DIESEL ENGINE AIR-PATH MANAGEMENT

Commercial vehicle applications

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THESES

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1 INTRODUCTION AND RESEARCH AIMS

The key component of a road vehicle is the propulsion system which creates propulsive force from an energy source. Since its invention more than hundred years ago diesel engines became the dominant propulsion system in road vehicles between petrol engines at the early of the nineteenth century. Rudolf Diesel's invention could initially be used only for stationary applications. It was to be decades before the diesel engine finally "hit the road", after the solution of difficulties concerning fuel injection. At these early stages, the main driver of the development was motivated by the need for increasing brake and specific power. This led to the increasing of the number of cylinders and especially by diesel engines to the turbocharging. [1]

The air pollution problem became apparent in the 1940s in Los Angeles. It was demonstrated that the smog results mainly from the reaction of the nitrogen oxides and hydrocarbon compounds. It revealed that the internal combustion exhaust gases of the automobiles are the primary sources of the high levels of the NO_x and HC in urban areas. Therefore, emission standards were introduced first in California in the 1960s followed by regulations worldwide [3]. Since then, legislative emission limitation requirements dominated the process of diesel engine development.

At the end of the 1990s the focus of interest turned to the vehicle CO_2 emission. Not only for the economical operation and dwindling oil reserves but it became clear that with high probability the increasing level of CO_2 and other greenhouse gases in the atmosphere are warming the globe. At the end of the 90s first voluntary agreements were made between the European Commission and the automotive industry then California emerged the first mandatory regulation in 2004 [4] These steadily tightening CO_2 restrictions parallel with the similarly more and more rigorous emission restrictions gave the fundamental challenges for nowadays diesel engine development and the motivation of this work.

This thesis aims to focus primarily on commercial vehicle diesel engine applications. The main difference between the commercial vehicle and the passenger car market that customers are mainly motivated by the achievable economic profit. Therefore, the low vehicle and maintenance cost and reliability are extremely important factors in the competition for the market share of vehicle manufacturers and their suppliers.

Current and next generation emission standards (e.g., Euro 6 and US EPA 13) include significant limitations. The most challenging for engine developers are especially the reduction of PM and nitrogen oxide contents of the exhaust gases. Basically, there are two possibilities to achieve this: exhaust gas aftertreatment and a decrease in raw emissions. The use of a DPF to reduce the PM emission of a diesel engine results in higher fuel consumption caused by the generated backpressure and the filter regeneration. SCR catalysts are expensive and reach their nominal efficiency only in a limited exhaust gas temperature range. The required urea and its reservoir further increase the costs and reduce the space available for the fuel tanks. Due to the above disadvantages, diesel engine development today aims to reduce aftertreatment system size [5].

In an air-path system of a turbocharged diesel engine, there are several possible locations for the installation of the flap valves: upstream and downstream the compressor and upstream and downstream the turbine. Some flap actuators are commonly used nowadays, see, e.g., the exhaust brake. However, exhaust brakes are usually on/off valves that are able to realize fully closed or fully opened positions. [10, 11] The installation of flap valves with a fast and accurate position control into the engine air-path offers several possible new and extended functionalities which are investigated in this work. These include cylinder charge composition control, exhaust gas thermal management, brake blending, and automated manual transmission support. The realization and demonstration of these functions on an engine give the motivation for this work.

Flap valve operation at different locations of the air-path system shows a different effect on the engine operation measures, e.g., on fuel consumption, emission. To be able to choose an optimal solution the detailed model of the investigated engine is built and validated in the GT-Suite environment. Using the simulation model for a comparison of an optimal air-path flap valve actuator setup is derived in the second part of this thesis. Based on the evaluation an HP-EGR valve in cooperation with exhaust throttling downstream of the turbine was chosen as an optimal engine air-path throttling setup as a practical trade-off (see Fig. 1.1). This layout serves as a basis for the realized new engine functions in further parts.

Based on the targeted possible new engine functions of the brake blending, AMT support, exhaust gas thermomanagement, cylinder charge composition control strategies were worked out.

In the third part of this thesis, the backpressure control function is worked out. As a first step, the control aims and requirements are defined. Thereafter, a first-engineering-principle-based, mean-value, control-oriented, nonlinear model of the engine and the actuator is described and validated with test bench measurements. The design and performance comparison of four model-based controller structures are presented: an LQ servo, an LQ servo with a model-inversion-based feedforward, an LPV model based H-infinity and a sliding

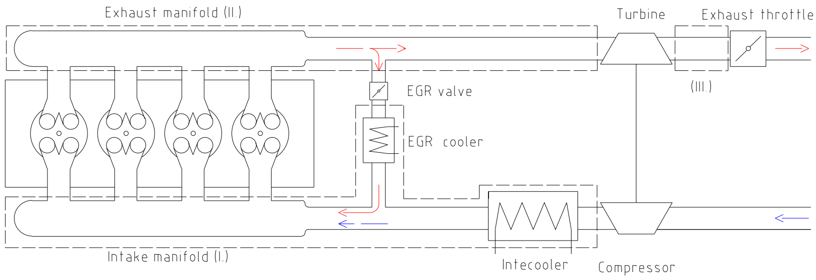

Figure 1.1: Optimal diesel engine air-path throttle actuator layout

mode. The controller performance and the compliance of requirements are evaluated in three different test cycles on a medium-duty diesel engine, simulating brake blending, thermomanagement, and EGR support operations. The proposed LQ servo controller with model inversion based feedforward fulfills all the defined requirements.

In Part 4 the cylinder charge air controller design process with high-pressure EGR and exhaust throttling is described. It reveals from the analysis of the exhaust gas recirculation [6–9] that the commonly used EGR-rate can't give accurate information about he composition of the cylinder charge and moreover the engine emission cannot be predicted from it [2]. For this reason, the intake manifold oxygen concentration was chosen as the performance measure. A first-engineering-principle-based, mean-value, nonlinear model of the engine air-path system with HP-EGR valve and throttling downstream the turbine is introduced and validated with test bench measurements. Finally, an LQ servo controller is synthesized that can minimize the engine pumping work. Its performance is demonstrated with engine dyno measurements.

The last part of the thesis contains the conclusions, proposed theses statements, directions for future research and summarizes the contribution of this thesis.

2 MATERIALS AND METHODS

The availability of an engine dyno was essential for both the validation and identification of the detailed and simplified models and for the demonstration of the designed function. For this reason, in the laboratory of the BME Department of Automotive Technologies (located in building MG) a turbocharged and intercooled, medium duty commercial vehicle, common rail diesel engine was installed on an engine dyno. (see in Fig. 2.1). The test bench was able to perform both static and transient measurement cycles. All the relevant operating parameters of the engine were measurable: engine speed, load, gravimetric fuel consumption, pressures and temperatures at different locations of the air-path (ambient, upstream and downstream the compressor, etc.). All the cylinder pressures of the engine could be indicated. Low pressure indicating sensors were also installed.

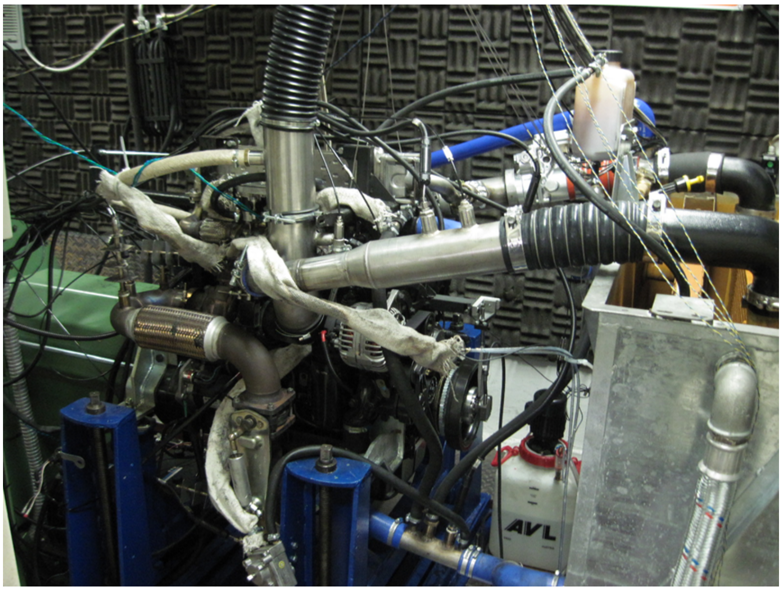

Figure 2.1: Test engine installed on the dynamometer

For the control of the engine dynamometer and for data acquisition a dSpace MicroAutoBox rapid prototyping hardware was used. The intake and exhaust oxygen concentrations were measured by wide-band lambda sensors. The raw nitrogen oxide emission was also measured by a smart sensor installed in the exhaust pipe. In the air-path system electromechanical, position controller flap valves were used developed by Knorr-Bremse R&D Center Budapest.

The detailed model was implemented in GT-Suite environment. The control-oriented models were built-up in MATLAB/Simulink similarly to the parameter identification and model validation.

The control models were defined based on first engineering principles. Differential equations routed from conservation principles are needed for the definition of lumped parameter dynamical models. These equations can be solved after the augmentation with algebraic equations. At the beginning of the modeling process, certain simplifications can be made for the omission of dynamics slightly related to the outputs.

Control-oriented models must have the ability to reproduce all of the important dynamical properties of the system (e.g., stability properties or the main time constants). Nevertheless, behaviors should be excluded if their effect is negligible or have no relations to the control aims. For the state space model definition, it should be investigated, whether all of the algebraic equations can be substituted into the differential ones. If all of them can be substituted, at the end of the modeling process ordinary differential equations result that can form into nonlinear state space model.

3 THESES

The main contributions and the proposed theses of this work are summarized below. The relevant chapter of the thesis and the labels of the related publications (enumerated below) are indicated in parenthesis.

THESIS 1 Definition of new engine functions achievable with a flow area control in the engine air-path and optimal diesel engine air-path flap actuator setup for the realization (Part i and ii of the dissertation), [**P1, P2, P3, P4**].

New commercial vehicle diesel engine functions were described which could be achieved by suitable actuation of flap valves in different locations of the engine air-path system. These include brake blending, automated manual transmission support, exhaust gas thermomanagement and cylinder charge composition control. The effect of flow area control at different locations in the engine intake-, exhaust- and EGR path on the engine performance were analyzed with a validated detailed engine model. As a result of this study, the optimal engine air-path system for the target functions was defined with throttle valves realized in the form of a HP-EGR valve and exhaust flap downstream the turbine. It was concluded that all of the targeted functions are achievable by backpressure and intake manifold oxygen concentration control with the above defined optimal air-path actuator setup.

THESIS 2 Simplified, control-oriented, nonlinear, dynamic models of the engine air-path system for exhaust backpressure and cylinder charge composition control (Part iv and Chapter 8 of the dissertation), [**P5, P6, P7, P8, P9**].

The simplified, control-oriented, nonlinear, dynamic models of the engine air-path system with a throttle valve installed downstream of the turbine, and high-pressure exhaust recirculation path considered as a mixed thermodynamical, mechanical system were built and verified. It was shown that the model exhibits the following unique properties:

1. The dynamic models of the engine air-path system with a throttle valve installed downstream of the turbine, and an HP-EGR valve is given by a set of nonlinear differential–algebraic equations. The differential equations are balance equations for the mass and internal energy of the gas in the intake manifold, exhaust manifold and the volume between the turbine and the exhaust throttle as balance volumes.

2. The model for the cylinder charge composition control uses a performance output of the intake manifold oxygen concentration.

3. It has been shown that the two state equations of the backpressure model and the five state equations of the cylinder charge composition model can be rewritten into standard input affine form.

$$\frac{d\mathbf{x}}{dt} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})\,\mathbf{u},\ \mathbf{y} = \mathbf{h}(\mathbf{x})\,.$$

4. The coordinate functions of the nonlinear models have the following properties:

   a) The coordinate function $\mathbf{f}(\mathbf{x})$ depends also on the disturbance vector $\mathbf{d}$ and includes hybrid modes: $\mathbf{f}(\mathbf{x}) = \mathbf{f}(\mathbf{x}, \mathbf{d}, r)$, where $r : \mathbb{R}^n \to \mathbb{N}$ is a piecewise constant switching function mapping from the state space to the finite integer set $\mathbb{N} = \{1, 2\}$ for the backpressure model and $\mathbb{N} = \{1, 2, 3, 4, 5, 6\}$ for the cylinder charge composition model. $\mathbf{x}$ is the state vector.

   b) The coordinate function $\mathbf{g}(\mathbf{x})$is affine with respect to the state vector, i.e., $\mathbf{g}(\mathbf{x}) = \mathbf{B}\mathbf{x} + \mathbf{b}$ with $\mathbf{B}$ being a constant matrix and $\mathbf{b}$ a constant vector.

   c) The output equation has the following form: $\mathbf{h}(\mathbf{x}) = \mathbf{C}\mathbf{x} + \mathbf{e}(\mathbf{d})$, where $\mathbf{C}$ is a constant matrix and $\mathbf{e}$ is a nonlinear function of the disturbance vector $\mathbf{d}$.

THESIS 3 Specification of the backpressure control problem and design of the pressure controller for the exhaust manifold pressure (Chapter 9 of the dissertation), **[P5, P6, P7]**.

1. The exhaust manifold pressure tracking control problem is given using a position controlled exhaust throttle installed downstream the turbine with respect to the exhaust manifold pressure oscillation caused by the exhaust processes of the cylinders which is a non-modeled dynamics of the system.

2. Control aims and requirements were defined in five points which need to fulfill by the controller.

3. With the above assumptions, four different controllers were designed and tuned. The properties of the closed loop-systems were investigated and compared in different engine dynamometer measurement cycles (covering brake blending, thermomanagement, and EGR support operations) which lead to the following observations:

   a) The LQ servo controller shows an accurate tracking but cannot fulfill at the same time the closed-loop response time requirement.

   b) The H-infinity controller shows quick response times but with high control activity and computational demand.
   c) The sliding-mode controller shows a fast dynamics, but its steady state error exceeds the predefined limit in some cases.
   d) The LQ servo controller with the inclusion of a model based feedforward can fulfill both the response time and low control accuracy challenge parallel.

4. Distilled from the above comparison results the LQ servo with the model inversion based feedforward controller structure was chosen as the proposed controller. It fulfills all the predefined requirements, namely the pressure overshoot, tracking accuracy, control activity, computational demand and easy calibration.

THESIS **4** Specification of the cylinder charge composition control problem and design of the intake manifold oxygen concentration controller with high-pressure exhaust gas recirculation and exhaust throttling (Part iv of the dissertation), [**P9, P10, P11**].

1. The cylinder charge gas composition tracking control problem using a position controlled exhaust throttle installed downstream of the turbine, and HP-EGR valve was defined.
2. A novel performance output was chosen as the intake manifold oxygen concentration after highlighting disadvantages of the commonly used EGR rate based control.
3. With the above assumptions, an LQ servo controller has been designed and tuned. The properties of the closed-loop system were investigated by engine dynamometer measurements which lead to the following observations:
   a) The controller fulfills the requirement on tracking accuracy.
   b) The controller fulfills the requirement on minimizing the engine pumping losses.

4 PUBLICATIONS DIRECTLY RELATED TO THE THESIS

The results of this thesis have been presented at conferences and published or accepted in journals as follows (in parenthesis the relevant Thesis is indicated):

[P1] Ádam Bárdos and Huba Németh. "EGR Support Investigation on a Diesel Engine." In: A Jövő Járműve 3-4 (2011), pp. 48–53. (**Thesis 1**)

[P2] Bárdos Ádám and Németh Huba. "Dízelmotor légmenedzsmentje - a gázcserefolyamat irányítása." In: I. BME Doktorandusz Konferencia. Nov. 2011. (**Thesis 1**)

[P3] Huba Németh, Ádám Bárdos, and Jörg Mellar. "Selektive Turboaufladung des Luftpressers an NFZ Dieselmotoren." In: 5. MTZ Fachtagung Ladungswechsel im Verbrennungsmotor. Stuttgart, Németország: Wiesbaden, 2012.10.23-2012.10.24, pp. 1–10. (**Thesis 1**)

[P4] Ádam Bárdos, Sándor Vass and Huba Németh. "Validation of a detailed commercial vehicle turbocharged diesel engine model." In: A Jövő Járműve 1-2 (2014), pp. 25–31. (**Thesis 1**)

[P5] Ádam Bárdos, Barna Szimandl, and Huba Németh. "Feedforward LQ servo backpressure controller for engine exhaust throttles." In: I. Zobory (szerk.) VSDIA 2014 14th Mini Conference On Vehicle System Dynamics, Identification and Anomalies. Budapest, Hungary, 10.11.2014-12.11.2014. (**Thesis 2 and 3**)

[P6] Ádám Bárdos, Barna Szimandl, and Huba Németh. "H-infinity Backpressure Controller for High Response Engine Exhaust Throttles." In: Periodica Polytechnica Transportation Engineering 44.4 (2016), pp. 201–208. doi: 10 . 3311 / PPtr . 8470. (**Thesis 2 and 3**)

[P7] Ádam Bárdos, Barna Szimandl and Huba Németh. "Controller structure for high response engine exhaust throttles." In: International Journal of Heavy Vehicle Systems (accepted for publication). (**Thesis 2 and 3**)

[P8] Ádam Bárdos and Huba Németh. "Control oriented air path model for compressed air boosted Diesel engines." In: Periodica Polytechnica 41.1 (2013), pp. 3–12. doi: 10.3311/PPtr.7093. (**Thesis 2 and 4**)

[P9] Ádám Bárdos and Huba Németh. "Model development for intake gas composition controller design for commercial vehicle diesel engines with HP-EGR and exhaust throttling." In: Mechatronics 44.Supplement C (2017), pp. 6–13. (**Thesis 2 and 4**)

[P10] Bárdos Ádam and Németh Huba. "Haszonjármű dízelmotor szívótartályi oxigén koncentrációjának szabályzása magasnyomású EGR szeleppel és kipufogó oldali fojtással." In: Gép 3 (2017), pp. 9–14. (**Thesis 4**)

[P11] Ádam Bárdos and Huba Németh. "Diesel engine cylinder-charge composition control with HP-EGR and exhaust throttling" In: I. Zobory (szerk.) VSDIA 2018 16th Mini Conference On Vehicle System Dynamics, Identification and Anomalies. Budapest, Hungary, 5-7 November 2018 (**Thesis 4**)

5 EXPLOITATION OF THE RESULTS

The optimal engine air-path actuator setup that uses throttle valves achieved as the result of this research work can be applied in serial applications too. It can decrease the cost of manufacturing, engine out emission and can prolong vehicle service life. Both in the development of the backpressure controller and the cylinder charge (oxygen concentration) controller, the applicability in embedded hardware was a primary consideration. It is ensured by the low computational demand. Moreover, as the results of the physical model-based design, the controller application can be tuned by a few numbers of real-world parameters. The designed models (engine backpressure and intake manifold oxygen concentration) can be further used for the analysis of construction parameters, optimization, or for observer design (for reducing the number of used sensor thereby achieving a cost-effective product).

[1] Richard van Basshuysen and Fred Schäfer. *Handbuch Verbrennungsmotor. Grundlagen, Komponenten, Systeme, Perspektiven*. Springer Vieweg, 2015. DOI: 10.1007/978-3-658-04678-1 (cit. on p. 1).

[2] Olaf Erik Herrmann. "Emissionsregelung bei Nutzfahrzeugmotoren über den Luft- und Abgaspfad." PhD thesis. Aachen: Technische Hochschule, 2005, 145 S. : graph. Darst. URL: http://publications.rwth-aachen.de/record/52065 (cit. on p. 3).

[3] B. J. Heywood. *Internal Combustion Engine Fundamentals*. McGraw-Hill, Inc., 1988. (Cit. on p. 1).

[4] Timothy V. Johnson. "Review of CO_2 Emissions and Technologies in the Road Transportation Sector." In: *SAE Int. J. Engines* 3 (1 2010), pp. 1079–1098. DOI: https://doi.org/10.4271/2010-01-1276 (cit. on p. 1).

[5] Thomas Körfer, Ludger Ruhkamp, OlafErik Herrmann, René Linssen, and Dirk Adolph. "Verschärfte Anforderungen an die Luftpfadregelung bei Nutzfahrzeugmotoren." German. In: *MTZ - Motortechnische Zeitschrift* 69.11 (2008), pp. 958–965. DOI: 10.1007/BF03227504. URL: http://dx.doi.org/10.1007/BF03227504 (cit. on p. 2).

[6] N. Ladommatos, S. Abdelhalim, H. Zhao, and Z. Hu. "The Dilution, Chemical, and Thermal Effects of Exhaust Gas Recirculation on Diesel Engine Emissions - Part 1: Effect of Reducing Inlet Charge Oxygen." In: *SAE Technical Paper 961165* (1996). DOI: 10.4271/961165 (cit. on p. 3).

[7] N. Ladommatos, S. Abdelhalim, H. Zhao, and Z. Hu. "The Dilution, Chemical, and Thermal Effects of Exhaust Gas Recirculation on Diesel Engine Emissions - Part 2: Effects of Carbon Dioxide." In: *SAE Technical Paper 961167* (1996). DOI: 10.4271/961167 (cit. on p. 3).

[8] N. Ladommatos, S. Abdelhalim, H. Zhao, and Z. Hu. "The Dilution, Chemical, and Thermal Effects of Exhaust Gas Recirculation on Diesel Engine Emissions - Part 3: Effects of Water Vapour." In: *SAE Technical Paper 971659* (1997). DOI: 10.4271/971659 (cit. on p. 3).

[9] N. Ladommatos, S. Abdelhalim, H. Zhao, and Z. Hu. "The Dilution, Chemical, and Thermal Effects of Exhaust Gas Recirculation on Diesel Engine Emissions - Part 4: Effects of Carbon Dioxide and Water Vapour." In: *SAE Technical Paper 971660* (1997). DOI: 10.4271/971660 (cit. on p. 3).

[10] D. Thompson and R. G. Baines. “Exhaust pressure modulation valve US5394901 patent.” US5394901 (A). 1995-03-07 (cit. on p. 2).

[11] D. Thompson and M. E. Flett. “Exhaust brake and pressure modulation valve EP0578373 patent.” EP0578373 (A1). 1994-01-12 (cit. on p. 2).