Engines using the Venturi Booster Technology

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Abstract: In conventional operation of Diesel engine applications there is a tradeoff limiting performance and emission targets, as these targets are counteracting. One interesting new approach to improve both performance and emission at the same time is the use of the so called venturi booster technology. Providing additional fresh air from a compressed air tank to the intake manifold during transients has been successfully applied to diesel engines in the past. However the support of fresh air only has some disadvantages with regards to EGR transport. The venturi booster technology in contrast is able to provide the required amount of fresh air and the necessary amount of recirculated exhaust gas as well during transient operation. System setup, control strategy and promising test results are presented.

Keywords: Diesel engines; Automotive control; Exhaust gas recirculation; emissions; Transient torque; Control applications.

1. INTRODUCTION

1.1 Background

The heavy duty diesel engine combustion development for engines without SCR has since the introduction of EURO3 in 2000 focused on the trade-off between reducing the oxygen concentration in the cylinder by applying EGR and the resulting disadvantages of increased particulate emission, heat rejection and reduced load response as reported by Moser et al. (2004) and Krüger et al. (2009). The particulate emission has been greatly reduced by improving the combustion chamber and nozzle design in combination with higher injection pressure and the introduction of the diesel particulate filter. Improved turbocharging (including two-stage turbocharging) and EGR shut-off during transient operation have been implemented to improve the load response of the heavy duty diesel engine. Fulfilling future emission regulations such as EURO6 and TIER4 without NOx exhaust gas aftertreatment will not permit EGR shut-off during transient operation due to the resulting high NOx emission peaks. Avoiding EGR shut-off during transient operation with the current technology will reduce the load response of the engine to a low level not accepted by the customer.

1.2 The new solution

This paper presents the successful application of the Venturi Booster concept which is capable of injecting compressed air and EGR into the intake manifold during transient operation and thereby reducing NOx emission and improving the load response.

Former solutions such as the Knorr-Bremse PBS air injection system to improve the load response and emission behaviour of turbocharged diesel engines reported by Németh and Palkovics (2008) and patented by Németh and Gerum (2006) consist of a pressurized air injection valve combined with a throttle valve after the compressor outlet. By injecting air and at the same time closing the throttle valve, the compressor wheel is rapidly accelerated. The throttle valve is then opened and the compressor delivers high amounts of air due to the high rotational speed. This leads to fast load response. However the pressure difference between intake and exhaust is positive for approximately 0.5-1.0 seconds during a load step. As a consequence EGR cannot be transported from the exhaust to the intake during this period of time resulting in an increased NOx emission.

The Venturi Booster concept combines air injection with a venturi capable of keeping a negative pressure difference between the intake and the exhaust during a load step thereby assuring EGR for the combustion during the air injection at transient operation.

1.3 Contents

This paper starts with a description of the engine hardware setup necessary in order to implement the Venturi Booster concept to an existing EURO5 series production heavy duty diesel engine. A detailed description of the Venturi Booster control system is presented. The performance of
the control system is seen as a key factor for the success of the Venturi Booster concept in transient operation. Additionally test bed measurements are presented showing improved load response and reduced NOx emission during a specified load step for the Venturi Booster concept compared to the series production engine.

2. ENGINE HARDWARE SETUP

The base engine is a 7 litre in-line 6 cylinder engine with EGR. It is equipped with a two stage turbocharging system with intermediate and high pressure charge air coolers. In its original configuration the engine complies with the EURO5 emission legislation.

2.1 Modified Engine

The installation of the Venturi Booster System required heavy modification on the periphery of the base engine as shown in Figure 1. Following components had to be installed additionally:

- pressurized air container
- pressure hose (from pressurized air container to pressurized air valve)
- pressurized air valve
- venturi
- throttle valve
- compressor bypass

Fig. 1. Venturi System Overview

2.2 System Description

The pressurized air streams from the compressed air container to the venturi nozzle. Thereby it passes the pressurized air valve. This valve doses the amount of air which is supplied to the engine in order to meet a target $\lambda$ value. Downstream of the valve the venturi nozzle body is installed (see Figure 2). In this unit the recirculated exhaust gas is sucked into the nozzle. Hence an EGR mass flow can be generated although the intake manifold pressure is higher than the exhaust manifold pressure during air injection. After the venturi nozzle the mixed gas is channelled into the series production intake manifold. To avoid losses of compressed air by blowing through the charge air path against the natural direction of flow, a throttle valve was installed downstream the high pressure charge air cooler.

Fig. 2. Venturi nozzle body

3. BOOSTER CONTROL

3.1 Objectives

In order to operate the Venturi Booster on the testbed, the newly introduced actuators as well as some of the existing ones have to be coordinated during boosting. The main objective of the Venturi Booster control is therefore to command at least the actuators referenced by the indices 9, 11 and 13 in Figure 1.

As the target of the investigations was to proof the concept and estimate the potential at a prototype level, the control software was designed to be as simple as possible, but provide necessary tuning parameters to assist the performed investigations.

3.2 Implementation

Diesel engine control software today is a large and complex software system covering different control tasks. The interested reader is referred to Guzzella and Onder (2010), which gives a good introduction to the topic. Extending the software of the original engine control unit usually is a very time consuming task. To perform small adaptations efficiently, control algorithms at the early stage of development are often executed and tested using a separate rapid prototyping hardware as explained in detail in Hanselmann (1996). This method was also applied to implement the Venturi Booster control.

The used rapid prototyping hardware, on which the control algorithms were implemented, can access internal signals from the engine control unit using bypass technique. Additionally signals were measured on test bed using standard
data acquisition and transmitted to the control via CAN-bus. All actuators were commanded from the rapid prototyping system (Figure 3). The proposed control structure focuses the use of standard sensors used in automotive systems.

![Control Structure Diagram](image)

**Fig. 3.** Communication diagram of control components.

### 3.3 Control Structure

An overview of the used control software is shown in Figure 4. The components and their tasks are described in the following.

![Control Structure Diagram](image)

**Fig. 4.** Causality diagram of nonlinear feedforward controller.

**Data Acquisition** The inputs for the applied control algorithms are provided over ETK-bypass from the ECU. Additional input values regarding the actual pressure and temperature of the air tank are provided by the test bed and transmitted over CAN-bus to the control hardware.

**Dynamic Detection** The amount of compressed air available is limited. Only in selected transients boosting can be activated. To determine when boosting is needed a transient detection function using actual engine speed as well as current injected fuel mass flow is implemented. Dynamic operation is detected if an engine speed dependent rate of change of the injected fuel mass flow is exceeded.

**Allow Boosting** Although boosting is required due to the transient operation, boosting is only allowed for certain conditions of the boosting system and the engine air path. If these necessary conditions are not met (e.g., air tank temperature, air tank pressure, turbo compressor speed, intake manifold pressure outside defined boundaries) boosting is inhibited.

**Air Request** The requested air mass flow \( \dot{m}_{air} \) is calculated according to (1) as a product of the current fuel mass flow \( \dot{m}_{fuel} \), the stoichiometric constant \( f_{st} \) and a demand \( \lambda \), which depends on the current operation parameters of the engine (e.g., actual engine speed \( n_e \) and fuel mass flow \( \dot{m}_{fuel} \)).

\[
\dot{m}_{air} = \dot{m}_{fuel} \cdot f_{st} \cdot \lambda(n_e, \dot{m}_{fuel}) \tag{1}
\]

**Inverse Booster Throttle** Ideal gas with gas constant \( R \) and constant \( \kappa \) (ratio of specific thermal capacity at constant pressure and specific thermal capacity at constant volume) are assumed. Further assuming isentropic flow based on the well known orifice-equation (3) (see Heywood (1988)) the opening cross section area \( A \) of the boosting throttle necessary for delivering the requested amount of fresh air \( \dot{m}_{air} \) into the intake manifold is derived. Required for calculation of (3) is the measurement of the actual pressure \( p_t \) and actual temperature \( T_i \) of the air tank as well as the pressure ratio \( p_c \), computed according to (2) (\( p_c \) reflects the critical pressure ratio of the isentropic flow for ideal gases).

\[
p_c = \max\left(\frac{p_t}{p_i}, \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa}{\kappa - 1}}\right) \tag{2}
\]

\[
\dot{m}_{air} = \frac{A \cdot p_t}{\sqrt{R}}, \sqrt{\frac{2 \cdot \kappa}{\kappa - 1}} \left(\frac{p_t^2}{p_c^2} - \frac{\kappa + 1}{\kappa - 1}\right) \tag{3}
\]

The demanded booster throttle actuation angle \( \phi \) can be expressed as a geometry dependent function of the required cross-sectional area \( A \) as shown in (4). The implementation of the above model based precontrol of \( \lambda \) by commanding the pressurized air valve was realized using lookup-tables to avoid high level mathematical operations (power and square root) used in the equations above.

\[
\phi = f(A) \tag{4}
\]

**Booster Limitation** Dependent on engine operating a limitation of the booster valve is applied. On the one hand this limitation avoids too high pressure in the intake manifold, which would harm the engine. On the other hand the maximum boosting time is limited to avoid excessive consumption of compressed air.

**Booster Coordinator** Derived from the limited pressurized air valve command all other actuators are coordinated. These actuators are the throttle valve and the compressor bypass valve. The task of the coordinator is to realize smooth shifting between boosting and normal operation.

### 4. MEASUREMENT

Two major test series were carried out to investigate the performance of the venturi booster system: EGR suction...
tests in motored engine operation and load response tests with load ramps. Different venturi nozzle diameters were tested in the EGR suction tests by applying different nozzle body inserts (see Figure 2) and closing the EGR inlet. The final nozzle diameter was selected to have sufficient EGR suction potential needed to generate EGR flow during pressurized air injection.

In order to test the venturi booster under real life conditions, load response tests at constant engine speed of 1200 rpm were performed. The pressurized air container had a pressure of 800 kPa relative to ambient at the start of boosting. Within 3 seconds the acceleration pedal was increased from 10% to 100%. Figure 6 and 7 show the direct comparison between standard and boosted operation.

It becomes obvious that the engine in its standard configuration is not capable of following the desired torque response from the acceleration pedal. The main reason is the slow response of the turbo chargers and the resulting lack of oxygen in the cylinders. In boosted operation the torque response is greatly improved.

The ratio (5) of the the recirculated exhaust gas mass flow \( \dot{m}_{egr} \) and the mass flow into the cylinders \( \dot{m}_{cyl} \) is called the EGR rate.

\[
\tau_{egr} = \frac{\dot{m}_{egr}}{\dot{m}_{cyl}} \times 100\%
\] (5)

In standard transient operation, the EGR rate is rapidly reduced to increase the amount of fresh air to improve the engines response. However this results in increased NO\(_x\) emission compared to Venturi Booster operation as shown in Figure 6 and 7.

Due to the EGR suction effect with the Venturi Booster, it is possible to achieve a fast acceleration keeping the EGR rate at around 35% (see Figure 7) even though the pressure is higher in the intake manifold compared to the exhaust manifold as shown in Figure 8.

This results in a low NO\(_x\) emission during the rapid acceleration (second 28 to 30.5). After the acceleration, the NO\(_x\) value stabilizes at the level determined by the EURO5 stationary calibration of the engine.

Figure 9 presents the position of the pressurized air valve and lambda value during the acceleration with Venturi Boosting. The pressurized air valve is opened due to the dynamic detection allowing boosting. The position is determined by the air request dependent upon the demanded lambda and injected fuel amount. After approximately 0.5 sec, the demanded lambda is reached with a high amount of EGR due to the Venturi EGR suction effect. The torque

Fig. 5. EGR suction test

Figure 5 shows the pressure curves of an EGR suction test at the three measuring positions as marked in Figure 2. At the beginning of the air injection the venturi effect generates a pressure difference of around 90 kPa between the pressurized air inlet and the EGR inlet. As the pipe diameter downstream the venturi nozzle is considerably bigger than on the upstream side of the nozzle the pressure recovery effect leads to a higher static pressure value than upwards the nozzle.

Fig. 6. Comparison of NO\(_x\) mass flow and torque rise

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Fig. 7. Comparison of EGR rate and torque rise

Fig. 8. Intake versus exhaust pressure

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delay experienced at second 28.5 can be avoided by further optimizing the control parameters.

Figure 10 and 11 present requested engine speed and torque of the World Harmonized Transient Cycle (WHTC) as well as injected fuel mass flow and its rate of change for a 7 litre heavy duty engine measured on testbed. The duration of the WHTC cycle is 1800 sec. including 450 sec. motored operation. By actuating the 880 cm$^3$ air pump during motoring operation in WHTC, it is theoretically possible to pump about 7.5 kg air into the compressed air tank with an average absolute pressure of about 10 bar.

5. DISCUSSION

The results presented show the NO$_x$ reduction potential combined with remarkably improved torque response for the Venturi Booster technology. The torque response time for a 10% to 100% acceleration is reduced from 6 seconds to 2.5 seconds with the Venturi Booster and at the same time the NO$_x$ emission is greatly reduced during the acceleration.

Applying the Venturi Booster in an engine with very low steady state NO$_x$ emission gives the potential of fulfilling future emission regulations such as EURO6 and TIER4 without DeNOx, assuming that sufficient pressurized air is available.

5.1 Consumption of compressed air

For estimating the pressurized air consumption a scenario for the Venturi Booster using a series production brake system air pump with a displacement of 880 cm$^3$ is analysed below. It is assumed that the air pump is applied with a clutch, thereby only being activated during motoring operation.

Looking at the rate of change of fuel mass flow during the WHTC cycle, it gets obvious that around 85% of the WHTC cycle is operated in steady state or with slow accelerations below 1 g/s$^2$ rate of change of the fuel mass flow as shown in Figure 12. Around 93% of the cycle is operated with accelerations below 2 g/s$^2$.

The Venturi Booster is assumed to be only activated at the fastest accelerations depending upon the base steady state NO$_x$ emission level and pressurized air available. Testbed measurements showed, that an average Venturi Boosting duration of approximately 1 sec is required to perform the fastest accelerations in WHTC thereby achieving a very low NO$_x$ emission and accelerating the compressor and turbine wheel. As a Venturi Boosting duration of 1 sec. requires in average about 0.12 kg of fresh air and based on the assumptions above, the number of necessary Venturi Boosting events and the required amount of pressurized air can be estimated as a function of the threshold rate of change of the fuel injection mass flow shown in Figure 13. One single series production brake system air pump (880 cm$^3$), operated only during motoring operation, will deliver about 7.5 kg air during the motored operation.

Fig. 9. Lambda during Venturi Boosting

Fig. 10. Requested engine speed and torque in WHTC

Fig. 11. Fuel mass flow and its rate of change

Fig. 12. Accumulated time below limit of fuel mass flow rate of change.
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REFERENCES


Appendix A. ABBREVIATIONS

EGR Exhaust gas recirculation
ECU Engine control unit
CAN Controller-area network is a message based protocol, designed specifically for automotive applications.
SCR Selective catalytic reduction is a means of converting nitrogen oxides, also referred to as NO₂ with the aid of a catalyst into diatomic nitrogen, N₂, and water, H₂O.
λ Lambda is the ratio of actual air to fuel ratio to stoichiometry for a given mixture.
ETK Real-time capable interface which provides direct access to control variables and parameters of an ECU.
PBS Pneumatic booster system enhances the engines performance by injecting compressed air from the pneumatic system into the inlet manifold of the engine.

in WHTC - sufficient to operate the Venturi Booster for all accelerations above 1 g/s² rate of change of fuel mass flow. A further increase of the number of necessary Venturi Boosting events depending upon the base steady state NO₂ emission level can be achieved by applying a larger air pump or by operating the air pump during fired operation thereby increasing the fuel consumption. It must be noted that measurements have shown a lower fuel consumption during Venturi Boosting due to higher lambda and negative pumping work (intake pressure > exhaust pressure). Due to the fact that the motored operation events in WHTC occur evenly throughout the cycle, the theoretical volume of about 150 litres of the pressurized air container is needed.

Fig. 13. Boost events and air consumption estimation.

5.2 Control

The presented Venturi Booster control strategy is a key feature for the achievement of such promising results. Additionally to further optimizing the control parameters the control strategy itself shows potential of improvement especially at the process of shifting to normal operation. The main challenge from current point of view is the coordinated control of the various actuators in the air and fuel path path at the end of boosting. In order to minimize the amount of compressed air, the control of the air path actuators has to be extended to enable sooner handing over to normal operation, but at the same time generating a smooth boost pressure trajectory. The authors also see potential for further improvement of the transient behaviour, if additionally actuators of the fuel path are included into the control, e.g. the limitation of the maximum injected amount of fuel during transients, which was not done in the proposed setup.

6. CONCLUSION

It can be concluded that the Venturi Booster concept with the presented control strategy is capable of greatly improving the torque response and reducing the transient NOₓ emission for heavy duty engines. Next step is to implement the Venturi Booster in an engine having very low steady state NOₓ emission values to experience the full NOₓ reduction potential with regards to future emission regulation limits such as EURO6 and TIER4. Application of the control strategy to the entire engine map as well as the extension of the model based control will be necessary. Finally further considerations regarding the influence of pressurized air delivery on fuel consumption will have to be made, to quantify the overall benefit of using the Venturi Booster.