Preprints of the 21st IFAC World Congress (Virtual)
Berlin, Germany, July 12-17, 2020

Development of an Integrated Control Strategy for engine and SCR system based on effective EGR rate

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Abstract: The introduction of actual and upcoming emission standards, move the industrial attentions from laboratory towards real-world emission performance, In-Service Conformity testing (ISC) and life-time periods. Besides advanced air management, fuel injection pattern optimization and aftertreatment systems, the goal to realize optimal and robust powertrain setting under varying operating conditions, while ensuring the proper operation of ATs is challenging and require a massive calibration effort. To accomplish this task, the present research deals with supervisory controller for the integrated engine-SCR system, also referred in literature as EGR-SCR balancing. The goal is to comply with NO_x emissions limit and, at the same time, to minimize global costs over transient operating conditions. The potential of this IEM strategy is demonstrated for a typical type-approval test case. The optimization identifies the effective EGR actuation, based on the actual powertrain state, engine settings and ATs performances. The resulting control strategy optimizes the overall performance.

Keywords: Engine modeling and control, NO_x emissions, SCR, EGR-SCR balancing, Nonlinear and optimal automotive control, Automotive system identification and modelling, exhaust gas after-treatment systems.

1. INTRODUCTION

With the introduction of light-duty and heavy-duty Diesel engines Euro-6/VI regulations in 2013/2014, an increasing attention in the reduction of pollutant emissions and air-quality improvement is observed. In the perspective to meet the NO_x emission standards to reduce pollutants emissions below limit values, without foregoing the advantages of Diesel engines (Parliament and the Council of the European Union, 2007), the European standards refer to more real-world emissions (RDE test procedure is introduced). Particularly they focus on stricter OBD requirements, off-cycle emission limits (OCE), In-Service Conformity testing (ISC) and life-time periods. To meet these requirements, a combined design of Exhaust Gas Recirculation (EGR) and exhaust gas after-treatment systems (i.e. DOC, DPF, SCR and LNT) is required. After-treatment technologies, such as lean NO_x traps (LNT) or urea based selective catalytic reduction (SCR), coupled with ammonia oxidation catalyst (AMOX), may be added alongside technologies already adopted to meet CO, HC, and PM limits, including Diesel oxidation catalysts (DOC) and Diesel particulate filters (DPF). These technologies, on one hand, should counteract nitrogen oxides emissions which could results from engine calibration, designed to maximize fuel economy, and from technologies that utilize NO_2 to oxidize particulate (DPF during passive regeneration); on the other hand, they should guarantee the optimal interaction with the engine, the so called "EGR-SCR balancing" which also promotes the reduction of heat rejection and DPF regeneration frequency.

The need to deal with the optimized engine and after-treatment interaction under real-world circumstances is challenging and not straightforward, due to the growing number of sensors, actuators, devices and extensive variety of operating conditions. Particularly, the SCR system requires careful and accurate modeling approach and identification methods (Arsie et al., 2018). The non-linearity of the system, makes SCR map-based control not suitable to optimize NO_x conversion efficiency, whilst prevent NH_3 slip during transients. Therefore feedback non-linear model-based control is generally adopted to infer adaptive features vs. systems aging and plant-model mismatch (Mentink et al., 2015; Willems et al., 2013; Ramachandran et al., 2016). The optimal design of the engine and after-treatments, can be achieved by a supervisory controller that manages, simultaneously, the urea injection strategy and fuel injection pattern. The objective of the controller is to offer an emission control, based on the actual state of the engine and ATs, which in turn defines online the optimal engine control settings that minimize operational costs (fuel and urea) within NO_x and NH_3 slip emission constraints along a wide range of operating conditions.

Research focus in this domain has been mainly devoted to electrified powertrains (HEVs), where the main objective is to optimise the torque split between the combustion engine and the electric machine (Larsson et al., 2014). For this applications, the energy management strategy shows the potential to reduce fuel consumption and improve electric generator performances (Bouwman et al., 2017; Guzzella and Sciarretta, 2013). MPC with dynamic programming and PMP are common approaches for optimal supervisory powertrain control as used in (Donkers et al., 2017a; Chen and Wang, 2013). However computationally less intensive solvers need to be developed for implementation in on-board real-time controllers. Formally, the control problem can be formulated by using Pontryagin's Minimum Principle which provides a sub-optimal solution through a local optimization, with the advantage of lower computational burden requested. Nevertheless, the proposed structure could be interestingly used in an online optimization strategy if predictive short horizon conditions can be estimated (ECMS strategy). Several control approaches are proposed in the literature to manage the EGR-SCR balance, particularly (Willems et al., 2013) performed a cost-based optimization by setting the optimal air-management set points, resulting in a 2.1% of fuel consumption, the strategy has been further improved with the addition of a feedback scheme to control the tailpipe NO_x (Ramachandran et al., 2016).

The paper proposes a supervisory controller for the integrated engine-aftertreatments system, thereby extracting benefits from the overall powertrain in the perspective to comply with NO_x emissions limit and, at the same time, to minimize operating costs over transient operating conditions. The optimization strategy identifies the effective EGR actuation, based on the actual powertrain state: engine settings and ATs performances. The potential of this IEM strategy is demonstrated for type-approval test case. This study focuses on a light-duty Diesel engine, equipped with a common rail fuel injection system, Variable Turbine Geometry (VTG), and cooled Exhaust Gas Recirculation (EGR). The after-treatment system consists of a Diesel Oxidation Catalyst (DOC), coated Diesel Particulate Filter (DPF), Cu-Zeolite SCR catalyst. For NO_x conversion, an aqueous urea solution (AdBlue) is injected upstream of the SCR catalyst by the air assisted dosing system. The paper is organized as follows: in section 2 the overall driveline model implemented in the supervisory controlled is described, in section 3 the optimal control problem formulation is defined, finally the potential results are shown for type-approval test case.

2. INTEGRATED EMISSION CONTROL STRATEGY

The Integrated engine-aftertreatments supervisory controller is aimed at jointly managing the engine and after-treatment systems. To accomplish this task, it is based on a simulation model of both powertrain and SCR, whose global model scheme is shown in Figure 1.

The model assumes as input the driving cycle, that is processed by the longitudinal sub-model to define the target driving torque along the specific mission profile.

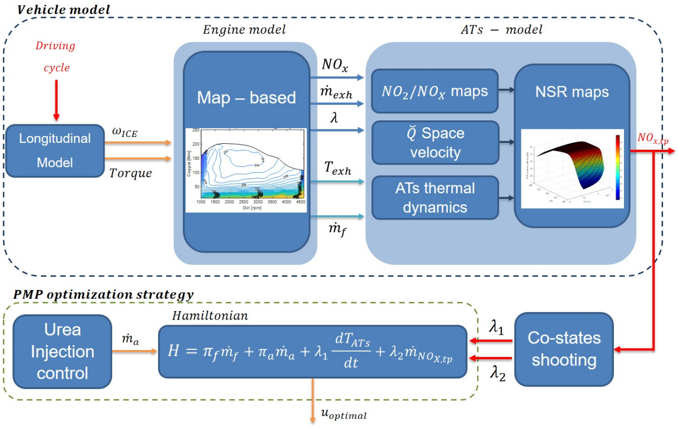

Fig. 1. Integrated engine and after-treatments models integration in the supervisory control strategy.

2.1 Stationary Engine model

A stationary map-based modeling approach is adopted for the internal combustion engine, in order to reduce the computational cost. Fast black-box models are implemented in the optimization algorithm to predict the engine variables of interest: engine out NO_x emissions $[g/kWh]$, exhaust temperature $T_{exh}[K]$, fuel mass flow $\dot{m}_f[kg/h]$, exhaust gas mass flow rate $\dot{m}_{exh}[kg/h]$ and exhaust equivalent air-to-fuel ratio $\lambda[-]$. With the perspective to be implemented in a real-time control strategy and to find the correct link between the engine and after-treatment systems operating conditions, the Effective Exhaust Gas Recirculation (EGR_{eff}) has been selected as useful control variable. Generally, Mean Value Models (MVM) allow reproducing the intake/exhaust manifold and EGR systems dynamic, by considering the typical phenomena occurring during transient operation (Wahlström and Eriksson, 2011). Nevertheless for the present application, a black box modeling approach was preferred to reduce the computational time of the optimization algorithm. This approach is useful to define the effective EGR linked to the exhaust recirculated gas percentage $\%EGR$ as below (Wahlström and Eriksson, 2011):

$$EGR_{eff} = \frac{\dot{m}_{EGR}}{\dot{m}_{cyl,in}}\left(\frac{1+\alpha_{st}}{1+\alpha}\right) \tag{1}$$

where α is the air-to-fuel ratio, α_{st} is the stoichiometric value for typical Diesel application; $\dot{m}_{EGR}$ is the recirculated exhaust gas rate and $\dot{m}_{cyl,in}$ is the in-cylinder intake mass flow rate. The EGR_{eff} accounts for the amount of recirculated inert gas whose effect is the engine temperature decrease, thereby resulting in lower engine out NO_x emissions. The effective amount of recirculated gas depends, not only from the valve actuation, but from the engine operating conditions. The differential pressure between exhaust and intake pipes drives the recirculated mass flow. On one hand, the pressure at the intake is driven by the engine speed, intake gas temperature and fluid-dynamic effects; on the other hand, the pressure at the exhaust is mainly affected by the VGT actuation. Therefore, the exhaust gas recirculation percentage is corrected with the effective air mass, instantaneously present in the intake manifold, by considering overall fluid-dynamic phenomena (i.e. valve dynamics, channel length and variable pressure conditions). Therefore, EGR_{eff}, defined as in eq. 2, has been established as useful control variables in the management strategy. The EGR_{eff} directly affects the total amount of oxygen in the intake and then the air to fuel ratio in to the combustion chamber.

$$EGR_{eff} = f(\omega_{ICE}, T_{ICE}, \frac{d(\omega_{ICE})}{dt}, \frac{d(T_{ICE})}{dt}, C_{EGR}, C^{LP}_{EGR}); \tag{2}$$

The engine variables of interest are simulated depending on engine speed (ω_{ICE}) and torque (T_{ICE}), as well as their time derivatives, by the following equations:

$$\begin{cases} NO_x = f(\omega_{ICE}, T_{ICE}, \frac{d(\omega_{ICE})}{dt}, \frac{d(T_{ICE})}{dt}, EGR_{eff}, T_{H2O}); \\ T_{exh} = f(\omega_{ICE}, T_{ICE}, \frac{d(\omega_{ICE})}{dt}, \frac{d(T_{ICE})}{dt}, EGR_{eff}, T_{H2O}); \\ \dot{m}_{fuel} = f(\omega_{ICE}, T_{ICE}, \frac{d(\omega_{ICE})}{dt}, \frac{d(T_{ICE})}{dt}, EGR_{eff}); \\ \dot{m}_{exh} = f(\omega_{ICE}, T_{ICE}, \frac{d(\omega_{ICE})}{dt}, \frac{d(T_{ICE})}{dt}, EGR_{eff}); \\ \lambda = f(\omega_{ICE}, T_{ICE}, \frac{d(\omega_{ICE})}{dt}, \frac{d(T_{ICE})}{dt}, EGR_{eff}); \end{cases} \tag{3}$$

The black-box models were validated vs. the experimental data collected at the vehicle test rig along the NEDC transient. The correlation coefficients related to models validation are reported in table 1.

Table 1. Correlation coefficients resulting from engine model validation results.

Variable	R^2
$NO_x[g/kWh]$	0.99
$T_{exh}[K]$	0.94
$\dot{m}_{fuel}$	0.84
$\dot{m}_{exh}$ [kg/s]	0.65
λ	0.70

2.2 After-treatment systems modeling approach

The SCR after-treatment system is considered as the device to be optimized coupled with the engine. The deNO_x ability of the SCR, can be accurately predicted from the control oriented model described by (Arsie et al., 2018; D'Aniello et al., 2019). The latter considers the hypothesis of continuously stirred tank reactors (CSTR) for developing 0-D model and, at the same time, to take into account the spatial dependence of the main states. For each section, mass balances based on chemical kinetics are solved, while thermal and pressure balances are neglected. Based on this dynamic mean value SCR model, a steady state low fidelity SCR conversion efficiency model (NSR map) has been derived (Mentink et al., 2013). The SCR efficiency maps also referred as Nominal Stoichiometric Ratio (Mentink et al., 2013) depend on SCR catalyst Temperature, the NO_2/NO_x ratio and space velocity ($\grave{Q}$ [1/h]).

The ATs temperature dynamics is essential for the supervisory control, since the ATs performance highly depends on thermal state of the devices. At the same time, tail pipe thermal state, is strictly related to the engine operating conditions, which are directly controlled by the control strategy. The authors in (Willems et al., 2013; Donkers et al., 2017b) predict the thermal behavior of the DOC-SCR system by two coupled differential equations. By using this approach, $\dot{T}_{DOC}[K]$ and $\dot{T}_{SCR}[K]$ are evaluated as two separate first order dynamic responses, forced respectively by the exhaust flow rate temperature and the gas coming out from the DOC. In the current application, due to the perspective to integrate the thermal dynamics in a supervisory control strategy, the whole after-treatment thermal state is described by single second order dynamics $\dot{T}_{ATs}$ as follows:

$$\begin{aligned} \dot{T}_{ATs} = & \frac{c_{exh}}{C_{DOC} + C_{SCR}} \dot{m}_{exh}(T_{exh} - T_{ATs}) + \\ & + \frac{h_\infty}{C_{DOC} + C_{SCR}} (T_{exh} - T_{ATs}) \end{aligned} \tag{4}$$

Where $\dot{T}_{ATs}$ is representative of the whole after-treatment systems; c_{exh} is the exhaust mass flow heat capacity (it is assumed $c_{exh} = 1000[J/kgK]$); $C_{DOC} and C_{SCR}$ are respectively the heat capacity of DOC and SCR components ($C_{DOC} = 738[J/K]$ and $C_{SCR} = 1470[J/K]$); h_∞ is the heat transfer coefficient with the external environment ($h_\infty = 15[J/Ks]$); This simplified approach proposed by (Donkers et al., 2017b) is adopted to make the model compliant with ECU time-constrain. The single thermal balances for each component are reduced in a single Temperature dynamics $\dot{T}_{ATs}$ and the heat capacities of the entire system result from lumping the heat capacities of the individual components.

The NO_2/NO_x - ratio highly affects the SCR conversion efficiency, due to the different reactivity of SCR reactions (i.e. Standard, Fast and Slow). Therefore, NO_2/NO_x - ratio is a key factor in predicting the system performance. The most useful approach requires the generation of static maps which are suitable to predict the DOC behavior and in turn the NO_2/NO_x - ratio upstream the SCR (Donkers et al., 2017b; Mentink et al., 2013), alternatively higher order model of the DOC device could be exploited. To obviate the expensive and time-consuming methods, a steady-state regression-based model, able to predict this ratio during the generic engine transient, has been developed (refer to Eq.5).

$$\begin{aligned} & NO_x/NO_2 = \\ & f(\omega_{ICE}, T_{ICE}, \frac{d(\omega_{ICE})}{dt}, \frac{d(T_{ICE})}{dt}, NO_x, T_{exh}, \breve{Q}); \end{aligned} \tag{5}$$

The SCR efficiency η_{SCR} is a non linear function Eq.6 that depends on the actual SCR temperature (T_{SCR}), the DOC temperature (T_{DOC}) and the exhaust gas mass flow $\dot{m}_{exh}$. Particularly, the exhaust mass flow rate is accounted by the more effective space velocity ($\breve{Q}$), while The DOC temperature highly affects the NO_2/NO_x-ratio in the exhaust gas (Donkers et al., 2017b).

$$\eta_{SCR} = f(T_{SCR}; \breve{Q}; NO_2/NO_x - ratio); \tag{6}$$

An operating range for T_{exh} vs. $\dot{m}_{exh}$ has been selected to generate the static NSR maps, while stepwise variations of NO_2/NO_x-ratio is considered. Particularly T_{exh} ranges between (450-800 C), $\dot{m}_{exh}$ range between (0.01 to 0.1 [kg/s]) and NO_2/NO_x-ratio is considered between (0-1 [/]). The AdBlue dosing ($\dot{m}_a$) is achieved from the stoichiometric NH_3 - NO_x reaction. The SCR conversion efficiency is evaluated for the global NO_x specie and the case of NO_2/NO_x-ratio=0.25, is shown in the Figure 2.

It can be observed that the best SCR efficiency occurs in case of the same amount of NO_2 and NO at the inlet feed stream (NO_2/NO_x-ratio = 0.5), because the Fast SCR reaction, which has lower activation energy and fast reaction rate, is promoted. Whereas, when the exhaust consist only of NO, the SCR efficiency is drastically reduced. These latter considerations are in accordance with the positioning of the SCR after the DOC.

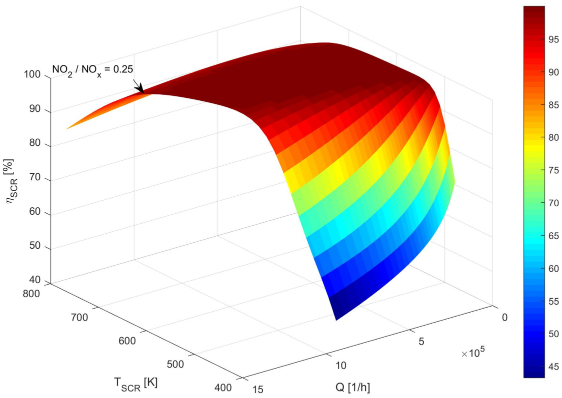

Fig. 2. NSR map, NO_2/NO_x=0.25.

3. OPTIMAL CONTROL STRATEGY

Modern powertrains require an optimal and robust control, but due to the increased complexity of engine and after-treatment systems, it is no longer straightforward to optimize overall system performance with the goal to minimise engine operational costs (in terms of fuel and AdBlue) over the drive cycle, while ensuring low level of emissions and ammonia slip, as imposed by legislation. The urea dosing and SCR conversion efficiency are strictly related to the gas composition and flow rate of the inlet feed stream, the catalyst temperature and the amount of ammonia stored in the catalyst (whose dynamics is relatively slow if compared with the engine). Therefore, NO_x conversion is not immediately controllable by the urea injection rate, mainly managed to ensure high NO_x conversion while avoiding excessive ammonia slip in case of a sudden temperature increase (Cloudt and Willems, 2011). Instantaneous tailpipe NO_x emissions are then controlled by the engine, exhaust gas flow rate and temperature. Nevertheless, by controlling the NO_x engine-out emissions through the EGR rate involves higher operational costs. Therefore, the objective of the Integrated Engine-SCR control is to offer an emission control solution that is based on the actual state of the engine and aftertreatment system and to determines online the optimal engine control settings that minimize operational (fuel and AdBlue) costs within NO_x and NH_3 slip emission constraints under all operating conditions.

3.1 Integrated Engine and After-treatments optimal control problem formulation

The architecture of Integrated Emission Strategy is formulated as a supervisory optimal control problem, offline-optimized along a priori mission profile. The most used and know non-causal strategies to solve optimal control problems are Dynamic Programming (DP) and Pontryagins minimum principle (PMP) (Guzzella and Sciarretta, 2013). The first guarantees that the solution found is globally optimal but it requires heavy computational burden, the second provides a sub-optimal solution through a local optimization, with the advantage of lower computational burden. Pontryagin's Minimum Principle is used to find the optimal control for a dynamic system, especially in presence of constraints on either or both state x and control u. The control-oriented model is written in state space formulation as reported in Eqs. 7. The state variables are $\dot{T}_{ATs}$ representative of the whole after treatment system and the tail pipe NO_x emissions $\dot{m}_{NOx,tp}$:

$$\dot{x} = \begin{cases} \dot{T}_{ATs} = \dfrac{c_{exh}}{C_{DOC} + C_{SCR}} \dot{m}_{exh}(T_{exh} - T_{ATs}) + \\ + \dfrac{h_\infty}{C_{DOC} + C_{SCR}} (T_{exh} - T_{ATs}); \\ \dot{m}_{NOx,tp} = \dot{m}_{NOx,eo}(1 - \eta_{SCR}) \end{cases} \tag{7}$$

Where c_{exh} is the exhaust mass flow heat capacity; C_{DOC} and C_{SCR} are respectively the heat capacity of DOC and SCR components; h_∞ is the heat transfer coefficient with the external environment; $\dot{m}_{NOx,tp}$ and $\dot{m}_{NOx,eo}$ are respectively the NO_x tail pipe and engine-out emissions flow rate. Then the optimization problem can be formulated 11:

$$J(\hat{x}(t), \hat{u}(t)) = \min_{u(t) \in \Upsilon(t)} \int_0^{t_f} \pi_f \dot{m}_f + \pi_a \dot{m}_a dt \tag{8}$$

subject to:

$$\frac{\int_0^{t_f} \dot{m}_{NOx,tp} dt}{\int_0^{t_f} P_d/(3.6e^6) dt} \leq L_{NOx,tp} \tag{9}$$

with Diesel price $\pi_f = 1.34$ [Euro/l] and AdBlue price $\pi_a = 0.5$ [Euro/l]. $L_{NOx,tp}$ is the final constrain for the state variable $\dot{m}_{NOx,tp}$ in terms of amount of NO_x that can be emitted for the given driving cycle expressed in [g/km]. $\dot{m}_f$ and $\dot{m}_a$ are the fuel and AdBlue mass flow required for the applied control strategy. Particularly, the fuel mass flow is evaluated as a result of the steady-state engine model described in the previous chapter, while the desired AdBlue dosing $\dot{m}_a$ is calculated assuming that all of the injected urea is immediately available for conversion of engine out NO_x emissions, then neglecting the urea conversion phenomena upstream the catalyst. $\dot{m}_a$ is then evaluated as follows, by assuming the stoichiometric ratio between AdBlue and NO_x equal to 2.0067:

$$\dot{m}_a = 2.0067 \eta_{SCR} NO_{x,eo} \tag{10}$$

According to the optimal control philosophy, the Hamiltonian (H) is formulated. The Hamiltonian entails the objective function from Equation 11, which is augmented with Lagrange multipliers, λ and the state dynamics f(x,u,t):

$$H(x, u) = \pi_f \dot{m}_f(x, u) + \pi_a \dot{m}_a(x, u) + \lambda^T f(x, u) \tag{11}$$

Where $\lambda^T = [\lambda_1, \lambda_2]^T$. The Lagrange multipliers, represent equivalent costs associated with raw NO_x emissions and temperature changes and have the following interpretation:

- λ_1 [Euro/C] is the equivalent cost associated with a 1 C temperature drop of the after treatment systems within 1 s, or alternatively is the value associated with a temperature raise of 1 C within 1 s;
- λ_2 [Euro/g] equivalent cost associated with 1 g of tailpipe NO_x emission.

The complete formulation of co-states can be provided by the 12, particularly they came from Lagrange multipliers for the incorporation of dynamic constraints, which, possess physical meanings. In the Integrated emission control strategy, the co-state can be interpreted as a "weight" coefficient of the time variation for after-treatment thermal dynamics with respect to T_{ATs} and NO_x. Particularly $\dot{\lambda_1}$ is a linear function of η_{SCR} variation with respect to ATs system temperature, (this derivative is complex to be evaluated mathematically). The co-state λ_2 in the problem 11 can be considered as a constant. The SCR perfomance only depends from the upstream conditions:

$$\begin{cases} \dot{\lambda_1}(t) = -\dfrac{\partial H}{\partial x_1} = f(u(t), \dfrac{\partial \eta_{SCR}(T_{ATs,t,NO_2/NO})}{\partial T_{ATs}}) \\ \dot{\lambda_2}(t) = -\dfrac{\partial H}{\partial x_2} = 0 \end{cases} \tag{12}$$

The model integration in the supervisory control strategy is shown in the Figure 1.

The defined problem, requires the solution of a two-point boundary value problem (TPBVP) for the state dynamics equations 7 and the co-state equations 12. A rigorous solution of the formulated problem could be obtained from the forward-backward sweep method (FBSM) (Donkers et al., 2017b; McAsey et al., 2012), but due to difficulty to solve the PMP with an analytical method, the PMP-based problem, converted into a two-point boundary value problem (TPBVP), can be solved numerically by using the shooting method (Guzzella and Sciarretta, 2013).

4. CONTROL STRATEGY RESULTS

In this section the potential of the proposed strategy to the optimal control problem is discussed. Based on the state of the after-treatment system, the engine settings can be adjusted in a limited number of discrete steps changing engine performance in order to enable the SCR to come in a desired NO_x conversion state (i.e. increasing engine out exhaust gas temperature when the engine is cold, temperature is too low or decrease EGR actuation when the SCR has the best efficiency). The feasible range of EGR mass flow at each operating point is assumed as reported by (Willems et al., 2013). Thus resulting in EGR position ranging between 0 - 40%. This strategy, enables low fuel consumption when the SCR is in a desired NO_x conversion state, while it switches to less fuel efficient settings to meet tailpipe NO_x emission limits in case of sub-optimal SCR working operation. The adopted control strategy optimizes the entire test cycle instead of the actual operating condition, thus the controller could enable instantaneous not optimal operating conditions (in terms of fuel mass and NO_x emissions), if overall improvements during the cycle can be achieved. The comparison between the baseline strategy, adopted to set benchmark results, and optimal strategy are shown in the figures 4 and 4. The typical type-approval New European Driving Cycle (NEDC) has been adopted, the table 2 summarizes the results over the test cycle. Particularly, the supervisory controller determines optimal engine settings depending on actual operating conditions performing the so called EGR-SCR balancing. When the actual SCR conversion efficiency is moderate, engine-out NO_x emissions are kept low by applying sufficient EGR. This is the case of cold start condition, time ranging between 0-200 s, when the actual NO_x emissions are controlled by the higher EGR rate. Conversely, high engine-out NO_x emissions are allowed when high SCR conversion efficiency can be realized; this is the case of high load conditions, during the extra-urban part of the test cycle (starting from 800 s). The resulting cumulative engine-out NO_x emissions of PMP-based solution is smoother than the baseline during the UDC part of the test (refer to Fig. 3), as a results of higher EGR actuation; while the cumulative NO_x emission rate increase faster than the corresponding baseline strategy, due to the SCR usage optimization during the highway part of the cycle. At the same time, as a result of the supervisory controller application, after-treatments temperature increases, thus resulting in higher SCR efficiency and less EGR globally required. The supervisory strategy is a balance between keeping the SCR efficiency high (by increasing T_{ATs} or changing space velocity) and producing the minimum amount of engine out NO_x emissions (by setting the EGR rate), while minimizing the total cost of the system. Finally, to compare different strategies, the respectively fuel and AdBlue consumptions have been evaluated by considering the current market costs of fuel and AdBlue.

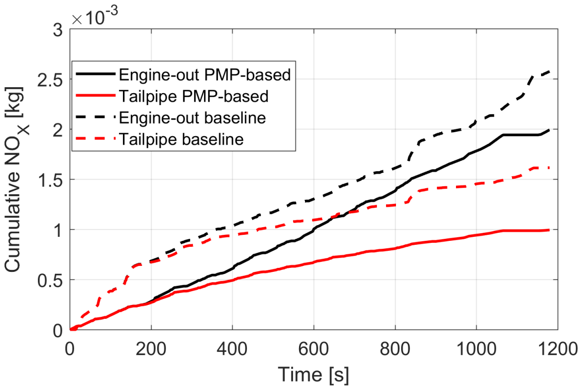

Fig. 3. Cumulative engine-out and tail-pipe NO_x emissions for both baseline and optimized powertrain.

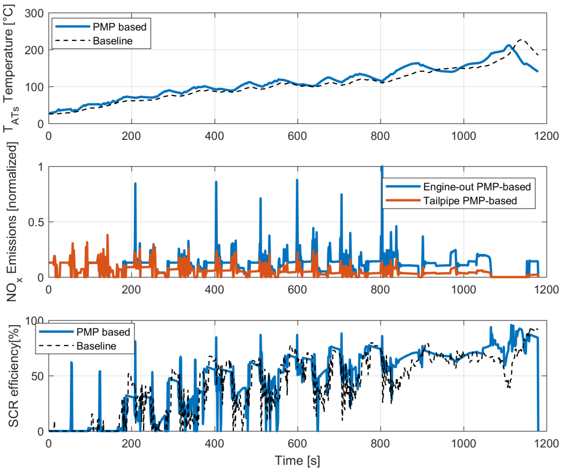

Fig. 4. Engine-out and after-treatments results for both baseline and optimized powertrain.

Table 2. Overview of NEDC test cycle results.

Variable	**Baseline**	**IEAS**	**Variation**
Global cost	0.52	0.30	-42%
NO_x emission	1.6	0.84	-48%

5. CONCLUSION

The present research activity proposes a supervisory controller for the integrated engine-aftertreatments system. The optimization strategy, based on the Pontryagin minimum principle, identifies the effective EGR actuation depending on the actual powertrain state: engine settings and ATs performances. To be suitable with online application, steady state models have been developed to predict powertrain behavior and then integrated in the supervisory controller. The potential of this integrated management strategy is demonstrated for NEDC type-approval test case. The results show that controller is able to optimize engine operation if the desired SCR performances are achieved, thus resulting in improved fuel economy. Nevertheless, the proposed structure could be interestingly used in an online optimization strategy if future short horizon conditions can be estimated by using GPS-based data (T-ECMS), on the basis of present and past driving conditions.

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