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# Supervisory Framework and Model-based Control of Engine and Exhaust Aftertreatment System

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***Abstract*— In this article, a modular control framework for integrated engine and exhaust aftertreatment management is proposed. The framework includes a supervisory controller which has three function blocks: engine setpoint generator, exhaust aftertreatment system (EATS) setpoint generator and emission limits generator. The focus of the article is on development and evaluation of a model based optimal control strategy for the engine setpoint generator. The control objectives of this block and the framework, in general, are to improve the fuel economy while fulfilling emission legislation. The framework is proposed for heavy duty diesel engines, and the strategy for the engine setpoint generator is evaluated using a high-fidelity simulation platform where a validated GT-POWER model of a 13L turbo compound diesel engine and first principles model of an EATS are used. The developed engine setpoint generator—a first step towards a complete implementation of the proposed framework—has reduced complexity compared to a standard controller used in industry consisting of feedforward maps and feedback control. Simulation results show 0.5% decrease in fuel consumption, compared to the standard controller, while maintaining $NO_x$ emissions under the legislative limit.**

***Index Terms*— Diesel engines; Exhaust aftertreatment system; Integrated engine and exhaust aftertreatment management; Dynamic programming; Pontryagin's minimum principle.**

## I. INTRODUCTION

The development of engine controllers nowadays is mostly based on experience and relies heavily on rule and map based solutions with many manually tunable parameters. Because of higher demands on fuel economy and emissions, the control functions are continuously growing. Consequently, dependencies between functionality become hard to understand and the effort to further evolve the system becomes unmanageable.

One way of reducing the number of maps and sorting out dependencies is model based development of control strategies. In general, model based control strategies are developed for the engine system, where engine and exhaust aftertreatment system (EATS) are optimized separately [1-4]. In [1], an overview of model based diesel engine control strategies is given. A model based optimal control strategy to calculate setpoints for the engine controller is developed and evaluated in [2], where setpoints are tracked by an engine controller. The strategy minimizes engine fuel consumption and satisfies the limit on engine-out $NO_x$ emissions. This paper, however, does not discuss the relation to the EATS controller and it is not apparent how the legislative tailpipe $NO_x$ emissions are fulfilled. Model based control strategies of EATS are discussed in [3] and [4].

Tailpipe emission regulations are becoming more and more stringent, and automotive industries are facing difficulties to meet the regulations with existing emission management strategies. For fulfilling future emission legislation [5] and further reduction of fuel, a control system incorporating a combined engine and EATS optimized operation seems to be a natural next step in the development. An integrated engine and exhaust aftertreatment management system is developed in [6] for a diesel engine, where setpoints for exhaust gas recirculation (EGR) and variable geometry turbocharger (VGT) mass flows are generated by the supervisory controller. It is assumed in [6] that the engine controller has perfect tracking of the setpoints. In [7], a supervisory control of a heavy-duty diesel engine with an electrified waste heat recovery system is developed. Both [6] and [7] generate setpoints directly for the actuators of the engine controller, which may require redesigning a new supervisory controller, if, e.g., the engine is to be replaced with configurations that employ different actuators. Our goal is to develop a supervisory controller that is independent of the engine configuration, by, e.g., generating a setpoint for the engine-out $NO_x$ flow rate, which is a common signal in all configurations. This also reduces the dimension of the problem and, hence, decreases computation time. Another goal of our work is to propose a modular control framework (each subsystem with its local controllers is considered as a module), where each module can have limited interaction with other modules and higher level controllers.

This article is a continuation of our work towards model based efficient development of engine control, which reduces the tuning of feed-forward maps and sorts out dependencies between functionality. As a step towards integrated engine and exhaust aftertreatment management, in [8], an engine controller is developed for a 13 L diesel engine based on model predictive control (MPC) strategy. An EGR valve, a VGT and an intake throttle valve (ITV) are controlled to minimize fuel consumption and maximize exhaust thermal power under certain conditions. The controller also accepts soft constraints on engine exhaust temperature to allow the EATS to be within the required range of operation. A desired setpoint of burned gas fraction, strongly related to engine-out $NO_x$ flow rate, is tracked by the controller. A similar engine control strategy is developed in [9] for a six-cylinder diesel engine, equipped with a dual-stage fixed geometry

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turbo system and a variable valve actuation (VVA) system. In this case, a desired setpoint of engine-out $NO_x$ flow rate is tracked by the control strategy. For optimal performance of both [8] and [9], optimized setpoints for engine and EATS need to be generated.

This paper provides two main contributions. Firstly, we propose a modular control framework for integrated engine and exhaust aftertreatment management, intended for online implementation, including a supervisory controller which has three function blocks: engine setpoint generator, EATS setpoint generator and emission limits generator. Then we focus on the engine setpoint generator as the second contribution: a model based optimal control strategy for the engine setpoint generator is developed and evaluated over an entire driving mission. The engine controller used for the work is similar to the one in [8], but designed for a 13 L turbo compound (TC) engine to track a desired setpoint of engine-out $NO_x$ flow rate provided by the engine setpoint generator. Similarly, EATS controller tracks setpoint for SCR $NO_x$ conversion efficiency provided by the EATS setpoint generator.

The organization of the paper is as follows. The different system components that interact with the supervisory controller are presented in Section II. The detailed description of the proposed modular control framework for integrated engine and exhaust aftertreatment management is given in Section III. Development of model based optimal control problem for the engine setpoint generator is discussed in Section IV. Discussion on the numerical algorithms used to solve the optimal control problem is carried out in Section V. Optimal results are evaluated and compared to results with a standard control strategy in Section VI. The paper is ended with conclusions in Section VII.

## II. SYSTEM DESCRIPTION

A schematic representation of a long haul heavy-duty diesel engine used in this work is illustrated in Fig. 1. The engine comprises several components including EGR, ITV, TC and EATS. In the following, the most important characteristics of the subsystems and actuators are explained.

Demanded power of the engine is delivered by controlling the fuel flow. Hence, air fuel ratio increases with the decrease of demanded power, if air intake to the cylinders does not decrease in same proportion. The result of increased air fuel ratio is the decrease in engine exhaust temperature. Thus, at low power, ITV can be controlled to decrease air intake to the cylinders and eventually increase the exhaust temperature whenever required. Similarly, ITV can also be controlled to decrease the exhaust temperature at high power demand. ITV response should be fast enough to handle rapid changes in demanded power. In [10], ITV is used to increase the engine exhaust temperature for regeneration of a particulate filter. Different methods of controlling exhaust temperature are discussed in [11].

The EGR system is used to recirculate a fraction of the exhaust gas back to the combustion chamber to primarily reduce $NO_x$ emission from the engine. It consists of an EGR valve, an EGR cooler and a venturi which provides

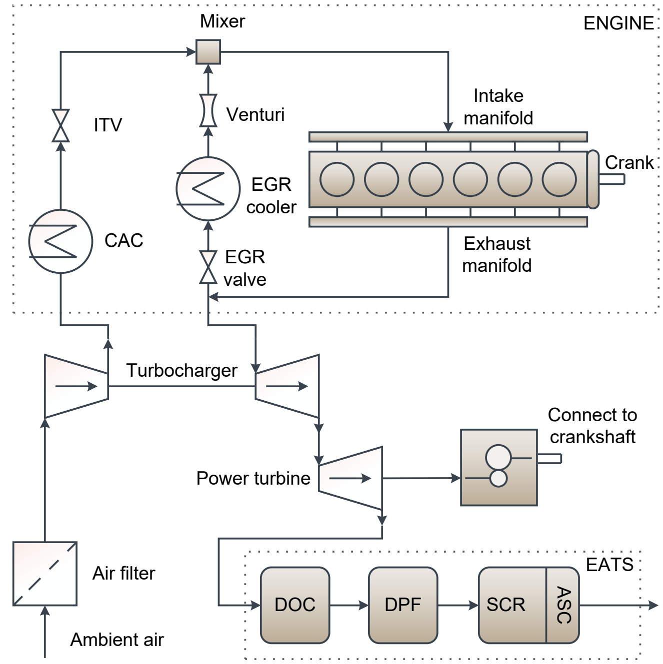


Fig. 1. Schematic representation of diesel engine comprising engine with exhaust gas recirculation (EGR), intake throttle valve (ITV), turbo compound (TC) and exhaust aftertreatment system (EATS).

feedback signal to maintain EGR flow rate. The EGR valve is controlled to regulate the exhaust flow rate through the EGR system. The EGR cooler is used for cooling down the recirculated exhaust gas to maintain lower temperature of charged air, a mix of fresh air and cooled exhaust gas. Extra exhaust gas in the charged air absorbs part of the heat energy. Therefore, recirculated exhaust gas decreases peak combustion temperature and eventually reduces $NO_x$ emission [12].

The TC includes a power turbine, connected in series with a traditional turbocharger, and an advanced gear train that connects the turbine with the crank shaft. The power turbine re-uses exhaust gases from the turbocharger, which contain 20-25% of total fuel energy, and is able to recover up to 5% of the total fuel energy [13]. The power turbine increases exhaust back pressure leading to increased pumping loss. Thus, considering the increased pumping loss for long haul application, TC can add additional 3% of the total fuel energy to the crank shaft via an advanced gear train. Further information on TC diesel engine can be found in [14].

The EATS has three components - diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and selective catalytic reduction (SCR) including ammonia slip catalyst (ASC). The DOC oxidizes NO to generate $NO_2$ which is used to enhance SCR $NO_x$ conversion efficiency and passive regeneration in DPF. The DOC also burns particulate matter through oxidation. DPF accumulates the particulate matter and burns it through active or passive regeneration. This study considers only the cases when DPF removes particulate matter through passive regeneration. The SCR takes an aqueous urea solution (contains 32.5% urea and 67.5% water) as input, known

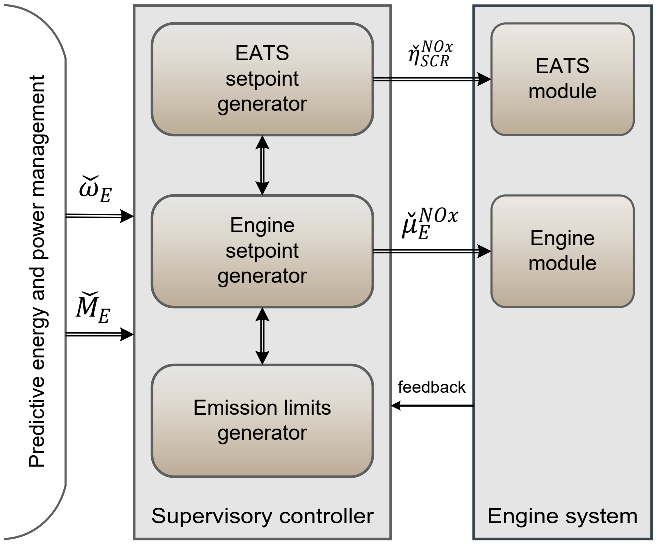


Fig. 2. Schematic representation of a modular control framework for integrated engine and exhaust aftertreatment management (scalar signals are depicted by thin arrows, while vector signals are indicated by thick arrows).

as diesel exhaust fluid (DEF) or AdBlue. After vaporization of the aqueous solution, the urea decomposes into $NH_3$ which reduces $NO_x$ through reaction. The ASC is used to reduce $NH_3$ slip out of the SCR.

## III. MODULAR CONTROL FRAMEWORK FOR INTEGRATED ENGINE AND EXHAUST AFTERTREATMENT MANAGEMENT

Fig. 2 shows the proposed framework for integrated engine and exhaust aftertreatment management. The approach used for the framework is as follows: each of the powertrain subsystems, i.e. engine and EATS together with their respective local control systems, is considered as a *module* with a high degree of autonomy. Local control functions acting at a relatively short time scale are responsible for the proper operation of the respective subsystem. By encapsulating local system functions and properties within the modules, only limited number of signals remain to be manipulated at the higher, supervisory level.

### A. Engine Module

The engine together with its control systems is termed *engine module*. The module takes engine-out $NO_x$ flow rate setpoint[1] $\check{\mu}_E^{NO_x}$ as input, generated by the supervisory controller. The local engine control system also takes minimum limit[2] of engine exhaust temperature $\underline{T}_E^{exh}$ and maximum limit of engine exhaust temperature $\overline{T}_E^{exh}$ as inputs. A change in $\underline{T}_E^{exh}$ or $\overline{T}_E^{exh}$ has an impact on fuel consumption and on maximum achievable SCR $NO_x$ conversion efficiency $\overline{\eta}_{SCR}^{NO_x}$. As a first attempt to approach the problem, these setpoints are not manipulated from supervisory level, rather heuristically fixed to constant values; $\underline{T}_E^{exh}$ is set based on the SCR temperature $T_{SCR}$ when local EATS control system stops AdBlue dosing, and $\overline{T}_E^{exh}$ is equal to the steady state engine exhaust temperature $T_E^{exh}$ when the engine operates at maximum power. Further, the demanded engine torque and engine speed are considered to be major disturbances. The engine controller can use either current demands, determined by the driver, or look-ahead information of engine torque $\check{M}_E$ and engine speed $\check{\omega}_E$. Our MPC based engine controller uses the current demands of engine torque and engine speed and predicts driver behavior for very short prediction horizon. The control strategy tracks $\check{\mu}_E^{NO_x}$, tries to keep $T_E^{exh}$ within the soft limits $\underline{T}_E^{exh}$ and $\overline{T}_E^{exh}$, minimizes fuel consumption and maximizes exhaust thermal power under certain conditions by controlling EGR and ITV. Two outputs of this module are $M_E$ (delivered engine torque) and $\mu_E^f$ (fuel flow rate), which are important from drivability and fuel efficiency point of view, respectively. Other important outputs, e.g. $\mu_E^{NO_x}$ (engine-out $NO_x$ flow rate), $\mu_E^{exh}$ (exhaust mass flow rate), and $T_E^{exh}$ are inputs to the EATS module.

### B. EATS Module

The EATS together with its control systems is named *EATS module*. It takes SCR $NO_x$ conversion efficiency setpoint $\check{\eta}_{SCR}^{NO_x}$ as input, generated by the supervisory controller. The EATS control system has additional settings - it can alternatively allow manipulation of setpoint for ammonia coverage $\theta$ (ratio of ammonia adsorbed on the catalyst to ammonia adsorption capacity of the catalyst) or tailpipe $NO_x$ flow rate. The EATS module is also affected by the engine exhaust characteristics (temperature and flow rates of the main species) and the ambient temperature. For example, the $NO_x$ conversion efficiency of SCR is function of $NO_2$ fraction (defined as the ratio $NO_2/NO_x$), $T_{SCR}$ (SCR temperature) and $\mu_E^{exh}$. The EATS controller tracks $\check{\eta}_{SCR}^{NO_x}$ by controlling AdBlue dosing. Two outputs of this module, tailpipe $NO_x$ flow rate $\mu_{tp}^{NO_x}$ and ammonia slip, are important for emission legislation.

### C. Supervisory Controller

The *supervisory controller* takes look-ahead information of engine torque $\check{M}_E$ and engine speed $\check{\omega}_E$ as inputs. These trajectories can be, for example, generated by a predictive energy and power management unit [15] as setpoints to the supervisory controller. It also takes current $M_E$, $\omega_E$, $T_E^{exh}$, $T_{SCR}$, $\mu_{tp}^{NO_x}$, $\theta$ etc. as feedback signals. The controller provides optimized $\check{\mu}_E^{NO_x}$ to the engine module, and $\check{\eta}_{SCR}^{NO_x}$ to the EATS module. It co-ordinates with the engine module and the EATS module to fulfill emission legislation and optimize total fluid consumption, consisting of diesel fuel and AdBlue. All blocks inside the supervisory controller can communicate with each other. For example, emission limits generator and EATS setpoint generator provide limit on accumulated mass of tailpipe $NO_x$ $\overline{m}_{tp}^{NO_x}$ and SCR $NO_x$ conversion efficiency $\overline{\eta}_{SCR}^{NO_x}$ to engine setpoint generator respectively. The setpoints to the engine module and EATS module are selected carefully for broader goal. They are common signals in all configurations and hence, there would be no change of control problem formulation at the supervisory level in case there

[1]Check sign and $\mu$ mean setpoint and mass flow rate respectively.
[2]Underline and overline mean minimum and maximum limit, respectively.

is any change in the engine or EATS configuration. If a configuration change within a module does occur, then only the local control and the abstractions of input-output relations of that module may need to change.

## IV. PROBLEM FORMULATION

Maximum allowed engine-out $NO_x$ flowrate limit $\overline{\mu}_{E}^{NO_x}$ is carefully defined so that tailpipe $NO_x$ emission is almost negligible during the steady state operation of the heavy-duty engine. The chosen limit makes it possible to reach high $\overline{\eta}_{SCR}^{NO_x}$ for most of the engine operating points during steady state operation. Exceptions are low power regions where $T_{SCR}$ is low and $\overline{\eta}_{SCR}^{NO_x}$ may drop to a lower value. However, the tailpipe $NO_x$ emission is still negligible, since engine-out $NO_x$ is also low at low power regions.

During transient operation, the tailpipe $NO_x$ emission experiences higher values. This may happen when, after longer operation at a low power region, the engine rapidly switches to a high power region. In this case, both $T_{SCR}$ and $\theta$ have low values due to lower $T_{E}^{exh}$ and AdBlue dosing respectively during the operation at the low power region. When the engine operation switches to a high power region, $T_{SCR}$ and $\theta$ take some time to increase because of their slow dynamics, but $\mu_{E}^{NO_x}$ and $\mu_{E}^{exh}$ increase rapidly. Thus, lower $T_{SCR}$ and $\theta$ during transient period lead to a significant decrease in maximum achievable SCR $NO_x$ conversion efficiency $\overline{\eta}_{SCR}^{NO_x}$, i.e. a significant increase in tailpipe $NO_x$ emission.

In the control problem formulation, $\check{\eta}_{SCR}^{NO_x}$ can be either set to $\overline{\eta}_{SCR}^{NO_x}$ or chosen any value between minimum and maximum achievable $\eta_{SCR}^{NO_x}$. For the latter case, the minimum achievable $\eta_{SCR}^{NO_x}$, denoted as $\underline{\eta}_{SCR}^{NO_x}$, is a function of $\theta$ (can be estimated from an online SCR model, where $\mu_{E}^{NO_x}$, $T_{E}^{exh}$, $\mu_{E}^{exh}$ and AdBlue are inputs [4]). Based on $\theta$, ammonia slip can also be controlled by regulating $\check{\mu}_{E}^{NO_x}$. Here, we have chosen to set $\check{\eta}_{SCR}^{NO_x}$ to $\overline{\eta}_{SCR}^{NO_x}$ and to not control ammonia slip explicitly. A descriptive optimal control problem for the supervisor can then be formulated as follows:

$$\text{minimize accumulated total fluid consumption} \tag{1a}$$
subject to:
$$\dot{m}_{tp}^{NO_x} = (1-\overline{\eta}_{SCR}^{NO_x})\check{\mu}_{E}^{NO_x} \tag{1b}$$
$$\text{initial condition on } m_{tp}^{NO_x} \tag{1c}$$
$$\text{constraints on } m_{tp}^{NO_x} \tag{1d}$$
$$\text{static maps to calculate } \underline{\mu}_{E}^{NO_x} \text{ and } \overline{\mu}_{E}^{NO_x} \tag{1e}$$
$$\text{dynamics to calculate } \overline{\eta}_{SCR}^{NO_x}. \tag{1f}$$

The optimal control problem (1) has one control input $\check{\mu}_{E}^{NO_x}$, two disturbances $\check{\omega}_{E}$ and $\check{M}_{E}$, a state variable $m_{tp}^{NO_x}$, and state variables related to dynamics to calculate $\overline{\eta}_{SCR}^{NO_x}$. Minimum allowed engine-out $NO_x$ flowrate limit $\underline{\mu}_{E}^{NO_x}$ in (1e) is defined by considering the drivability of the vehicle during steady state case. The nonlinear state equation (1b) uses the definition of SCR $NO_x$ conversion efficiency

$$\eta_{SCR}^{NO_x} = \frac{\mu_{E}^{NO_x} - \mu_{tp}^{NO_x}}{\mu_{E}^{NO_x}}.$$

Finally, the objective function (1a) is a sum of a nonlinear map to calculate diesel cost and a nonlinear function to calculate cost of AdBlue. Hence, a highly nonlinear dynamic optimization problem should be solved, which requires a trade-off between computation time and accuracy. A similar problem is studied in [7], where solutions are sought by applying Pontryagin's minimum principle. The authors of [7] have overcome the computational burden by introducing costate heuristics related to thermal dynamics. In this paper, we overcome computation complexity by decoupling problem (1) into three different blocks inside the supervisory controller—an engine setpoint generator, an EATS setpoint generator and an emission limits generator—to iteratively co-optimize $\check{\mu}_{E}^{NO_x}$ and $\overline{\eta}_{SCR}^{NO_x}$.

To formulate an optimal control problem for the engine setpoint generator using a co-optimization approach, we assume the following: the EATS setpoint generator provides a prediction of the $\overline{\eta}_{SCR}^{NO_x}$ trajectory (this prediction will depend on the previous iterate of the $\check{\mu}_{E}^{NO_x}$ trajectory), and the emission limits generator provides only terminal state constraint $\overline{m}_{tp}^{NO_x}(t_f)$ for an entire driving mission. The predicted $\overline{\eta}_{SCR}^{NO_x}$ trajectory becomes a function of disturbances $\check{\omega}_{E}$ and $\check{M}_{E}$. Considering that the disturbances $\check{\omega}_{E}$ and $\check{M}_{E}$ are dependent on time $t$, the engine setpoint generator calculates the optimal trajectory of $\check{\mu}_{E}^{NO_x}$ by solving the following simplified problem

$$\min \int_{t_0}^{t_f} \left( \overbrace{c^{f}\mu_{E}^{f}(\check{\mu}_{E}^{NO_x}(t),t)}^{\text{fuel consumption}} + \overbrace{c^{ab}\overline{\eta}_{SCR}^{NO_x}(t)\check{\mu}_{E}^{NO_x}(t)}^{\text{AdBlue consumption}} \right) dt \tag{2a}$$
subject to:
$$\dot{m}_{tp}^{NO_x}(t) = \left(1-\overline{\eta}_{SCR}^{NO_x}(t)\right)\check{\mu}_{E}^{NO_x}(t) \tag{2b}$$
$$m_{tp}^{NO_x}(t_0) = 0 \tag{2c}$$
$$m_{tp}^{NO_x}(t_f) \leq \overline{m}_{tp}^{NO_x}(t_f) \tag{2d}$$
$$\check{\mu}_{E}^{NO_x}(t) \in [\underline{\mu}_{E}^{NO_x}(t), \overline{\mu}_{E}^{NO_x}(t)]. \tag{2e}$$

The resulting optimal $\check{\mu}_{E}^{NO_x}$ trajectory can now serve as a new iterate. The co-optimization procedure is initialized with a $\check{\mu}_{E}^{NO_x}$ trajectory obtained by bilinear interpolation in a 2D map with $\check{M}_{E}$ and $\check{\omega}_{E}$ as inputs. The map is generated offline by solving a problem similar to (2), but for a pre-defined transient driving cycle. Readers are referred to [2] for further details.

## V. METHODS

In problem (2), the objective function is independent of the state variable $m_{tp}^{NO_x}$. The problem has initial and terminal state constraints and a time-varying constraint on the control input $\check{\mu}_{E}^{NO_x}$. In this paper, a benchmark optimal solution of problem (2) is computed by using dynamic programming (DP) [16], while Pontryagin's minimum principle is used to obtain a real-time implementable algorithm. In the following, a brief overview of both algorithms is given.

The benchmark solution of problem (2) is obtained by first discretizing the problem with forward Euler method, with sampling interval of 1 s. Thus, the number of time instances in the DP algorithm becomes equal to the duration of the look-ahead horizon in seconds. The state and control input are densely quantized in order to avoid numerical errors that appear close to the boundary of the backward reachable set because of terminal state constraint [17].

A solution to problem (2) can also be obtained by Pontryagin's minimum principle [18]. The principle uses the Hamiltonian function

$$\begin{aligned}H(u(t),\lambda(t),t) = c^{\mathrm{f}}\mu_{\mathrm{E}}^{\mathrm{f}}(u(t),t) + c^{\mathrm{ab}}\overline{\eta}_{\mathrm{SCR}}^{\mathrm{NO_x}}(t)u(t)\\ + \lambda(t)\left(1-\overline{\eta}_{\mathrm{SCR}}^{\mathrm{NO_x}}(t)\right)u(t)\end{aligned}$$

where $u(t) = \check{\mu}_{\mathrm{E}}^{\mathrm{NO_x}}(t)$ and $x(t) = m_{\mathrm{tp}}^{\mathrm{NO_x}}(t)$. According to Pontryagin's minimum principle, the necessary condition for optimality

$$\min_{u(t)\in U(t)} H(u(t),\lambda(t),t) = H(u^*(t),\lambda(t),t)$$

requires that the time derivative of the costate satisfies

$$\dot{\lambda}(t) = -\frac{\partial}{\partial x}H(u^*(t),\lambda(t),t).$$

Since $H(u^*(t),\lambda(t),t)$ is not an explicit function of $x(t)$, it follows that $\dot{\lambda}(t) = 0$, i.e. $\lambda(t)$ is a constant value. The consequence is that minimization of the Hamiltonian

$$\min_{u(t)\in U(t)} H(u(t),\lambda,t)$$

gives a solution of $u(t)$ for any fixed $\lambda$. In this work, global optimum of the Hamiltonian is found by quantizing $u(t)$ and applying grid search algorithm. The difficulty lies in determining $\lambda$ which fulfils the constraint on $x(t_f)$. However, as $x(t)$ has known initial and final condition, the time-varying linear differential equation

$$\dot{x}(t) = \left(1-\overline{\eta}_{\mathrm{SCR}}^{\mathrm{NO_x}}(t)\right)u(t)$$

can be used for obtaining the optimal value of $\lambda$, by solving a two point boundary value problem (2PBVP). In this work, the 2PBVP is solved by the bisection method that terminates when $|x(t_f) - \overline{m}_{\mathrm{tp}}^{\mathrm{NO_x}}(t_f)|$ becomes small enough. The numerical algorithm is as follows: firstly, guess a constant value of $\lambda$; then, minimize the Hamiltonian for $u(t)$ based on the choice of $\lambda$; after that, solve the differential equation using the initial condition $x(t_0)$ up to time $t_f$; finally, guess $\lambda$ again based on deviation of $x(t_f)$ from $\overline{m}_{\mathrm{tp}}^{\mathrm{NO_x}}(t_f)$ and repeat.

## VI. SIMULATION RESULTS

The performance of the developed model based optimal control strategy for the engine setpoint generator is evaluated in this section. A high-fidelity simulation platform, a transient drive cycle and a baseline control strategy are used for this purpose. The high-fidelity simulation platform includes a validated GT-POWER model of a 13 L turbo compound diesel engine with EGR and ITV, and a first principles model of EATS. The strategy for the engine setpoint generator is developed for an online control algorithm and evaluated over a vehicle driving cycle called Borås-Landvetter-Borås (BLB) cycle, considering optimization problem (2) over the entire driving mission. The cycle is measured by driving a heavy-duty truck from Borås to Landvetter to Borås in the Gothenburg area, Sweden. The demanded speed and torque trajectories for the engine, shown in Fig. 3, are estimated from the BLB cycle. A standard controller used in industry, consisting of feedforward maps and feedback control, is used as the baseline control strategy to compare the results with our control strategy.

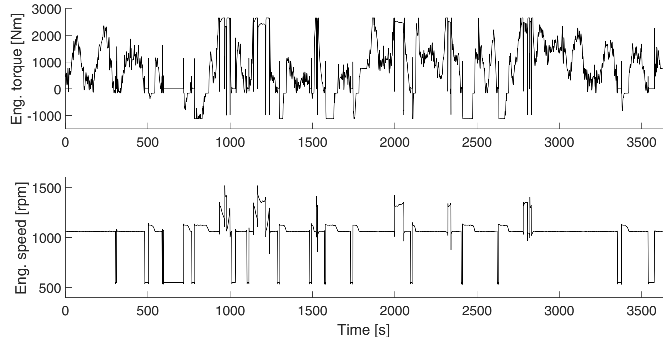


Fig. 3. Borås-Landvetter-Borås (BLB) transient drive cycle.

The simulation results obtained by using the Pontryagin's minimum principle algorithm show no significant differences with the benchmark optimal solution computed by the DP algorithm, except that the DP approach has somewhat bigger quantization errors. In this section, the results obtained by using the real-time implementable algorithm based on Pontryagin's minimum principle is compared with the results obtained by the baseline control strategy.

Fig. 4 shows the optimal setpoint trajectory of engine-out $\mathrm{NO_x}$ flow rate, calculated by solving the optimal control problem (2) using the real-time implementable algorithm, and the actual engine-out $\mathrm{NO_x}$ flow rate. The initial 500 s of the data from Fig. 5 is zoomed in and shown in Fig. 4, illustrating that the engine controller tracks the desired setpoint very well. Quantitative analysis of Fig. 4 reveals that actual engine-out brake specific $\mathrm{NO_x}$ ($\mathrm{BSNO_x}$) is 2.5% less than demanded engine-out $\mathrm{BSNO_x}$.

Fig. 6 illustrates that when the engine operates in low

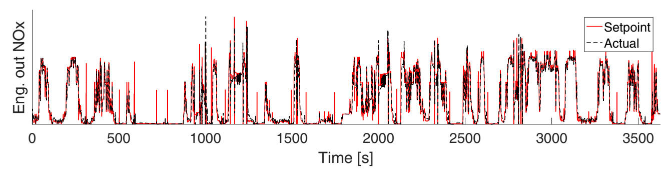


Fig. 4. Tracking of desired engine-out $\mathrm{NO_x}$ flow rate setpoint

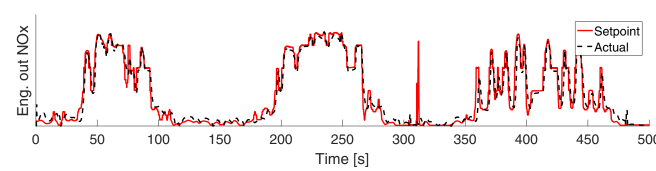


Fig. 5. Tracking of desired engine-out $\mathrm{NO_x}$ flow rate setpoint (zoomed).

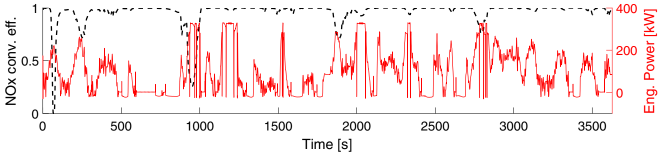


Fig. 6. SCR $NO_x$ conversion efficiency and power delivered by the engine.

TABLE I
COMPARISON OF FUEL, ADBLUE, AND TOTAL FLUID CONSUMPTIONS BETWEEN BASELINE AND SUPERVISORY CONTROL STRATEGY.

| Fuel consumption | Baseline | Supervisory |
|---|---|---|
| Brake specific diesel consumption | 100% | 99.08% |
| Brake specific AdBlue consumption | 100% | 125.47% |
| Brake specific total fluid consumption | 100% | 99.51% |

power region for a relatively long time and then rapidly switches to a high power region, SCR $NO_x$ conversion efficiency decreases significantly.

Table I shows that brake specific total fluid consumption, consisting of diesel fuel and AdBlue, using the proposed control strategy is 0.5% lower compared to the baseline control strategy, while both of them fulfil Euro VI emission legislation.

## VII. CONCLUSIONS

For fulfilling future emission legislation and further reduction of fuel, a modular control framework for integrated engine and exhaust aftertreatment management is proposed. The framework has a few other important properties: local system functions and properties are encapsulated within the modules; each module can have limited and understandable interaction with other modules and with the supervisory controller; setpoints generated by the supervisory controller are common signals in all engine system configurations, which makes the supervisory control problem formulation independent of the engine systems; the setpoints are chosen also to reduce the dimension of the problem, which decreases computation time, memory use and complexity of the algorithm.

As a first attempt to approach the supervisory control problem within the proposed control framework, engine exhaust temperature limits are not manipulated from supervisory level, rather heuristically fixed to constant values. Based on this simplification, a supervisory control problem is formulated and solved. Simulation results show 0.5% decrease in fuel consumption, compared to the standard controller, while maintaining emissions under the legislative limit.

Reduced dimensionality and model-based development of the supervisory control problem, and decoupling the problem into different blocks (subproblems) are all contributed to reduce complexity of the controller compared to a standard controller.

A natural next step is to let the supervisory controller be based on an optimization problem formulated over a finite, receding horizon in order to arrive at a model predictive control algorithm which can handle Euro VI emission legislation for in-service conformity test. Comparison of results, in terms of computation time and accuracy, between solving the nonlinear dynamic optimization problem (1) directly and using co-optimization approach, could be another future work.


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## REFERENCES


[1] L. Guzzella and A. Amstutz, "Control of diesel engines," *IEEE Control Syst. Mag.*, vol. 18, no. 5, pp. 53–71, Oct. 1998.
[2] M. Grahn, K. Johansson, and T. McKelvey, "Model-based diesel engine management system optimization for transient engine operation," *Control Engineering Practice*, vol. 29, pp. 103–114, Aug. 2014.
[3] C. M. Schär, C. H. Onder, and H. P. Geering, "Control of an SCR catalytic converter system for a mobile heavy-duty application," *IEEE Trans. Contr. Syst. Technol.*, vol. 14, no. 4, pp. 641–653, July 2006.
[4] F. Willems and R. Cloudt, "Experimental demonstration of a new model-based SCR control strategy for cleaner heavy-duty diesel engines," *IEEE Trans. Contr. Syst. Technol.*, vol. 19, no. 5, pp. 1305–1313, Sept. 2011.
[5] EC. (2016, Sept.) Commission regulation (EU) 2016/1718, official journal of the european union L 259/1. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32016R1718
[6] J. van Schijndel, M. Donkers, F. Willems, and W. Heemels, "Dynamic programming for integrated emission management in diesel engines," in *19th IFAC World Congress*, Cape Town, South Africa, Aug. 2014, pp. 11 860–11 865.
[7] E. Feru, N. Murgovski, B. de Jager, and F. Willems, "Supervisory control of a heavy-duty diesel engine with an electrified waste heat recovery system," *Control Engineering Practice*, vol. 54, pp. 190–201, Sept. 2016.
[8] E. R. Gelso and J. Dahl, "Diesel engine control with exhaust aftertreatment constraints," in *20th IFAC World Congress*, Toulouse, France, July 2017, pp. 8921–8926.
[9] E. R. Gelso and J. Lindberg, "Air-path model predictive control of a heavy-duty diesel engine with variable valve actuation," in *19th IFAC World Congress*, Cape Town, South Africa.
[10] A. Mayer, T. Lutz, C. Lmmle, M. Wyser, and F. Legerer, "Engine intake throttling for active regeneration of diesel particle," SAE International, Technical Paper 2003-01-0381, Mar. 2003.
[11] P. Spurk *et al.*, "Examination of engine control parameters for the regeneration of catalytic activated diesel particulate filters in commercial vehicles," SAE International, Technical Paper 2003-01-3177, Oct. 2003.
[12] M. Zheng, G. T. Readerb, and J. G. Hawley, "Diesel engine exhaust gas recirculation - a review on advanced and novel concepts," *Energy Conversion and Management*, vol. 45, no. 6, pp. 883–900, 2004.
[13] A. Greszler. (2008, Feb.) Diesel turbo-compound technology. greszler_volvo_session3.pdf. ICCT/NESCCAF Workshop on Improving the Fuel Economy of Heavy-Duty Fleets. [Online]. Available: http://www.nescaum.org/documents/improving-the-fuel-economy-of-heavy-duty-fleets-1/
[14] A. Boretti, "Dual fuel H2-diesel heavy duty truck engines with optimum speed power turbine," in *Proceedings of the FISITA 2012 World Automotive Congress*, Nov. 2012, pp. 77–99.
[15] L. Johannesson, N. Murgovski, E. Jonasson, J. Hellgren, and B. Egardt, "Predictive energy management of hybrid long-haul trucks," *Control Engineering Practice*, vol. 41, pp. 83–97, 2015.
[16] D. P. Bertsekas, *Dynamic Programming and Optimal Control*, 4th ed. Athena Scientific, 2017.
[17] O. Sundström, D. Ambühl, and L. Guzzella, "On implementation of dynamic programming for optimal control problems with final state constraints," *Oil Gas Sci. Technol.*, vol. 65, no. 1, pp. 91–102, 2010.
[18] A. E. Bryson, *Applied Optimal Control: Optimization, Estimation and Control*. CRC Press, 1975.