

Integrated Emission Management strategy for cost-optimal engine-aftertreatment operation

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ABSTRACT

A new cost-based control strategy is presented that optimizes engine-aftertreatment performance under all operating conditions. This Integrated Emission Management strategy minimizes fuel consumption within the set emission limits by on-line adjustment of air management based on the actual state of the exhaust gas aftertreatment system. Following a model-based approach, Integrated Emission Management offers a framework for future control strategy development. This approach alleviates calibration complexity, since it allows to make optimal trade-offs in an operational cost sense.

The potential of the presented cost-optimal control strategy is demonstrated for a modern heavy-duty Euro VI engine. The studied diesel engine is equipped with cooled EGR, Variable Geometry Turbocharger, and a DPF-SCR aftertreatment system. A simulation study shows that the proposed Integrated Emission Management strategy accomplishes 2% to 3% reduction in fuel consumption and operating costs compared to a baseline strategy. Further potential benefits include reduced heat rejection associated with the EGR system and reduced DPF regeneration frequency.

INTRODUCTION

Modern emission legislation requires ultra low emissions for a broad range of diesel powertrain applications, including commercial vehicles, heavy-duty trucks and non-road mobile machinery. These near zero emission levels have to be accomplished not only on a type approval test cycle, but also during real-life operation; there is growing attention for in-use compliance, including Not-To-Exceed (NTE) areas, demanding On-Board Diagnostics requirements and In-Use Performance Ratio (IUPR) monitoring. The next challenge

ahead for the industry is the reduction of CO₂ emission from road transport [1]. This will lead to the introduction of new technologies, which will further complicate powertrain control design.

The main challenge in powertrain control is to find an optimal, cost-efficient balance between fuel efficiency and driveability within the boundaries set by emission legislation. With the growing number of actuators, sensors and subsystems, it is no longer straightforward to optimize the overall powertrain performance. Powertrains have become increasingly complex from a hardware perspective as well as from a control software standpoint. More precisely, engine, drivetrain and aftertreatment subsystems show considerable interactions and interdependencies, which are hard to fully comprehend.

Up till recently, engine and aftertreatment development was conducted separately with individual targets set for both engine emissions and aftertreatment performance. Interaction between the engine and aftertreatment control systems was kept to a minimum. As emission limits get lower and as pressure to assure low real-life emissions under any operating condition increases, it is generally perceived that performance can be improved by exploiting the synergy between engine and aftertreatment system. Improved aftertreatment performance, increased robustness, fuel savings and improved durability are amongst the potential merits. In 2010, the first systems with rudimentary control interaction have been introduced to the market. EPA 2010 engine controllers switch between several discrete modes; e.g. thermal management and fuel efficiency mode. However, a control strategy that continuously seeks an optimum for overall powertrain performance under varying real-world operating conditions still appears to be missing.

This work presents a structured, innovative approach for designing and calibrating control strategies, that optimally exploits the interactions between engine and aftertreatment systems: Integrated Emission Management (IEM). The approach is rooted in optimal control theory, and it has an intuitive interpretation in terms of operating costs. Contrary to other results found in literature, e.g. [2, 3, 4], this approach deals with the synergy between engine and aftertreatment system and focuses on minimizing exploitation costs.

The purpose of this work is twofold:

1. introduction of the general Integrated Emission Management framework, and
2. demonstration of an Integrated Emission Management strategy applied to a simulation model of a Euro VI heavy duty powertrain. The Integrated Emission Management strategy optimizes engine-out NO_x emissions by on-line adjustment of air management based on the actual state of the exhaust gas aftertreatment system. Benefits will be demonstrated in terms of: fuel economy, operating costs and heat rejection.

INTEGRATED EMISSION MANAGEMENT

To meet EPA 2010 and Euro VI emission legislation, most truck manufacturers will rely on engine measures (Exhaust Gas Recirculation, advanced fuel injection equipment and turbo charging) in combination with exhaust gas aftertreatment systems (Diesel Particulate Filter (DPF), urea-based Selective Catalytic Reduction (SCR) system). Up to now, the desired performance is achieved by a time consuming calibration process [5]; setpoints are determined separately for each controller through extensive engine testing. Using Design-of-experiments (DOE) and off-line calibration tools, optimal control settings are specified, such that the engine realizes the desired fuel consumption and emissions and the SCR system realizes the desired NO_x reduction within the set ammonia slip limit. Engine and aftertreatment calibration are often optimized in separate iterations. Furthermore, safety margins are applied to make the engine robust for varying operating conditions, e.g. varying ambient conditions, component wear and aging, varying applications and duty cycles. This sets limits to the achievable fuel consumption.

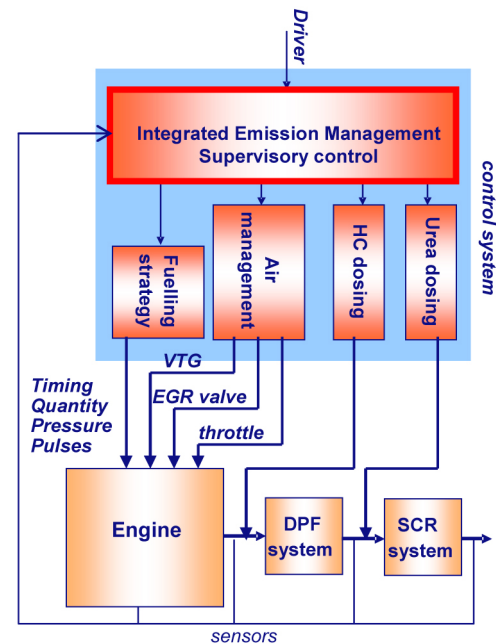


Figure 1. Integrated Emission Management concept for heavy-duty diesel engine

Future powertrains require an optimal and robust control solution that maximally exploits the interactions between engine and aftertreatment systems and that deals with real-world operating conditions. Due to the growing complexity, it is no longer straightforward to optimize overall system performance and the calibration effort has increased exponentially during the last decade. Therefore, it has become inevitable to introduce an integrated system approach: Integrated Emission Management.

Integrated Emission Management is a model-based control design philosophy for combined engine-aftertreatment systems that:

- minimizes fuel consumption, while meeting emission constraints;
- offers a robust emission control solution for both test cycles and real-life operation;
- deals with complex system interactions;
- uses models and optimal control theory to derive optimal control strategies;
- relaxes the calibration complexity.

In this systematic approach, the performance of the separate low-level controllers is coordinated by a supervisory 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 different low-level controllers using on-line optimization. With the available prediction of possible NO_x and PM reduction of the

DPF-SCR system, the Integrated Emission Management strategy specifies the engine settings that give the required exhaust gas temperature, EGR and air flow, and emissions to minimize fuel consumption (and operational costs) within the limits set for tailpipe emissions.

OPTIMAL ENGINE-AFTERTREATMENT INTERACTION

To illustrate the concept and its potential, an Integrated Emissions Management strategy is designed and simulated for a heavy-duty long-haul Euro VI truck application. This strategy coordinates engine air management and urea dosing control. This section discusses the studied engine-aftertreatment system and the developed control strategy in more detail. The new strategy's performance is compared with a baseline strategy.

SYSTEM DESCRIPTION

Powertrain Layout

The studied powertrain comprises a 340 kW 12.9 liter 6 cylinder engine equipped with cooled Exhaust Gas Recirculation (EGR), Variable Turbine Geometry (VTG), and charge air cooler. The exhaust line contains a Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), a 32.6 liter Cu-Zeolite SCR catalyst, and Ammonia Oxidation catalyst (AMOX). The DPF can be regenerated actively through oxidation of diesel fuel injected upstream of the DOC. The powertrain outline is shown in [Figure 2](#). The system is capable of accomplishing EPA 2010 and Euro VI tailpipe emission levels.

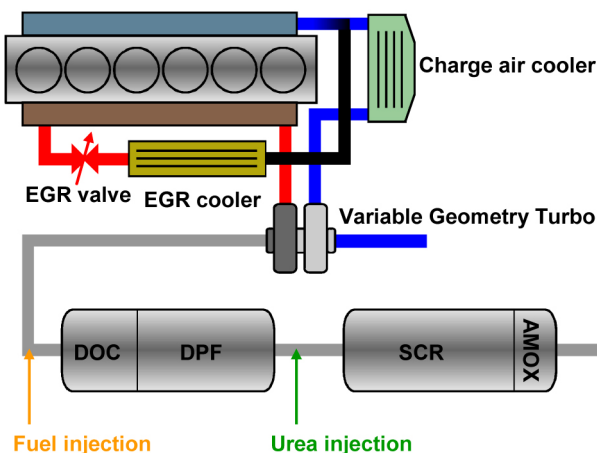


Figure 2. System layout of studied powertrain

Engine and Aftertreatment Models

A mean-value engine model [6] is available for the described engine. This mean-value model describes pressure, temperatures and mass flows throughout the engine based on a mix of fundamental thermodynamic principles, mass and energy balances and component maps (e.g. compressor and turbine maps). More information on this mean-value engine model is found in [7, 8]. Prediction of NO_x and PM emission is incorporated into the model through empirical relations dependent on O_2 concentration in intake manifold and air/fuel ratio λ , respectively.

Exhaust gas aftertreatment is simulated using a library of aftertreatment component models. This library includes one-dimensional first principle models of pipe sections, DOC, DPF, SCR and AMOX. All component models predict thermal behavior 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 [9].

INTEGRATED EMISSION MANAGEMENT STRATEGY

An Integrated Emission Management strategy is designed that schedules the control of the EGR valve position, the VTG position, and the urea dosing, as illustrated in [Figure 3](#). Focus is on NO_x reduction in this example.

SCR NO_x conversion efficiency is determined by the exhaust gas flow, catalyst temperature, and the ammonia storage on the SCR catalyst. The considered Cu-Zeolite SCR catalyst has very high ammonia storage capacity and ammonia adsorption and desorption rates appear slow at relatively low temperatures. These catalyst characteristics imply that the short term NO_x conversion is hardly controllable by the instantaneous urea injection rate. Consequently, the urea injection rate is controlled to keep a certain level of ammonia storage on the SCR catalyst. The SCR ammonia storage level is controlled to be safe from excessive ammonia slip in case of a sudden temperature increase. These ammonia storage control strategies have proven very successful for SCR catalysts with significant ammonia storage [10]. As the urea injection rate can not control short term NO_x conversion, instantaneous tailpipe NO_x emission is controlled by the engine through engine-out NO_x rates, exhaust gas flow and temperature. Note that this paradigm is different from Euro IV/V-like systems for which tailpipe NO_x emission is controlled by adjusting the urea injection rate for a Vanadium based SCR system.

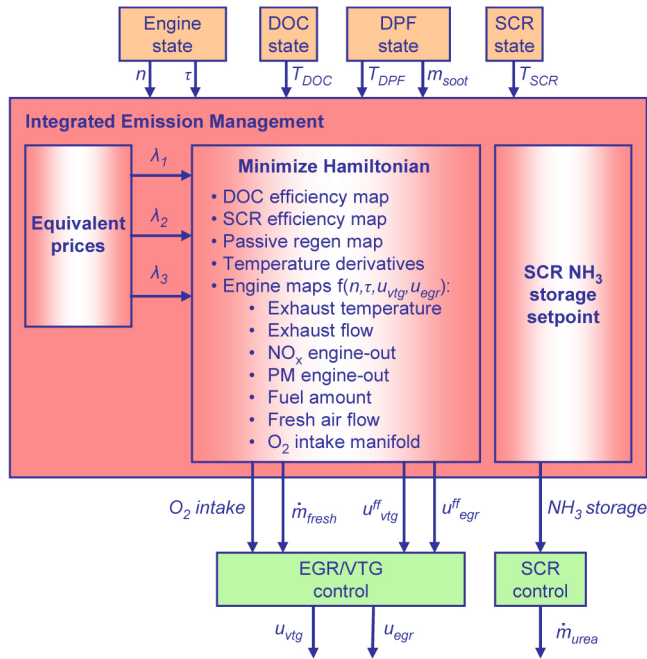


Figure 3. Structure of proposed Integrated Emission Management strategy that coordinates the control of EGR position (u_{EGR}), VTG position (u_{VTG}) and urea dosing (m_{urea})

Optimal Control

The control challenge is concentrated on engine air management: control EGR valve and VTG position to meet engine out emission constraints while minimizing operational costs associated with fuel and urea consumption. Adopting the proposed Integrated Emission Management philosophy, this control problem has to be solved in an optimal sense. Optimal control theory offers a structured and sound approach for these problems. Mathematical derivation is intricate, but the structure of the optimal control solution has an intuitive interpretation. All boils down to optimizing an extended cost function, called the Hamiltonian [11]:

$$H = w(\pi_{fuel} \dot{m}_{fuel} + \pi_{urea} \dot{m}_{urea} + \pi_{pm} \dot{m}_{pm}) + \lambda_1 \dot{T}_{DOC} + \lambda_2 \dot{T}_{SCR} + \lambda_3 \dot{m}_{NO_x, eo} \quad (1)$$

where:

$w = w(n, \tau)$ an engine operating point dependent weight used to capture the duty cycle of the application;
 π_{fuel} fuel price in [€/g] (or any other currency);
 $\dot{m}_{fuel} = \dot{m}_{fuel}(n, \tau, u_{vtg}, u_{egr})$ fuel consumption as function of engine operating point and VTG and EGR setpoints in [g/s];
 π_{urea} price of urea solution in [€/g];
 $\dot{m}_{urea} = 2.007 \cdot \eta_{SCR} \dot{m}_{NO_x, eo}$ the consumption of urea solution in [g/s];
 π_{pm} fuel cost associated with active DPF regeneration per gram of accumulated soot [€/g];
 $\dot{m}_{pm} = \dot{m}_{pm, eo} - \dot{m}_{passive}$ net DPF soot accumulation rate [g/s];
 $\dot{T}_{DOC} = \dot{T}_{DOC}(n, \tau, u_{vtg}, u_{egr})$ the anticipated temperature change of DOC & DPF as a result of VTG and EGR setpoints [°C/s];
 $\dot{T}_{SCR} = \dot{T}_{SCR}(n, \tau, u_{vtg}, u_{egr})$ the anticipated temperature change of SCR as a result of VTG and EGR setpoints [°C/s];
 $\dot{m}_{NO_x, eo} = \dot{m}_{NO_x, eo}(n, \tau, u_{vtg}, u_{egr})$ engine-out NO_x rate in [g/s] (based on NO_2 mol mass);
 $\dot{m}_{pm, eo} = \dot{m}_{pm, eo}(n, \tau, u_{vtg}, u_{egr})$ engine-out PM rate [g/s];
 n, τ, u_{vtg} and u_{egr} denote engine speed, torque percentage, VTG setpoint and EGR setpoint respectively. The net DPF soot accumulation rate is limited to zero in case the DPF is ‘empty’. $\dot{m}_{passive}$ represents the passive soot oxidation rate in [g/s]. This quantity is sensitive to the NO_2 rate upstream of the DPF. This NO_2 rate is determined from a DOC efficiency map which is dependent on the current DOC temperature and the exhaust mass flow rate. The same map is used to account for the NO_2/NO_x ratio dependency of the SCR efficiency $\eta_{SCR}(T_{SCR}, \dot{m}_{exh}, NO_2 / NO_x \text{ ratio})$. T_{SCR} denotes the current SCR catalyst temperature and $\dot{m}_{exh} = \dot{m}_{exh}(n, \tau, u_{vtg}, u_{egr})$ is the exhaust gas mass flow as function of engine operating point and VTG and EGR setpoints. As the SCR ammonia storage is controlled to an SCR temperature dependent setpoint, the SCR efficiency is assumed to be completely described as a function of temperature, exhaust gas flow and NO_2/NO_x ratio.

A derivation of this optimal control structure is presented in the [Appendix](#). Given the engine operating point and aftertreatment temperatures, the Hamiltonian is only dependent on the VTG and EGR valve setpoints. The Hamiltonian, which has unit [€/s], has to be minimized at each time instance. The first term in the Hamiltonian represents the contribution of the (current) operating condition to the total operating costs of the application. The

additional terms stem from the fact that not only operating costs have to be minimized, but also a constraint on NO_x emission has to be met. They represent equivalent prices associated with raw NO_x emission and temperature changes. The three lambdas 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 engine-out NO_x emission.

The structure of the proposed control strategy is depicted in Figure 3. The urea dosing control is separate from the rest of the control strategy as it controls the SCR NH_3 storage independently. A well performing SCR NH_3 storage calibration is mainly dependent on the SCR temperature; direct dependency on engine-out conditions (i.e. raw NO_x emissions) is weak and therefore neglected. The low level SCR control controls the urea dosing to track the NH_3 storage setpoint. An on-line SCR NH_3 storage model is assumed to be available for this purpose.

The main task for the Integrated Emission Management layer is minimization of the Hamiltonian. The Hamiltonian is constructed online from several engine and aftertreatment maps that describe trade-offs between control variables, on one hand, and operating costs and emissions, on the other hand. All maps are generated from the one dimensional aftertreatment models and the mean-value engine model through an automated procedure. For the current implementation, instantaneous minimization of the Hamiltonian is performed by a gradient descent procedure. Minimization of the Hamiltonian yields setpoint values for EGR valve and VTG positions ($u^{\text{ff}}_{\text{EGR}}$ and $u^{\text{ff}}_{\text{VTG}}$). These are passed as feedforward signals to the low level EGR/VTG controller together with two associated performance parameters: fresh air flow and O_2 concentration in intake manifold. These performance parameters are closely related to the level of engine-out NO_x and PM emissions. The low level EGR/VTG controller's task is to track these performance parameters robustly in case of system deviations and to facilitate dynamic control.

Apart from several maps, the Hamiltonian is also constructed from estimates of anticipated aftertreatment temperature changes as a result of VTG and EGR setpoints. A simplified thermal model is used to describe these anticipated

temperature changes. The simplified model is described in the Appendix. The anticipated DOC and SCR temperature change rates can be calculated given EGR and VTG setpoints and the maps for engine-out temperature and exhaust mass flows as a function of engine operating point.

Selection of Control Parameters λ_1 to λ_3

Given all information to construct the Hamiltonian, the result of the minimization in terms of VTG and EGR setpoints is fully determined by the equivalent price parameters λ_1 to λ_3 . As an example, trade-offs are studied for one arbitrary stationary engine operating point: 1400 rpm, 50% torque (1174 Nm). Fixed prices for diesel fuel and urea solution as were used in this study are listed in Table 1. The prices are based on European currency and price level. The cost associated with soot reduction through active DPF regeneration is estimated based on an assumed soot load regeneration trigger level of 5 g/l and the energy requirement for a typical active regeneration in which the DPF is operated at 600 °C for 10 minutes.

Table 1. Prices

Fuel price π_{fuel}	$1.34 \cdot 10^{-3}$ €/g
Urea solution price π_{urea}	$0.50 \cdot 10^{-3}$ €/g
Fuel cost associated with active soot regeneration π_{pm}	$0.071 \cdot 10^{-3}$ €/g

Table 2 shows different BSFC- NO_x trade-offs for different values for the equivalent price parameters λ_1 to λ_3 . As the equivalent price on engine-out NO_x emission (λ_3) is increased, the engine-out NO_x emission drops at an expense of an increased fuel consumption. Lower engine-out NO_x emissions are realized by increasing the EGR rate through closing the VTG. An EGR actuator setpoint of 90% represents the maximum EGR valve opening for this engine operating point. The post-turbine exhaust gas temperature can be influenced through λ_1 . For this example, the temperature increase is realized through fully opening the VTG. Under different circumstances a temperature raise is accomplished by further closing the VTG. This is for example the case at situation with more EGR and at low load conditions (e.g. idle). It is maybe striking that λ_2 does not affect the engine-out exhaust gas temperature. This can be explained by the fact that λ_2 puts a price on heat convection from the DOC/DPF to the SCR substrate. This convection is often better off with a decent exhaust gas flow and does not directly benefit from a rise of exhaust gas temperature for instance through chocking the engine. Obviously the SCR heat up is affected indirectly via the DOC-SCR temperature difference.