Integrated Energy & Emission Management for Hybrid Electric Truck with SCR aftertreatment

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***Abstract*—Energy management in hybrid vehicles typically relates to the vehicle powertrain, whereas emission management is associated with the combustion engine and aftertreatment system. To achieve maximum performance in fuel economy and regulated pollutants, the concept of (model-based) Integrated Powertrain Control (IPC) is proposed.**

Based on results from optimal control and the Equivalent Consumption Minimization Strategy, this paper presents a novel IPC strategy for a series hybrid electric heavy duty vehicle with a SCR (Selective Catalytic Reduction) DeNOx aftertreatment system. This strategy makes use of a control model incorporating the dynamics of both the powertrain components as well as the aftertreatment system.

Simulation results demonstrate how IPC can optimize the classical trade-off between operational costs (comprising fuel use and AdBlue dosing) versus the production of tail-pipe NO_x emissions.

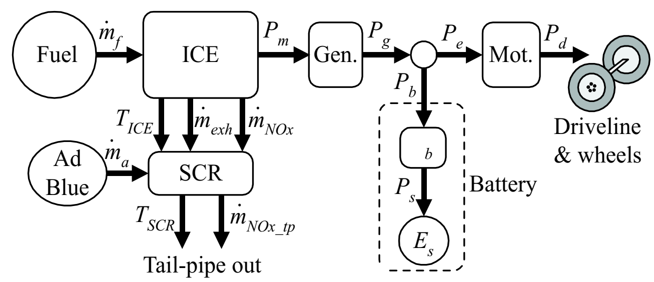

Fig. 1. Vehicle powertrain with aftertreatment system

I. Introduction

Hybrid drivetrains are typically associated with a green image through their reduced fuel consumption and accompanying CO_2 emission reduction. In line with this reasoning, research on control strategies for the hybrid powertrains mainly focusses on energy management strategies.

At present, excellent books and papers have appeared describing energy management strategies for HEVs [4], [6], [7], [9], [14]. Most of this work evaluates a control objective which minimizes CO_2 emissions and in some cases, other harmful emissions such as hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM) are included by means of weighting factors, see e.g. [1], [13]. Nonetheless, most strategies are restricted to engine-out emissions without paying attention to the dynamic influence of the aftertreatment system on the final tail-pipe emissions.

Over the years stringent legislation on tail-pipe emissions emerged for vehicle type approval. To satisfy these requirements, catalytic converters have been introduced in the aftertreatment system to cut down the hazardous emissions to negligible levels. Parameters that influence the performance of the aftertreatment system are mainly the temperature of the catalyst brick and the space velocity of the exhaust flow. It is generally known that catalytic converters suffer from a poor conversion efficiency below light-off temperature. A fast light-off strategy is desirable during cold-start to limit the polluting tail-pipe emissions. Unfortunately, this typically requires additional heat from the exhaust flow resulting in an extra fuel penalty for the Internal Combustion Engine (ICE). To come to a well balanced trade-off between fuel usage and emission reduction, energy management and emission management will become an integral part in future HEVs. This paper proposes a supervisory control strategy for Integrated Powertrain Control (IPC), incorporating both energy management and emission management. During the cold-start period emission management plays a dominant role, whereas the focus will change to energy management when the aftertreatment system has reached light-off temperature. More specifically, after satisfying the constraints on harmful emissions, the remaining freedom will be exploited to gain maximum performance in energy efficiency and accompanying CO_2 emissions. Similar concepts are also discussed in [8], [11], [16]. Since the dynamical behavior of the aftertreatment system dominates its conversion efficiency, a model based approach is indispensable to come to an effective IPC strategy.

II. System Description

In this paper, a model-based IPC strategy is developed for a heavy duty refuse truck equipped with a series hybrid electric powertrain. Selective Catalytic Reduction (SCR) technology is used in the exhaust aftertreatment system to achieve minimal NO_x emission levels. The topology of the powertrain, together with the SCR aftertreatment system, is depicted in Fig. 1.

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A. Powertrain model

The vehicle powertrain is a complex dynamical system. For control development, however, a simplified backwards vehicle model is used to describe the main vehicle characterize. The primary power source is the ICE. The speed and torque of the ICE are denoted by ω [rad/s] and τ [Nm], respectively. The fuel massflow $\dot{m}_f = f(\omega, \tau)$ [g/s] is available from a static fuel map. The power P_m [W] of the ICE is equal to:

$$P_m = \omega\tau. \quad (1)$$

The generator is rigidly connected to the ICE and supplies electric power P_g [W] to the high voltage bus. Losses that appear in the generator are modelled with a static efficiency map η_g [-]:

$$P_g = \eta_g P_m. \quad (2)$$

The electric motor takes care of the propulsion power P_d [W]. Similar to the generator, losses in the motor are incorporated in a static efficiency map η_m [-]. During vehicle deceleration, the motor recovers free braking energy by operating in generator mode. The accompanying losses are included by multiplication with the reciprocal of η_m. Altogether, the model of the motor becomes:

$$P_d = \begin{cases} \frac{1}{\eta_m} P_e & P_e < 0, \\ \eta_m P_e & P_e \geq 0. \end{cases} \quad (3)$$

A battery is available to store the surplus energy. Its model falls apart into two elements: a battery efficiency block and a net storage device (see also Fig. 1). The battery efficiency is build up with a static efficiency η_b [-]:

$$P_s = \begin{cases} \frac{1}{\eta_b} P_b & P_b < 0, \\ \eta_b P_b & P_b \geq 0. \end{cases} \quad (4)$$

An integrator is used to keep track of the energy E_s [J] stored in the battery:

$$\dot{E}_s = P_s. \quad (5)$$

Finally, the model of the high voltage DC bus is free from losses and connects the motor and generator to the battery storage device:

$$P_e + P_b = P_g. \quad (6)$$

B. SCR aftertreatment model

The SCR aftertreatment system is build up from a Vanadium catalyst brick accompanied by an AdBlue dosing system. Excellent models exist for this SCR technology, where state-of-art models take into account ammonia (NH_3) storage at the catalyst surface to improve the response of the NO_x conversion efficiency during transient situations, see e.g. [12], [15]. Owing to the high level of accuracy, these models are typically used to develop the AdBlue dosing strategy. Nonetheless, not all details of the SCR system have to be taken into account when developing the supervisory IPC strategy. The IPC strategy considers only the general (slow dynamics) SCR characteristics, whereas the AdBlue dosing strategy takes care of the local chemical reactions and the storage buffers in the SCR system.

In this work, a simplified model is derived from the complex SCR model as described in [15]. This reduced SCR model entails two components: a temperature model and an NSR (Normalized Stoichiometric Ratio) map for the NO_x conversion ratio. The temperature model aggregates the energy flow in/out of the catalyst, Q_{in} [W] and Q_{out} [W], respectively. Altogether, the temperature model is described by the following differential equation, see also [10]:

$$\begin{aligned} \dot{T}_{SCR} &= \frac{1}{C_{SCR}} \{Q_{in} - Q_{out}\} \quad (7) \\ &= \frac{1}{C_{SCR}} \{\dot{m}_{exh} c_{exh} (T_{ICE} - T_{SCR})\} \quad (8) \end{aligned}$$

with:

T_{SCR}	SCR output temperature	[K]
C_{SCR}	Equivalent heat capacity	[J/K]
c_{exh}	Specific heat capacity exhaust gas	[J/(gK)]

The input signals for the SCR system come from the ICE block. Therefore, the ICE block also contains a static look-up table for the exhaust gas temperature $T_{ICE} = g(\omega, \tau)$ [K], the NO_x emissions $\dot{m}_{NOx} = h(\omega, \tau)$ [g/s] and the exhaust massflow $\dot{m}_{exh} = j(\omega, \tau)$ [g/s]. The tail-pipe NO_x emissions $\dot{m}_{NOx\_tp}$ [g/s] leaving the SCR system are calculated as follows:

$$\dot{m}_{NOx\_tp} = \dot{m}_{NOx} (1 - \eta_{NOx}), \quad (9)$$

where the NSR look-up-table η_{NOx} [-] describes the (quasi-static) SCR conversion efficiency. This NSR map depends on two parameters: T_{SCR} and space velocity SV [1/hr]. A typical example of this map is depicted in Fig. 2. The space velocity expresses the refreshment rate of the exhaust gas in the catalyst and its value can be approximated from the exhaust massflow $\dot{m}_{exh}$:

$$SV = 3600 \frac{\dot{m}_{exh}}{\rho_{exh} V_{cat}}, \quad (10)$$

where ρ_{exh} [g/m^3] denotes the exhaust gas density and V_{cat} [m^3] represents the catalyst volume.

From the NSR map also the required urea dosing strategy can be approximated by considering the main underlying chemical reactions. The aqueous urea solution ($(NH_2)_2CO$ + H_2O) is injected into the exhaust gas and decomposes into ammonia and carbon dioxide:

$$(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2 \quad (11)$$

On the catalyst surface various chemical reactions occur between ammonia and NO_x. The main reaction uses both NO and NO_2 and the corresponding reaction products are elemental nitrogen and water:

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \quad (12)$$

There should be noted that the formation of NO and NO_2 in a diesel engine is unbalanced and the raw exhaust emissions contain far more NO than NO_2. Therefore, oxidation catalysts are generally applied upstream the SCR system to promote the formation of NO_2:

$$2NO + O_2 \rightarrow 2NO_2 \quad (13)$$

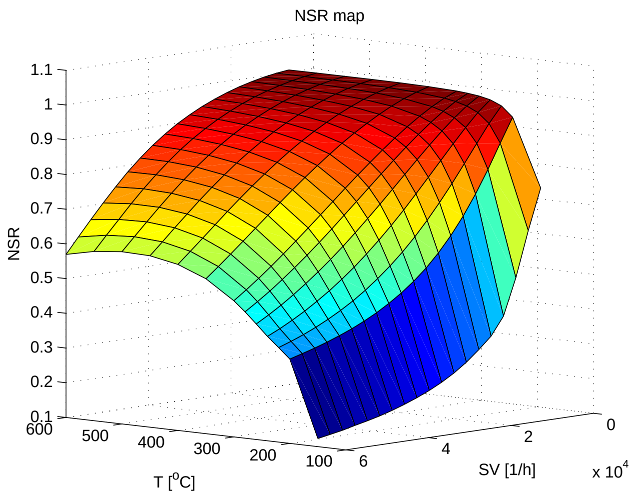

Fig. 2. Static conversion efficiency SCR catalyst

This way, it is reasonable to assume that NO_x entering the SCR catalyst appears with an equal distribution of 50% NO and 50% NO_2. For a detailed analysis of the NO / NO_2 ratio and its impact on the NO_x conversion efficiency, the interested reader is referred to [3].

The combination of the chemical reactions (11) and (12) yields the overall mole ratio between NO_x and $(NH_2)_2CO$ of 2:1. This ratio is used to calculate the net amount of urea needed to reduce the NO_x emissions in the SCR system:

$$\dot{m}_u = \frac{M_{(NH2)2CO}}{2M_{NOx}}\ \eta_{NOx}\,\dot{m}_{NOx} \quad \text{[g/s]}, \tag{14}$$

with molar mass $M_{(NH2)2CO} = 60.07$ [g/mol] and $M_{NOx} = 38.01$ [g/mol]. The aqueous urea solution AdBlue has a solubility of 32.5%, which means that 32.5 [g] $(NH_2)_2$)CO is dissolved in 100 [g] solution. Therefore, the corresponding AdBlue massflow $\dot{m}_a$ becomes:

$$\dot{m}_a = \frac{100}{32.5}\ \dot{m}_u \quad \text{[g/s]}. \tag{15}$$

III. Integrated Powertrain Control

The series HEV powertrain offers freedom to select the operating point of the ICE. This section proposes an IPC strategy which takes into account the following three requirements:

1) Minimize operational cost,
2) Limit tail-pipe NO_x emissions,
3) Establish charge sustaining State-of-Charge profile.

The main difficulty when developing a suitable IPC strategy is that the first two requirements have conflicting interests. Minimizing the operational cost implies low fuel consumption without paying attention to hazardous emissions. However, the aftertreatement system requires heat from the exhaust gas to reach light-off temperature fast in time and maintain good NO_x conversion efficiency.

From a control perspective, IPC must balance between a soft constraint on minimum operational cost versus a hard constraint on NO_x emissions to satisfy vehicle type approval. The majority of the NO_x emissions emerge during the cold-start period where the temperature of the aftertreatment system is low. In addition, extreme high engine power also contributes to NO_x emissions due to the combination of significant NO_x production with high space velocity. During these moments, the SCR system suffers from poor conversion efficiency so IPC will focus on emission management to keep the NO_x emissions limited. After reaching a suitable emission level, the focus of IPC can change to energy management. Here the remaining freedom will be exploited to keep the operational cost low. This complete IPC approach will be further explained in the following sections.

A. Control Objective

During vehicle operation, the engine consumes diesel whereas the SCR system requires urea. Both consumables are evaluated by the IPC strategy to come to a cost effective solution. When the engine fuel massflow $\dot{m}_f$ [g/s] is given and the price for diesel π_f [Euro/g] is known, the instantaneous fuel cost are described by: $c_f = \pi_f \dot{m}_f$.

To calculate the operational cost, the fuel cost are augmented with the cost for the SCR urea dosing strategy. The required AdBlue dosing $\dot{m}_a$ is calculated from the NSR map as described in (15). Next, the cost for the SCR dosing strategy is calculated with help of the price for AdBlue π_a [Euro/g]: $c_a = \pi_a \dot{m}_a$.

Altogether, the following objective function emerges for minimizing the operational cost:

$$\min_{\omega(t),\tau(t)} \int_0^{t_e} c_f + c_a\ dt \tag{16}$$

subject to

$$\frac{\int_0^{t_e} \dot{m}_{NOx\_tp}\ dt}{\int_0^{t_e} \frac{P_d}{3.6\times 10^6}\ dt} \le M_{NOx} \qquad \text{(tail-pipe } NO_x \text{ limit)} \tag{17}$$

$$\int_0^{t_e} P_s\ dt = 0 \qquad \text{(charge sustaining)} \tag{18}$$

Note that in (17) the NO_x emission limit M_{NOx} [g/kWh] normalizes the tail-pipe NO_x emissions with respect to the total energy request from the driveline.

B. ICE efficient operating lines

The series HEV delivers the required propulsion power by means of the electric motor. This offers freedom to the ICE to keep both speed ω [rad/s] and torque τ [Nm] in a preferred operating range. When considering the ICE fuel map, the efficiency line can be calculated where the engine consumes minimal fuel for each power demand:

$$\text{E-line fuel:} \quad (\tau,\omega)|_{P_m} = \arg\min_{\mathcal{Q}(P_m)} \dot{m}_f \tag{19}$$

where $\mathcal{Q}(P_m)$ denotes the set of admissible operating points for constant engine power P_m:

$$\mathcal{Q}(P_m) = \{\ (\tau,\omega)\ |\ P_m = \omega\tau\ \}. \tag{20}$$

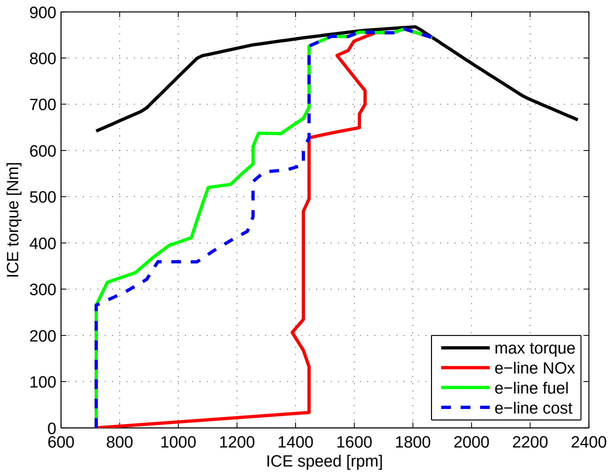

Fig. 3. Visualization of various ICE e-lines

In a similar way, the e-line for minimal NO_x can be defined:

$$\text{E-line NO}_x\text{:} \quad (\tau,\omega)|_{P_m} = \arg \min_{\mathcal{Q}(P_m)} \dot{m}_{NOx}. \tag{21}$$

Both the e-line for fuel and NO_x are visualized in Fig. 3. Next it is important to recognize that the control objective in (16) applies a weighting function between these e-lines. After all, c_f depends on $\dot{m}_f$ from (19), whereas c_a depends on $\dot{m}_a$ and using (14)-(15) this is directly related to $\dot{m}_{NOx}$. For any engine operating point (ω,τ) the operational cost $c_f + c_a$ can be evaluated with respect to ICE power and an e-line is determined:

$$\text{E-line cost:} \quad (\tau,\omega)|_{P_m} = \arg \min_{\mathcal{Q}(P_m)} c_f + c_a. \tag{22}$$

This e-line represents a cost effective e-line where the prices π_f and π_a have to be considered as weighting parameters. For European reference prices medio 2010, there holds $\pi_f/\pi_a \approx 2$ and the corresponding cost e-line is also shown in Fig. 3.

In the remainder of this paper, the operating range of the ICE will be restricted to the cost effective e-line. This yields a well defined relation between the engine power P_m and the output signals T_{ICE}, $\dot{m}_{NOx}$ and $\dot{m}_{exh}$. These relations will be used in the next section to come to an appropriate IPC strategy.

C. Integrated energy & emission management

At the beginning of this section the aim of the IPC strategy is defined by means of three requirements: operational costs, emissions and charge sustaining. The solution method for this control problem is characterized by minimizing an objective function (requirement 1), subject to constraints (requirement 2 and 3). The framework from optimal control [5] is adopted to come to a model based control strategy. The associated control model entails a state-space description comprising the dynamic equations from (5), (8) and (9):

$$\dot{x} = f(x) = \begin{bmatrix} P_s \\ \frac{1}{C_{SCR}}\{\dot{m}_{exh}c_{exh}(T_{ICE} - T_{SCR})\} \\ \dot{m}_{NOx}\,(1-\eta_{NOx}) \end{bmatrix} \tag{23}$$

with state variable x:

$$x = \begin{bmatrix} E_s \\ T_{SCR} \\ m_{NOx\_tp} \end{bmatrix} = \begin{bmatrix} \text{stored battery energy} \\ \text{SCR catalyst temperature} \\ \text{total tail-pipe NO}_x \text{ emissions} \end{bmatrix} \tag{24}$$

The ICE power P_m is selected as decision variable and with help of the model equations from Section II the state-space description from (23) can be rewritten as function of input variable P_m. According to the philosophy of optimal control, a Hamiltonian is formulated which entails the objective function from (16) augmented with Lagrange multipliers λ and the state dynamics $f(x)$ from (23):

$$H \;=\; c_f + c_a + \lambda^\top f(x) \tag{25}$$

The Pontryagin's Maximum Principle poses 2 necessary conditions for optimality:

$$\frac{\partial H}{\partial P_m} \;=\; 0 \tag{26}$$

$$-\frac{\partial H}{\partial x} \;=\; \dot{\lambda} \tag{27}$$

The first condition (26) yields the optimal control input P_m^* [W]. This is a non-linear equation and will be solved numerically. The second condition (27) provides the dynamical equations for the controller and are calculated as follows:

$$\dot{\lambda}_1 \;=\; -\frac{\partial H}{\partial E_s} = 0 \tag{28}$$

$$\dot{\lambda}_2 \;=\; -\frac{\partial H}{\partial T_{SCR}} = \frac{\lambda_2}{C_{SCR}}\dot{m}_{exh}c_{exh} \tag{29}$$

$$\dot{\lambda}_3 \;=\; -\frac{\partial H}{\partial m_{NOx\_tp}} = 0 \tag{30}$$

Apparently, λ_1 and λ_3 remain constant for the optimal solution but more important to notice is that λ_2 is unstable. As a result, this controller can only be used without restrictions in fixed time window (e.g. during the cold-start period). After this period a new calibration is needed such that holds: $\lambda_2 = 0$.

Now the structure of the controller is given, but how to select the initial values $\lambda_1(0)$, $\lambda_2(0)$ and $\lambda_3(0)$ is still an open question. By considering (25) with (23) one can recognize the following dependencies:

- λ_1 represents a cost-equivalent factor for charging/discharging the battery and a lower initial value will result in a higher SOC at the end of the driving cycle.
- λ_2 weights the temperature of the SCR catalyst and by increasing its initial value a faster light-off strategy can be achieved.
- λ_3 takes into account the accumulated tail-pipe NO_x emissions and a higher initial value will more penalize the raw engine-out emissions.

TABLE I
OVERVIEW S-HEV VEHICLE CONFIGURATION

Component	*Manufacturer*	*Specification*
Chassis	DAF	LF series
ICE	Cummins	6 cyl. 165 [kW]
Generator	Siemens	Perm. magnet 160 [kW]
Motor	Siemens	Perm. magnet 185 [kW]
Battery	Magna Steyr	Li-ion 7 [kWh]

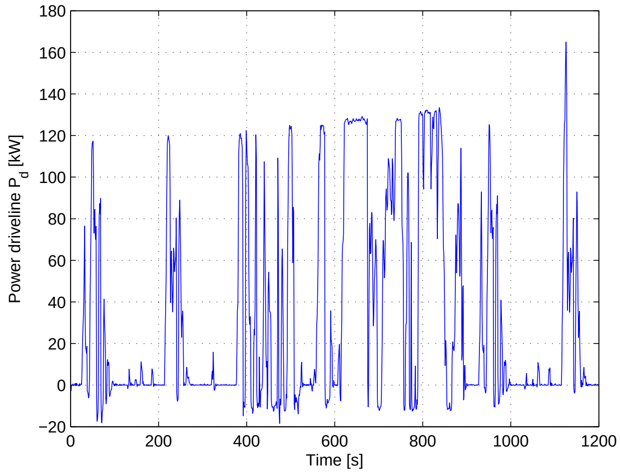

Fig. 4. Power request FTP driving cycle

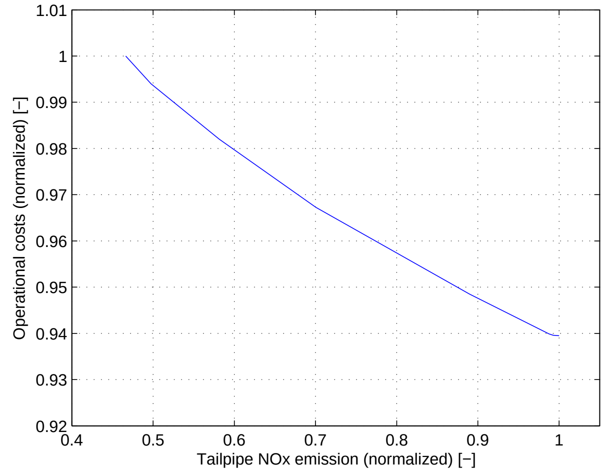

Fig. 5. Trade-off between operational cost and NO_x emissions

The reader which is familiar with the ECMS method [6], will recognize that here a similar approach has been chosen. Traditionally ECMS focusses on energy management and considers primarily the energy status E_s of the battery. By including here the state equations of the aftertreatment system, energy management is extended with emission management. Especially during the cold-start period the emissions play an important role, but after this period the dynamics of the SCR system still remains important. The controller state λ_2 must be set to zero after a certain time (e.g. when T_{SCR} reaches light-off temperature) to keep the controller stable.

IV. SIMULATION RESULTS

The vehicle under consideration is a series hybrid refuse truck. The main components are specified in Table I. Simulations are done for the FTP (Federal Test Procedure) heavy duty cycle. This is a transient engine dynamometer cycle, but it is based on the Urban Dynamometer Driving Schedule (UDDS), so also suitable for evaluation of hybrid vehicles. The corresponding power request at the wheels is shown in Fig. 4.

The IPC strategy from the previous section will be demonstrated by selecting different values for the initial controller state $\lambda(0)$. This way it becomes possible to analyze the trade-off between operational cost and NO_x emissions. For convenience $\lambda_2(0) = 0$ so the analysis will not take into account a faster light-off strategy for the SCR system. This way the unstable controller state is eliminated and no calibration changes are needed along the driving cycle.

The selection of $\lambda_1(0)$ and $\lambda_3(0)$ is done iteratively by considering the final value of the battery energy E_s. First $\lambda_3(0)$ is selected and using a bi-section search algorithm multiple simulations are done with different initial values for λ_1. This way, an unique value for λ_1 can be found where there holds that E_s at the end of the driving cycle is exactly equal to its initial value. Starting with a low value for $\lambda_3(0)$, the IPC strategy establishes a solution with high NO_x emissions but low operational costs. Conversely, a high value for $\lambda_3(0)$ leads to low NO_x emissions but higher operational costs. This trade-off has been visualized in Fig. 5 for a wide range of initial values.

In Fig. 5 it appears that the NO_x emissions can be influenced over a much broader range than the operational costs. The reason for this is that the operational costs are mainly determined by the costs for diesel and driving the FTP cycle requires always a minimum amount of energy. Changing the controls of the hybrid powertrain has only limited impact on this energy request. This is different for the NO_x emissions since the SCR system can achieve high conversion efficiency when the ICE operates in its preferred range. After the cold start period, the hybrid powertrain is able to make the NO_x emissions almost independent of the power request from the driver.

The two extreme values from the curve in Fig. 5 (i.e. minimum operational costs versus minimum NO_x emissions) are further analyzed in Fig. 6. This latter figure shows the ICE power, the temperature of the SCR catalyst and the battery SOC along the FTP driving cycle for both cases. One can see that the controller tries to keep the ICE at a steady-state operating point when minimizing the NO_x emissions. This is done to avoid NO_x emissions at high space velocity (associated with high engine power) which are undesirable for a good conversion efficiency of the SCR system. When

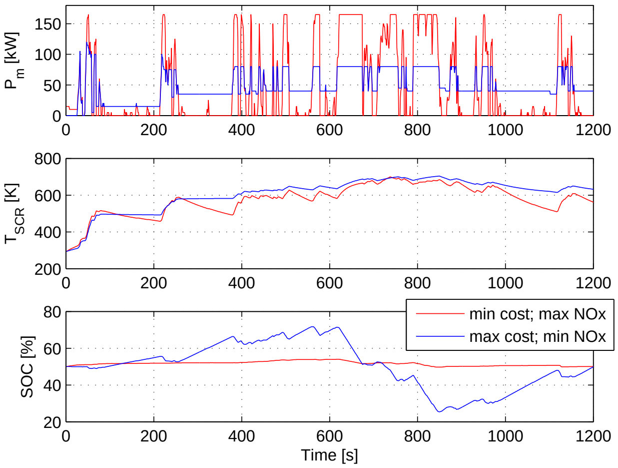

Fig. 6. Simulation results FTP driving cycle

minimizing the operational costs it turns out that the battery is very limited used, so the vehicle operates most of the time in diesel electric mode. This is because the losses in the battery are too high. Only free energy from regenerative braking is stored in the battery. In this example it becomes clear that the additional freedom of a hybrid powertrain could be more valuable for reducing emissions, rather than reducing the operational costs.

V. Conclusions and Outlook

A model based control strategy has been developed for a series hybrid electric truck. This strategy originates from the theory of optimal control and incorporates both energy management and emission management. Therefore, the dynamic behavior of the hybrid powertrain as well as the aftertreatment system are taken into account.

Simulation results have been presented for a known driving cycle. This makes it possible to select an initial value for controller states λ such that the energy stored in the battery at the end of the driving cycle equals its initial value. Additional research is needed for on-line selection of λ to achieve robust performance for an arbitrary driving cycle. See for example [9] where λ receives an on-line update from a PI-controller.

If the final performance shows not enough NO_x reduction, one can change the calibration of the controller by selecting $\lambda_2 \neq 0$ during the cold-start period. If this state is non-zero, the controller is encouraged to increase the temperature of the SCR temperature faster and a better NO_x conversion is achieved. When the SCR temperature is sufficient hot, a switch to $\lambda_2 = 0$ is needed to prevent that this state blows up. Also the possibility exists to change the e-line for operational cost and move the operating area towards the NO_x e-line during the cold-start period. This method has been presented in [11].

The simulation results presented in this paper make use of the reduced SCR model described in Section II-B. In future, simulations with the complex SCR model from [15] will be done to validate the quality of the simplified aftertreatment model.

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