

Robust Emission Management Strategy to Meet Real-World Emission Requirements for HD Diesel Engines

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ABSTRACT

Heavy-duty diesel engines are used in different application areas, like long-haul, city distribution, dump truck and building and construction industry. For these wide variety of areas, the engine performance needs to comply with the real-world legislation limits and should simultaneously have a low fuel consumption and good drivability.

Meeting these requirements takes substantial development and calibration effort, where an optimal fuel consumption for each application is not always met in practice. TNO's Integrated Emission Management (IEM) strategy, is able to deal with these variations in operating conditions, while meeting legislation limits and obtaining on-line cost optimization. Based on the actual state of the engine and aftertreatment, optimal air-path setpoints are computed, which balances EGR and SCR usage.

Due to IEM's adaptation characteristics based on the actual state of engine and aftertreatment system, the strategy is robust for varying conditions during real-world operation. This is especially of interest, since real-world emissions become increasingly important: in-use compliance, including Not-To-Exceed (NTE) areas, challenging On-Board-Diagnostics requirements and In-Use Performance Ratio (IUPR) monitoring.

The main contribution of this work is to demonstrate the robustness of IEM on a variety of real-world cycles by means of a simulation study. Whereas previous publications focus on demonstration of the IEM strategy on Type Approval cycles, this work can be seen as an extension, which also addresses In-Service Conformity (ISC).

This paper discusses in detail the performance and robustness of the IEM strategy at these cycles compared with a state-of-the-art Euro-VI engine control strategy (baseline). Consequent improvements are obtained among the different cycles. Fuel consumption and fluid cost are reduced up to 2% and 1.7%, respectively, compared to this baseline strategy.

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INTRODUCTION

To meet existing emission legislation for heavy-duty diesel applications, the vast majority of Original Equipment Manufacturers (OEMs) apply Exhaust Gas Recirculation (EGR) in combination with exhaust gas aftertreatment. These aftertreatment systems include Diesel Particulate Filters (DPF) and urea-based Selective Catalytic Reduction (SCR) systems. However, there are exceptions such as Iveco and Scania which offer non-EGR versions of their engines in combination with DPF and SCR technology [1][2].

Driven by system and fuel cost optimization and the ambition to reduce CO₂ emissions with 60% by 2050 compared to 1990 [3], the main challenge for OEMs is to further reduce fuel consumption and system costs. For engines with EGR, optimal engine-aftertreatment interaction by so-called EGR-SCR balancing is required. With the growing number of sensors, actuators and subsystems, optimization of the overall engine-aftertreatment performance is not straightforward.

Simultaneously, besides emission targets over a specified test cycle, more and more attention is paid to real-world performance. This sets new targets for on-road performance robustness.

For several years, TNO is developing an integrated control strategy for engine and aftertreatment systems, called Integrated Emission Management (IEM). This strategy is capable of on-line minimization of fuel and urea consumption within emission constraints. Based on the actual state of the engine and aftertreatment system, optimal air-path settings are determined for EGR-SCR balancing. Following a model-based approach, the strategy allows for a systematic control design and calibration procedure for engine and aftertreatment systems. Moreover, it targets for improved performance and robustness, regarding tailpipe emissions, for real-world circumstances. For this simulation study, validated dynamic high fidelity models are used to

represent a Euro VI heavy duty powertrain. Subsequently, the IEM control strategy has additional functionality which monitors the feasibility of the selected controller setpoints.

Several IEM related topics are already executed and developed in the past, such as desk studies, sensitivity analysis and proof-of-concept both in simulation as well as an experimental demonstration on an engine dyno [4][5]. This work is an extension by evaluating the robustness of IEM, focusing on tailpipe emissions and in-service conformity, for real-world cycles in a simulation environment. The robustness of IEM towards uncertainties within the system is a topic of current and future research. In this simulation study a nominal IEM calibration, obtained from previous work, is compared to a, state-of-the-art Euro-VI, baseline strategy. Subsequently, by varying calibration parameter λ_3 the potential of IEM is shown when a fixed or flexible λ_3 calibration is used. Furthermore, the effect of λ_3 on the conformity factor is discussed. For future applications, it is envisioned that IEM is extended with additional functionality, using route and traffic information, to transfer from offline calibration towards robust on-line, situation adaptive and predictive, calibration.

This work is organized as follows: first a description of the IEM strategy is given along with the control approach. Second, the engine and aftertreatment models, describing the engine and aftertreatment system are discussed, followed by the control model description. Subsequently, the simulation setup and results are reported. In the last part, the conclusions and an outlook of future work are stated.

INTEGRATED EMISSION MANAGEMENT

Modern heavy duty powertrains require an optimal and robust control solution that exploits the interactions between engine and aftertreatment systems and that deals with real-world operating conditions in the most optimal approach. Due to the increased complexity of engine and aftertreatment systems, it is no longer straightforward to optimize overall system performance. Therefore, TNO is investing in the further development of an integrated system approach: Integrated Emission Management. The philosophy behind Integrated Emission Management is that of a model-based optimal control approach that minimizes operational costs (fuel and urea), while meeting emission constraints. Therefore, offering an emission control solution that is based on the actual state of the engine and aftertreatment system for both test cycles and real-life operation.

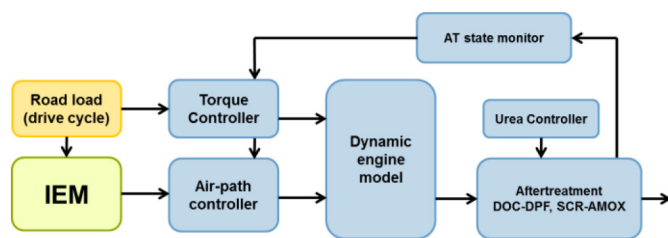


Figure 1. IEM integration in a heavy duty powertrain model

For this simulation study, the performance of the separate low-level controllers (torque, air-path and urea controllers) is the result of a supervisory IEM controller, as illustrated in Figure 1. Based on information of the actual status and the driver's torque request, this

controller determines the desired control settings for the air-path of the engine using on-line optimization. The Integrated Emission Management strategy specifies the engine settings that provide the required exhaust gas temperature, EGR and air flow, and emissions to minimize operational costs (fuel and urea) within the limits set for tailpipe emissions. This minimization is achieved by applying optimal control, forming the foundation of the IEM strategy. Note that for this study IEM is an extension for an existing powertrain layout, having little impact on the baseline system architecture.

Optimal Control Approach

Optimal control theory is applied to minimize operational or fluid cost. The operational cost are associated with fuel and urea consumption for the considered engine aftertreatment system, which results in the following objective function:

$$\min_{NO_{x, eo}, P_{exh, man}} \int_0^{t_e} (\pi_{fuel} W_{fuel} + \pi_{urea} W_{urea}) dt \quad (1)$$

Subject to:

$$\frac{\int_0^{t_e} W_{NO_{x, tp}} dt}{\int_0^{t_e} P_d / 3.6 \cdot 10^6 dt} \leq Z_{NO_x}, (NO_x \text{ tailpipe limit}) \quad (2)$$

Where:

- π_{fuel} represents the fuel price [€/kg];
- π_{urea} represents the urea price [€/kg];
- P_d is the power required from the drive cycle;

With the assumption that all injected urea decomposes in ammonia and is available for NO_x conversion, the desired urea dosing W_{urea} in (1) is determined from:

$$W_{urea} = 2.0067 \cdot \eta_{SCR} \cdot W_{NO_{x, eo}}$$

Optionally, a PM related term can be included in (1) which accounts for the costs associated with DPF regeneration. However, for this work the focus is on NO_x related fluid costs only.

The average fuel price in the Netherlands without VAT is 1.485 €/kg over 2013 and 2014 [6]. The urea price is taken from [7], where the bulk price is given. For this paper, bulk price of urea is used. The applied costs are summarized in Table 1.

Table 1. Used fluid prices

Type	Cost [€/kg]
π_{fuel}	1.485
π_{urea}	0.24

According to the optimal control philosophy, a Hamiltonian (H) is formulated. This Hamiltonian entails the objective function from Equation 1, which is augmented with Lagrange multipliers and the state dynamics $f(x,u)$:

$$H(x, u) = \left(\pi_{fuel} W_{fuel}(x, u) + \pi_{urea} W_{urea}(x, u) \right) + \lambda^T f(x, u) \quad (3)$$

with Lagrange multipliers $\lambda^T = [\lambda_1; \lambda_2; \lambda_3]$.

The state dynamics, $f(x, u)$ are given by:

$$\dot{x} = f(x, u) = \begin{bmatrix} \frac{W_{exh} \cdot C_{p,g}(T_{exh} - T_{DOC})}{C_{DOC}} \\ \frac{W_{exh} \cdot C_{p,g}(T_{DOC} - T_{SCR}) - h(T_{SCR} - T_{amb})}{C_{SCR}} \\ (1 - \eta_{SCR}) W_{NO_{x, eo}} \end{bmatrix} \quad (4)$$

with $x^T = [T_{DOC}; T_{SCR}; m_{NO_{x, tp}}]$ and $u^T = [p_{exh, man}; NO_{x, eo}]$

being the DOC temperature T_{DOC} , SCR temperature T_{SCR} and tailpipe NO_x flow $m_{NO_{x, tp}}$ [g]. The variables $p_{exh, man}$ and $NO_{x, eo}$ are the exhaust manifold pressure [kPa] and the engine-out NO_x emissions in [ppm], respectively. The parameters C_{DOC} and C_{SCR} represent the thermal mass of the DOC and SCR.

Minimizing the Hamiltonian is one part of the optimal control solution, the trajectories of the Lagrange multipliers have to be optimal also in order to find the real optimum. However, this would result in a control strategy that could only be fit for the particular trajectory it was designed for. Instead, for implementation of a realistic controller, a pragmatic suboptimal approach using heuristic rules for λ is applied. This is described in more detail in [11]. The Lagrange multipliers, represent equivalent costs associated with raw NO_x emissions and temperature changes and have the following interpretation:

- λ_1 [€/°C]: equivalent cost associated with a 1 °C temperature drop of the DOC/DPF combination within 1 s, or alternatively: $-\lambda_1$ is the value associated with a DOC/DPF temperature raise of 1 °C within 1 s;
- λ_2 [€/°C]: equivalent cost associated with a 1 °C temperature drop of the SCR catalyst within 1 s, or alternatively: $-\lambda_2$ is the value associated with an SCR temperature raise of 1 °C within 1 s;
- λ_3 [€/g]: equivalent cost associated with 1 g of tailpipe NO_x emission.

SIMULATION SETUP

To determine the Integrated Emission Management strategy potential at real-world cycles, the performance of IEM is compared with a state of the art Euro-VI strategy in simulation. Two aspects are covered in this paper:

- Cycle results comparison, regarding tailpipe emissions and fluid costs, of IEM (for various values of λ_3) and a state-of-the-art Euro-VI calibration for four real-world drive cycles.

- In-Service Conformity (ISC) analysis of the IEM strategy and the state-of-the-art Euro-VI calibration. More explicitly, focusing on tailpipe NO_x emissions.

Figure 2 shows the model layout chosen for this simulation study. The inputs for the IEM block are explained in more detail on the following pages and shown in Figure 6.

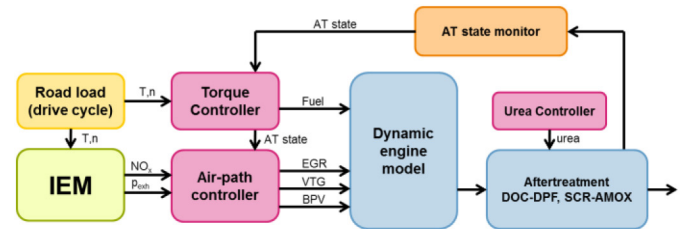


Figure 2. Simulation environment model layout

In this study, the engine and aftertreatment system are represented by validated high-fidelity models. Specifically, a dynamic engine model and Simcat aftertreatment models [8]. The engine and aftertreatment models used in the IEM controller consist of steady state and map based models having a lower level of detail.

System Description

Dynamic Engine Model

The dynamic Mean Value Engine Model (MVEM) represents a modern, Euro-VI, long haul application heavy-duty diesel engine. This engine is equipped with a cooled high pressure Exhaust Gas recirculation (EGR) system, a Charge Air Cooler (CAC), a turbocharger with Variable Turbine Geometry (VTG), a Back Pressure Valve (BPV) and a common-rail fuel injection system. A schematic of this setup is given in Figure 3.

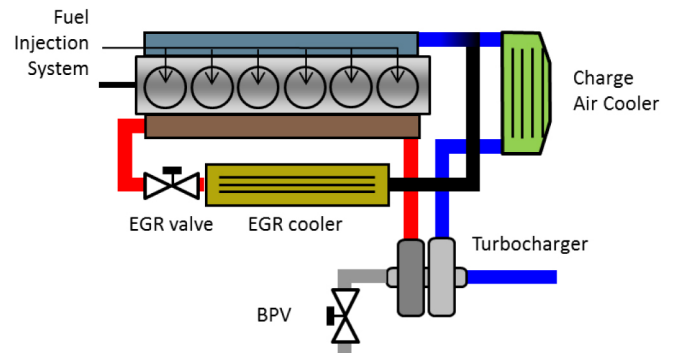


Figure 3. Overview of the Euro-VI heavy duty engine lay-out

The dynamic MVEM engine model is based on [9]. This dynamic MVEM has six states, being:

- Intake manifold pressure
- Exhaust manifold pressure
- Turbocharger rotational speed
- Oxygen mass fraction on the intake manifold
- Oxygen mass fraction on the exhaust manifold
- Exhaust wall temperature

The engine model is recently updated with new functionality. First, the model can now simulate engine braking by means of a BPV and compression release brake. Second, mode switching is included to simulate multi-mode engine operation. Third, the exhaust gas temperature T_{exh} (post BPV) is predicted. This extension is required to increase the accuracy of the temperature prediction during transients. For accurate temperature prediction it is important to take the heat capacity of the exhaust side into account. The exhaust gas temperature T_{exh} is given by:

$$T_{\text{exh}} = T_{\text{wall}} + (T_{\text{turbine-out}} - T_{\text{wall}}) \exp\left(-\frac{4Lh(v)}{DC_{p,\text{exh}}\rho_{\text{exh}}}\right) \quad (5)$$

where the heat transfer coefficient h is computed in the subsystem. L and D are the length and diameter of the pipe, respectively. The exhaust gas flow velocity v originates from:

$$v = \frac{W_{\text{exh}}}{\frac{1}{4}\pi D \rho_{\text{exh}}}$$

The sixth state, wall temperature T_{wall} , is given by the following energy balance:

$$m_{\text{pipe}} C_{p,\text{pipe}} \frac{dT_{\text{wall}}}{dt} = W_{\text{exh}} C_{p,\text{exh}} (T_{\text{turbine-out}} - T_{\text{exh}}) - \frac{1}{R_a(v_{\text{amb}}, T_{\text{wall}})} (T_{\text{wall}} - T_{\text{amb}}) \quad (6)$$

which has the underlying assumption that the temperature distribution of the wall and exhaust gas is uniform.

Aftertreatment Model

The aftertreatment system chosen for this simulation study is configured in a typical modern heavy duty layout, see Figure 4. The system consists of a Diesel Oxidation Catalyst (DOC), catalysed Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR) catalyst and an AMmonia OXidation (AMOX) catalyst. Figure 4 also shows 2 fluid lines supplying fuel and urea to the system. However, in this study, the fuel line that is used for active DPF regenerations, is not considered. All component models predict thermal behaviour and chemical reactions as well as relevant adsorption and desorption phenomena. A detailed overview and model validation results of the catalyst models are presented in [8].

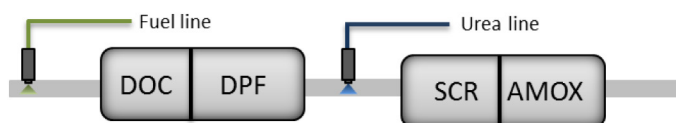


Figure 4. typical Euro VI aftertreatment hardware layout

Control Description

Low-Level Control Systems

In the simulation, several low level controllers are applied, being:

- Air-path controller

- Torque controller
- Urea dosing controller

These controllers are described in the successive subparagraphs.

Air-Path Controller

The air-path controller, shown in figure 2, is a model block, which relates VTG, EGR and BPV position to $NO_{x, \text{eo}}$ and $p_{\text{exh}, \text{man}}$ setpoints during steady state and transient operation. A combination of feedforward and feedback loops are used for achieving the desired actuator setpoints. For the baseline strategy the setpoint values of these actuators are fixed per operating point. In the IEM simulation the setpoints are given by the IEM controller.

Torque Controller

To control the engine torque, a fuel controller is implemented. From the difference between desired engine torque, given by the cycle, and actual engine torque a Throttle Pedal Position (TPP) in percent is determined. This is consequently translated to an engine fuel value. To avoid excessive smoke, the fuelling controller uses a Smoke Limiter (SL), which is set at 1.1.

Urea Dosing Controller

For urea dosing control, a model-based ammonia storage controller is applied. This low-level controller, based on the TNO Simcat SCR catalyst model, estimates the ammonia storage from SCR catalyst temperature TSCR and pre-SCR NO_x emissions. This estimated value is compared with a reference value. The difference is fed to a PID controller, which computes the desired urea dosing. By controlling the NH_3 storage we aim to achieve high NO_x conversion efficiency and avoid excessive NH_3 slip. More details on this controller can be found in [10].

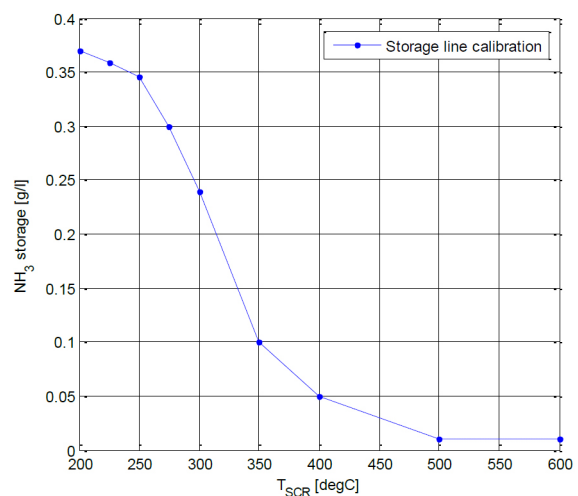


Figure 5. NH_3 storage set point for average SCR temperature (T_{SCR})

The urea control calibration is done by the NH_3 storage set point. The storage line used, throughout this simulation study for both baseline and IEM simulations, is depicted in figure 5. It is clearly seen that for