Predictive NO_x emission control of a diesel-HEV for CO_2 and urea consumption reduction

Cite as: AIP Conference Proceedings **2191**, 020035 (2019); https://doi.org/10.1063/1.5138768

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Predictive NOx emission control of a Diesel-HEV for CO2 and urea consumption reduction

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Abstract. In recent years, researchers and manufacturers have increased their interest on predictive control strategies for light-duty vehicles, based on electronic horizon availability**.** Despite this involvement, the on-board implementation of predictive features is still limited in modern automotive control systems. This paper deals with the development of a predictive NOx emissions control function for a diesel hybrid electric vehicle, equipped with an electrically heated after-treatment system composed by a Diesel Oxidation Catalyst (DOC), a Diesel Particulate Filter (DPF), and a Selective Catalytic Reactor (SCR). Such function makes use of an a-priori-known vehicle speed trajectory that would be made available by the electronic horizon provider, and it presents two main sections. The first one predicts the aftertreatment system temperature and the NOx emissions both at the engine out and at the tailpipe over the prediction horizon. The second section defines the powertrain and after-treatment control policy, with the objective of minimizing after-treatment electric heating energy and SCR urea consumption, while respecting the legal NOx limits for the given mission. Furthermore, if the estimated pollutant production exceeds the limits even if the aftertreatment system is operated in the highest efficiency conditions, the predictive control function redefines the torque demanded to the internal combustion engine (and the one requested to the electric motor) to match the legal limits. In terms of results, this novel approach to emissions control shows the benefits coming from the usage of predictive information in combination with powertrain hybridization, and it can be applied to any HEV configuration.

INTRODUCTION

The transportation sector has recently seen a huge increment of light-duty vehicles all over the world. Most of them are still considered “conventional”, since they only use fossil fuels as energy source, for example Diesel and Gasoline engine-based vehicles. The combustion of such fuels provides the energy needed for the propulsion but, as a drawback, it also produces emissions of pollutants and greenhouse gases (GHG). The main difference is that the first ones are controlled and minimized on-board also using after-treatment systems, to respect legal limits with no compromises in order to homologate the vehicle. GHGs aren’t strictly limited by regulations, but they should be minimized to reduce additional taxes on the manufacturers [1]. In the case of a Diesel engine, the main pollutant emissions to be considered are nitrogen oxides (NOx) and particulate matter (PM), since for hydrocarbons (HC) and carbon monoxide (CO) emissions, the DOC system represents a well-established solution. While PM emissions are substantially controlled by means of appropriate filters, NOx emissions are more complicated to minimize on-board. The latest technological solution for reducing NOx emissions is called Selective Catalytic Reactor (SCR). This system is a chemical reactor that makes use of urea (an ammonia-based fluid distributed in a water solution called AdBlue), to reduce nitrogen oxides into molecular nitrogen [2].

In this context, powertrain electrification is considered a viable solution to increase the overall vehicle efficiency, thus reducing GHG emissions [3-5]. At the same time, recent studies and experimental tests have demonstrated that

74th ATI National Congress
AIP Conf. Proc. 2191, 020035-1–020035-10; https://doi.org/10.1063/1.5138768
Published by AIP Publishing. 978-0-7354-1938-4/$30.00

frequent engine on/off transitions, commonly imposed to HEV powertrains, may have a strong, negative impact on aftertreatment systems operation and performance [6-7].

Several works can be found in literature about energy management strategies developed and optimized for hybrid electric vehicles [3-5,8-10]. Almost all of the proposed approaches are focused on optimizing the torque split factor between internal combustion engine and electric motor, in order to minimize the overall energy consumption. In few cases, the contribution of pollutant emissions is included in the optimization algorithm [11-13].

In the present work, an original energy management strategy has been developed to take into account the emissions production as a hard limitation to be respected. The aim of this new predictive control function is to keep the NOx emissions within the legal limits, while minimizing urea usage and electrical energy consumption related to the aftertreatment system operation. The powertrain considered for this study is a diesel parallel hybrid electric vehicle equipped with DOC, DPF and SCR systems, and an electrically heated catalyst (eHC). The first stage of the control algorithm outputs predicted aftertreatment system temperature and NOx production over the look-ahead horizon. Such information is used both to evaluate if the emissions will respect the legal limits and to detect when the aftertreatment system temperature will be below the catalyst light-off value, so that the subsequent engine start will have to be treated as "cold-start". According to the predicted emissions trend, the control function can optimally manage aftertreatment system external activation (turning on/off eHC and/or minimizing the urea injection), or even limit ICE torque request.

The proposed function is suitable for every Diesel HEV that can perform pure electric drive or, at least, that has a considerable engine boosting capability. Here it has been considered a P2 parallel HEV, which means that the electrical machine is mounted on the engine shaft but can be disconnected by means of a clutch. The reference route of this work is a real driving emission cycle with elevation (RDE), chosen for its duration and speed dynamics.

MODELLING AND CONTROL

The predictive function presented in this context receives as input the speed and torque profiles of the engine for the next driving mission. Such information is available on-board once the energy management strategy receives the information about the route ahead, and computes the optimal torque/power split factor between the electrical and thermal machines. In this section it is described in detail the modelling used to predict the aftertreatment system temperature and the NOx production over a given driving mission. The control algorithm used to decide whether to minimize the SCR usage and switch-off the eHC, or to limit the ICE torque gradient to respect the legal emission limitations is shown as well. The electrical catalyst heating is mainly designed for the DOC system, but since in this vehicle all the aftertreatment components are close to each other, there is a considerable effect even on SCR temperature.

System physics modelling

The first step of the control structure is the prediction of two main trends, which are important for the emissions production dynamics, that are: the aftertreatment system temperature and the nitrogen-related emissions.

Aftertreatment System Temperature Model

As widely known, temperature plays a key role in the emissions reduction efficiency of an aftertreatment system. In this paper, the aftertreatment system temperature has to be intended as the average value of the SCR hardware, which is the parameter that mostly influences the efficiency of that component.

The methodology partially derives from the solution found by authors of [14], where a similar approach is used to model a temperature sensor positioned on the aftertreatment system before the DOC.
Firstly, a quasi-static exhaust gases temperature model has been designed by using steady-state maps. Therefore, the instantaneous engine-out temperature is only function of the engine speed and load.

$$T_{exh\_ss} = f\left(n_{eng}, bmep\right) \tag{1}$$

Where T_{exh_ss} is the exhaust gasses temperature, n_{eng} is the ICE rotational speed and $bmep$ is the brake mean effective pressure of the engine.

Then the aftertreatment temperature is evaluated by summing the responses of two first-order systems to the T_{exh_ss}. The combination of the two dynamics is needed since each of them represents a specific physical behavior of the aftertreatment system. More in detail, in the following the two contribution are referred to as fast and slow dynamics.

$$T_{aft\_fast} = \frac{(1-b)d}{1-bz^{-1}} T_{exh\_ss} \tag{2}$$

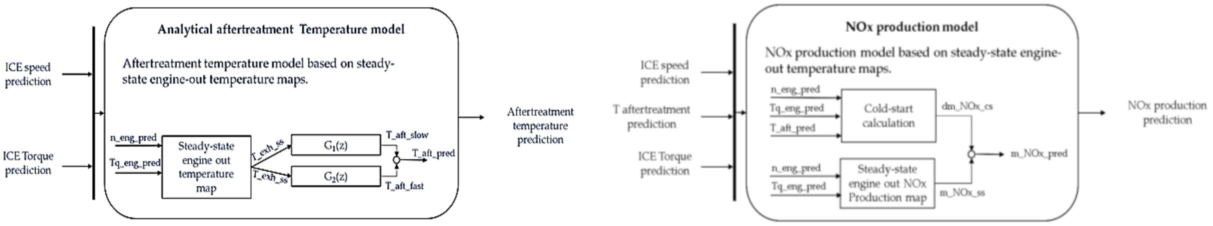
Here z is the z-transform variable, b is the filtering quantity and d is a weighting gain. This term represents the heat exchange between the exhaust gases and the aftertreatment line as a physical system.

$$T_{aft\_slow} = \frac{(1-c)(1-d)}{1-cz^{-1}} T_{exh\_ss} \tag{3}$$

Where the z is the z-transform variable, c is the filtering quantity and d is a weighting gain (as in Eq.2). The slow dynamics represent the thermal inertia of the aftertreatment line as a physical system.

Therefore, considering (2) and (3) in the superposition principle, the predicted aftertreatment temperature is:

$$T_{aft} = T_{aft\_fast} + T_{aft\_slow} \tag{4}$$



(a) (b)

FIGURE 1. Aftertreatment temperature (a) and NOx production (b) modelling principle

NOx Emissions Production Model

Emissions production has been modelled using experimental steady-state maps based on engine load and speed. In this context, they haven't been corrected to consider transient phenomena [6], but only to take into account cold-start related emission. "Cold-start" refers to the conditions in which the engine is restarted when the SCR temperature is below its light-off value (190°C). The additional contribution to the emissions production related to this specific scenario is due to the null conversion efficiency that the SCR system has when its temperature is below the activation limit.

According to this definition, the instantaneous production can be defined as:

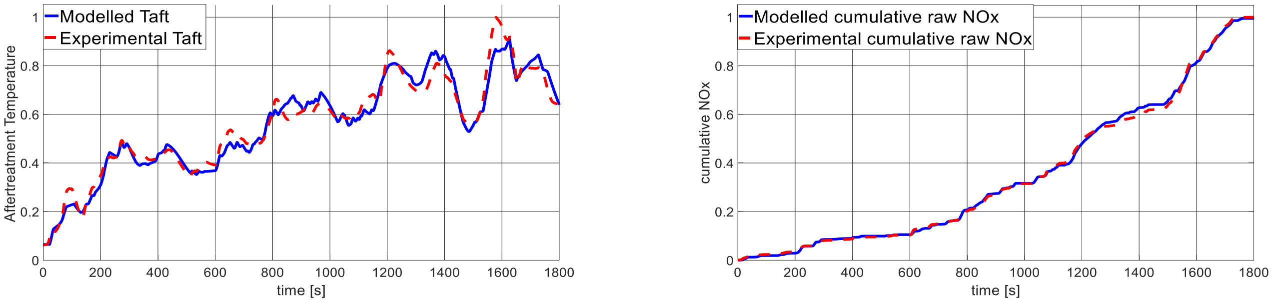
$$\dot{m}_{NOx} = f\left(n_{eng}, bmep\right) + d\dot{m}_{NOx\_CS} \tag{5}$$

Where $\dot{m}_{NOx}$ is the actual emission and $d\dot{m}_{NOx\_CS}$ is the additional contribution due to cold start events, if needed. The decision of adding the cold-start terms depends on the aftertreatment temperature and the contribution is proportional to the difference between the actual temperature at the engine re-start and SCR light-off temperature.

The value obtained with this modelling is representative of the emissions production at the engine-out, while the tailpipe emissions are obtained considering the presence of SCR and eHC systems. The selective catalytic reactor has been modelled considering its efficiency as a function of the system temperature, assuming a light-off temperature equal to 190°C. If also the electrically heating feature is used, then the cold-start related contribution is eliminated since, as it will be clarified in the next paragraph, the look-ahead nature of the function allows using the aftertreatment electrical heating in a predictive way, so that at the engine restart the SCR system is already warm enough to be efficient.

Models validation

The aftertreatment temperature and raw emissions production modelling validation has been done against experimental data. In the following Fig.2, the results have been normalized for confidentiality reasons. Validation has been performed on a WLTC cycle, since the experimental data were already available at the beginning of this activity.



(a) (b)

FIGURE 2. Modelling validation against experimental data for the aftertreatment system temperature (a) and cumulative raw NOx (b)

Figure 2(a) shows that the aftertreatment temperature is estimated quite well considering that the modelling is zero-dimensional and control oriented, therefore it needs to be fast, which is usually detrimental for the accuracy. Instead, the raw emissions production model is highly representative for the experimentally measured data (Fig.2 (b)).

Control strategies

Emissions control

The emission control is here meant as the strategy to be followed in order to ensure the NOx cumulative production over the driving mission will respect the legal limitations (to be always intended at the tailpipe), while reducing as much as possible the SCR and eHC usage. In general, when a prediction horizon is considered, it is assumed that the driving mission won't change in the future. Anyways, to take also into account small changes that can occur along the route, the emissions legal limitations are corrected with a safety factor k_s, as clarified in the following.

It is important to remark that the designed function has, by means of emissions production modelling, the capability to predict the NOx production over the mission before it starts. This is possible knowing in advance the engine torque and speed profiles, considered as predictive information. The control strategy foresees three different cases:

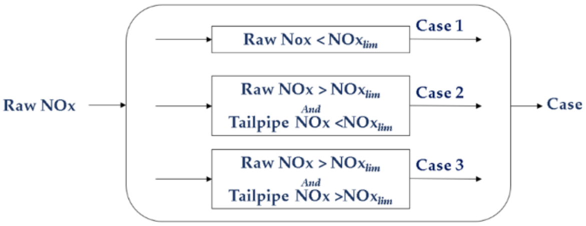


FIGURE 3. Strategy possible cases

- **"Case 1"**, the raw NOx emissions, at the engine-out and reported at the tailpipe without SCR and eHC activation, respect the limitation;
- **"Case 2"**, the raw NOx emissions don't respect the limits, but tailpipe emissions are within the limits (using SCR and eHC systems);
- **"Case 3"**, Tailpipe NOx emissions exceed the limit imposed by the regulation.

According to the actual case (Case_{act}) of the driving mission, i.e. the prediction horizon, the control function can make different choices:

- **Case_{act} = Case 1**, here the controller asks to the Engine Control Unit (ECU) to minimize the SCR operation and to disable the eHC system, for the whole driving mission;
- **Case_{act} = Case 2**, the function will calculate the exact position over the horizon from where on it is possible to minimize the usage of the SCR, while remaining within the legal NOx emission limitations;
- **Case_{act} = Case 3**, in this case the algorithm foresees the possibility of limiting the engine torque absolute value and gradient to avoid high emissions phases, in order to respect the limits.

TABLE 1. Control strategy possible actions

Control Strategy				
CASE	**SCR**	**eHC**	**ICE Torque**	**ICE Torque gradient**
1	Minimum	Off	Unconstrained	Unconstrained
2	On/Minimum	On/Off	Unconstrained	Unconstrained
3	On	On	Limited	Limited

The SCR "minimum" usage request has to be intended as an advice to the ECU. This latter would still manage the SCR system following its standard strategy, but assuming a very low NOx production at the tailpipe. Therefore, when possible and for the maximum time allowed, the AdBlue usage will be reduced.

At this point, a clarification for Case3 is probably needed. Since the vehicle has a hybrid powertrain, when the function asks for a torque gradient limitation of the ICE, it assumes that the battery has enough energy to provide the additional torque to the electrical machine, to still match the overall driver request. Therefore, such torque gradient limitation request is verified by the Hybrid Control Unit (HCU), that decides if it is possible to satisfy it or not, according to the driver demand and the battery State Of Charge level.

As briefly mentioned before, the control function also foresees the possibility of predictively requiring the eHC activation. In fact, combining the predictive knowledge of the engine switch-on events with the predicted aftertreatment temperature trend, it is possible to know in advance when it is needed to heat-up the aftertreatment system. Consequently, the function can ask to the ECU to switch-on the eHC before the engine firings, in order to avoid cold starts emissions, since the SCR system will be already warm enough to be efficient.

The outputs of the described control function have two different targets: the ECU and the Hybrid Control Unit (HCU). More in detail, the engine control unit will be asked for managing the SCR (On/Minimum) and the eHC (On/Off) according to the function calculations, while the HCU will receive the limitation on the engine torque gradient in order to respect the emissions limitation (only for Case 3).

At the highest level of the control function, the I/O signals are the ones reported in the following Fig.4.

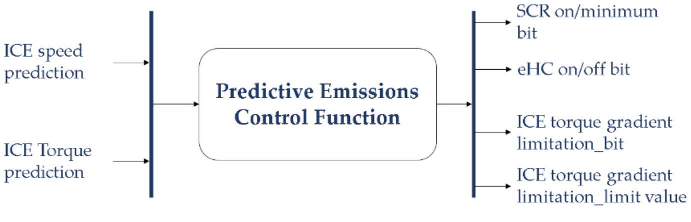


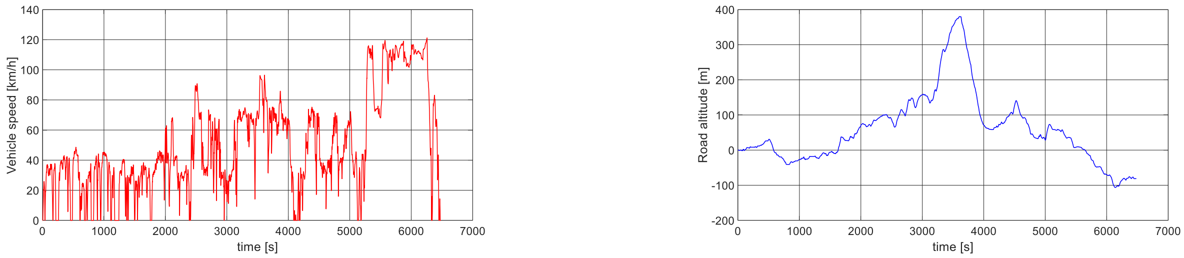
FIGURE 4. Predictive Emissions Control Function I/O

It should be clear, after the description, that the objective of respecting the NOx legal limitations is always considered, while the goal of reducing urea consumption and CO_2 emissions can be reached only in Cases 1 and 2.

The possibility of using the eHC as a heater also for the SCR system is due to proximity of such system to the rest of the aftertreatment components. This functionality has been developed during another sub-project, and is not considered within the scope of this paper.

RESULTS

In this section, the results obtained in simulation using the developed predictive function are presented. First of all, it is important to present the driving cycle taken as reference route for this work, shown in Fig. 5.

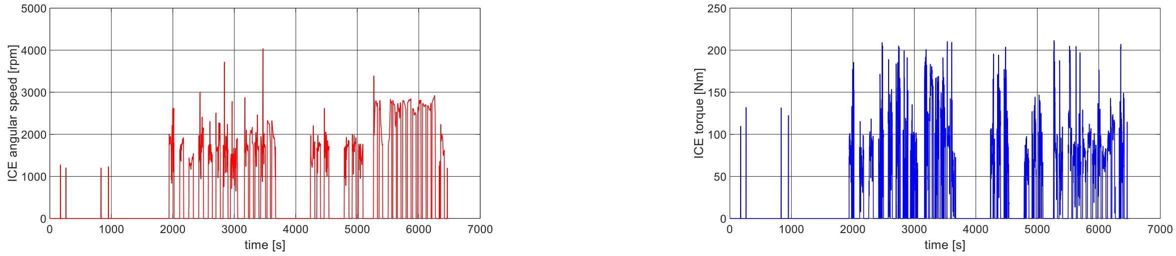


(a)

(b)

FIGURE 5. Cycle speed (a) and route altitude (b) profiles

Once the driving mission is defined, the inputs of the control function can be predicted, which are the engine speed and torque profiles. As clarified by Fig.7, the engine provides torque only when the energy management strategy decides that it is worth to switch-on the engine instead of driving in pure electric mode.



(a)

(b)

FIGURE 6. Predicted control function inputs, engine speed (a) and engine torque (b)

Modelling results

Showing the results according to the function algorithm, the first two main results are the aftertreatment temperature and the NOx emissions at the engine-out and at the tailpipe (considering the efficiency of the SCR system dependent on the system temperature, when active).

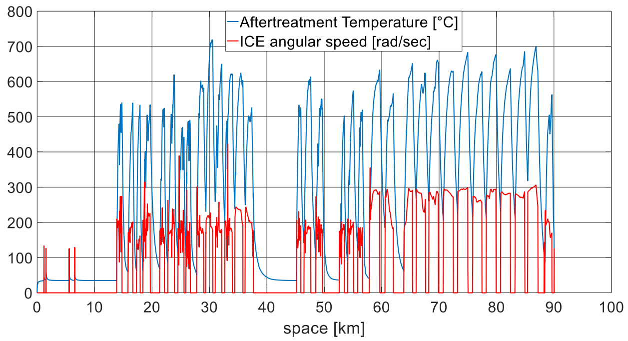


FIGURE 7. Aftertreatment temperature prediction

Figure 8 shows the predicted aftertreatment temperature calculated using the model of Eq. 4. To better understand the trend obtained, it is also reported the ICE angular speed, one of the inputs. In the following Fig. 8 (a) it is reported in blue the cumulative emissions production over the cycle. The other two constant values need a clarification: legal limitation refers to the maximum NOx production allowed for the considered reference route, calculated as follows:

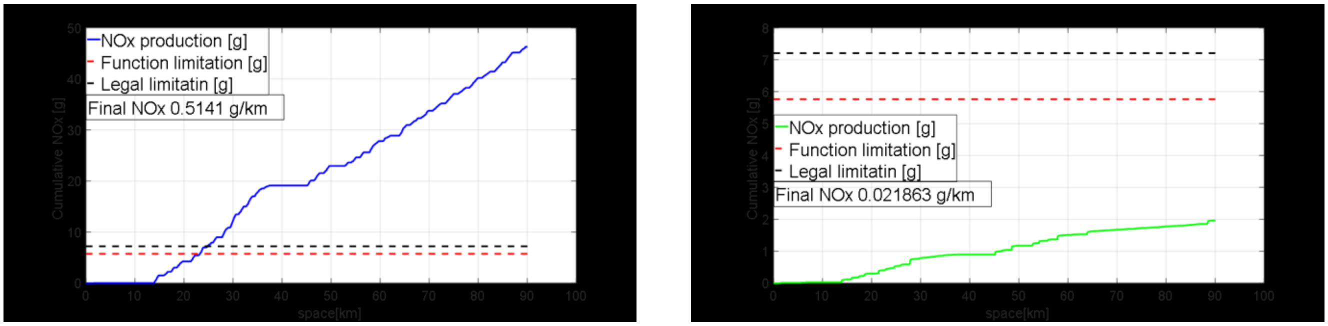
$$NO_{x\_leg\_lim} = NO_{x\_lim} * s \tag{6}$$

Where $NO_{x\_leg\_lim}$ is the cumulative value of the limit, NO_{x_lim} is the well-known limit of Euro 6 regulation for Diesel vehicles (80 mg/km) and s is the total driven distance (already known at the beginning of the calculation since it derives from the speed profile).

The function limitation is, instead, a virtual limitation implemented for ensuring that the control strategy won't exceed, in any case, the legal limitation. It is calculated as in (7), where $NO_{x\_fun\_lim}$ is the limit imposed considering k_s as equal to 0.8.

$$NO_{x\_fun\_lim} = NO_{x\_leg\_lim} * k_s \tag{7}$$

As last, Fig. 8 (b) shows the predicted emissions production at the tailpipe calculated as mentioned before.



(a) (b)

FIGURE 8. NOx production prediction at the engine-out (a) and at the tailpipe (b)

Fig. 8 (b) shows that using the SCR system for all the driving mission, supposing an efficiency dependent on the system temperature, both the legal and function limitation on cumulative NOx production won't be exceeded.

Control strategy results

Chosen driving mission: Case2

According to the rules defined in Tab.1, this driving mission can be categorized as a *Case2*.

As foreseen by the strategy for *Case2*, there would be a certain position over the route, from which on it would be possible to minimize the SCR system usage while respecting the function NOx cumulative limitation.

Fig.9 also shows that the strategy requires the SCR to be active until km 84.2, where the system usage can be minimized while respecting the cumulative emissions limitation. Unfortunately, the lack of experimental data doesn't allow a clear quantification of the AdBlue usage reduction. It is anyways possible to assess that for the 6.52 % of the total distance, the SCR consumption is minimized and, moreover, it happens in the high- speed portion of the mission, which would require a consistent urea injection if the SCR system was active. The SCR request outputted by the function needs a clarification: when it is set to 1, the function leaves to the ECU the freedom of using the system without constraints, while if it is set to 0, it means the function is suggesting to the ECU to avoid injecting more AdBlue than the minimum value, because it would be useless, since the NOx emissions limitation won't be exceeded.

Another information provided by Fig.9 is that, in *Case2*, the control function matches exactly the imposed limitation since the average NOx production is 0.064 [g/km], which is also the value of the virtual imposed limitation.

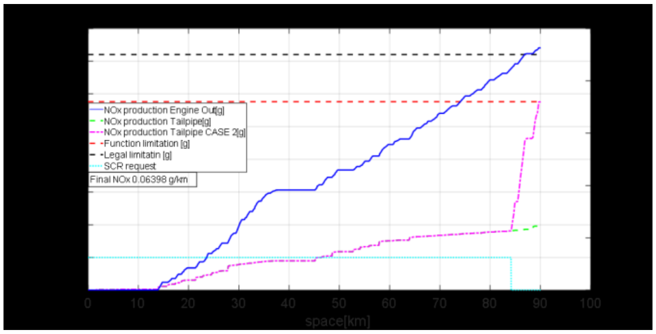
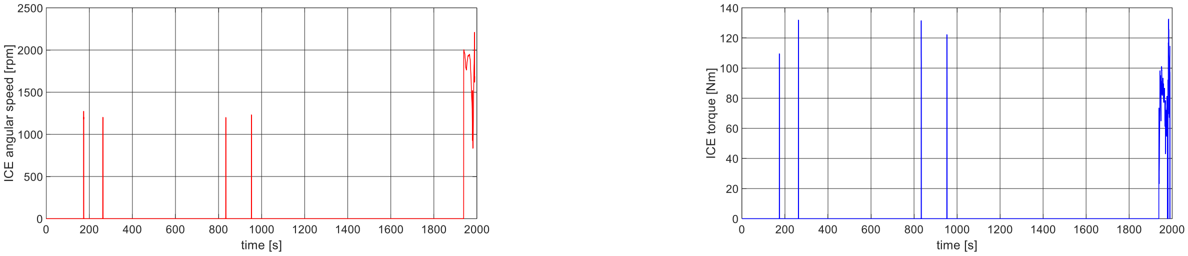


FIGURE 9. Control strategy decisions for case 2

Test-case: Case1

In this section are presented the results obtained on a limited portion of the same cycle, where it is possible to test the behavior of the control function in *Case1*.

Here the suggestion to the ECU is to minimize as much as possible the SCR usage since, from the NOx productions estimations, it is possible to assess that the limit won't be exceeded. For such test-case the chosen portion of the cycle is 0-1990 [s], where the inputs are as reported in Fig.10.



(a) (b)

FIGURE 10. Predicted control function inputs, engine speed (a) and engine torque (b) for Case1

As it can be noticed from the Fig. 11, the NOx production at the tailpipe (dot-dashed magenta line) are equal to the ones predicted at the engine-out (blue line), considering null the contribution of the SCR system (cyan line), for which the activation request is constantly zero over the considered cycle portion.

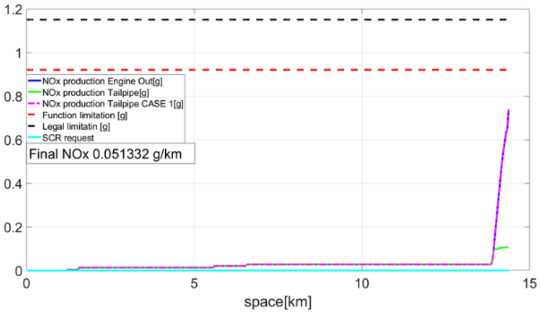
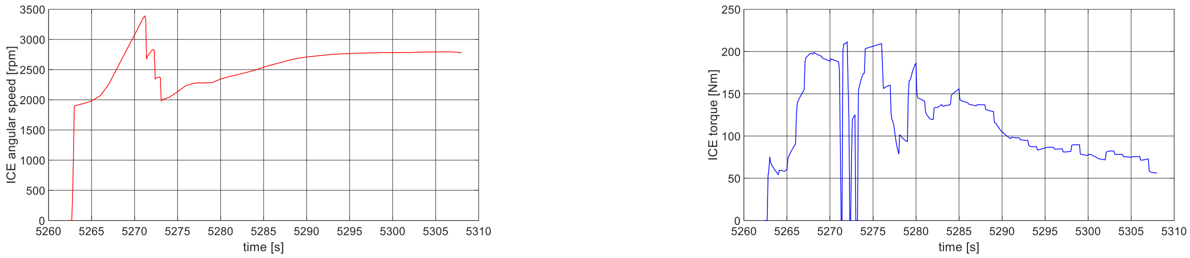


FIGURE 11. Control strategy decisions for Case1

Test-case: Case3

In *Case3*, the proposed control strategy estimates that both the raw and the tailpipe NOx emissions will exceed the function limitation, therefore it proposes to the supervisory controller to limit the engine torque gradient.

To show the behavior of the function in this case, the considered cycle portion is between 5262.5 and 5308 seconds.



(a) (b)

FIGURE 12. Predicted control function inputs, engine speed (a) and engine torque (b) for Case3

For the test, it is needed to have an "aggressive" portion of the cycle, which means the engine speed and torque are significantly high, to be sure that also the tailpipe emissions exceed the function limitation. With this aim, the input of the function is reported in Fig.12. The results for *Case3* are reported in the following figure.

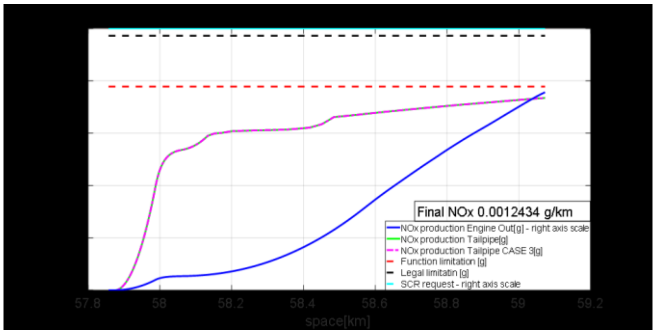


FIGURE 13. Control strategy decisions for Case3

In such particular scenario it could be interesting to show the second capability of the proposed function, that is the engine torque gradient limitation in order to match the function limitation.

(a) (b)

FIGURE 14. Torque gradient limitation (a) and consequent NOx production reduction (b)

As shown in Fig.14, the torque limitation (a) helps to reduce the NOx production (b) and, therefore, to respect the constraints. The dashed green line in Fig.14 (a) represents the limited engine torque, and it clarifies why this control policy can be considered only if the powertrain can drive in pure electric or, at least, has a large electric boosting capability.

CONCLUSIONS AND FUTURE WORKS

This paper presents a novel approach to the aftertreatment control of a diesel-HEV that makes use of predictive information for the pollutant emissions production optimization and, contextually, the minimization of the energy used for the exhaust gases treatment.

Aftertreatment system temperature and NOx production models have been used to estimate their evolution over the driving mission, in order to select the control strategy to be applied for the purpose of respecting the limitation and minimizing the AdBlue injection.

The proposed method also includes the limitation of the engine torque gradient for particular aggressive cycles, to be always compliant with the regulation on pollutant emissions.

The results collected in the previous section show the function capability in every possible case, making it robust enough to be implemented on-board (considering available the predictive input).

For this particular activity, the future works will include the integration of the developed control within an energy management strategy, in order to test its real-time capability and the reliability of the algorithm.

ACKNOWLEDGMENTS

This activity has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 724095 – ADVICE and the intellectual property of this work belongs to Alma Automotive s.r.l.

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