

## RESEARCH ARTICLE

# On the emission reduction through the application of an electrically heated catalyst to a diesel vehicle

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**Abstract**

Exhaust emissions from diesel engine powered vehicles are considerably high during cold start and warm-up, because of the poor catalyst performance due to the insufficient catalyst temperature. The controlled heat injection allowed by electrically heated catalysts can effectively reduce the catalyst light-off time with relatively moderate fuel penalty. This paper compares the exhaust temperature and emissions of a case study diesel vehicle in cold and warm start conditions, and proposes two electrically heated catalyst control strategies, which are evaluated in terms of emission reduction and energy consumption with different target temperature settings. In addition, a new performance indicator, that is, the specific emission reduction, is used to evaluate the after-treatment system and associated thermal management. For the worldwide harmonized light vehicle test cycle, the results without electrically heated catalyst show that from both cold and warm start conditions a large amount of operating points of the engine is located in the region of partial catalyst light off. Moreover, emissions, especially in terms of carbon monoxide and hydrocarbon, significantly decrease with the electrically heated catalyst implementation, for example, by at least 50% from cold start; however, they still tend to be rather substantial when the fuel is re-injected after the engine cutoff phases. The exhaust temperature is lower than the target values in the sections of the driving cycle in which the electrically heated catalyst power is saturated according to the maximum level allowed by the device. The carbon dioxide penalty brought by the electrically heated catalyst ranges from 3.93% to 6.65% and from 6.49% to 9.35% for warm and cold start conditions, respectively.

**KEYWORDS**

catalyst light off, diesel vehicles, electrically heated catalyst, energy consumption, exhaust emissions

## 1 | INTRODUCTION

Strong evidence shows the connection between emissions from diesel vehicles and smog, which is believed to contribute to severe respiratory diseases, particularly in urban environments.<sup>1,2</sup> Stringent emission regulations were put in action

and became the main drive for advanced engine technologies, such as partially premixed compression ignition (PPCI),<sup>3</sup> partially premixed combustion (PPC),<sup>4</sup> high pressure fuel injection,<sup>5</sup> split injection,<sup>6</sup> advanced control,<sup>7</sup> diesel oxidation catalysts (DOCs),<sup>8</sup> diesel particulate filters (DPFs),<sup>9,10</sup> selective catalyst reduction (SCR),<sup>11</sup> nonthermal plasma (NTP)

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systems,<sup>12,13</sup> and adoption of biodiesel.<sup>14,15</sup> Nevertheless, the challenge of high exhaust emissions during engine cold start and warm-up still remains, which is caused by the low cylinder and exhaust temperatures, resulting in poor catalyst efficiency.<sup>16</sup> Iodice et al<sup>17</sup> measured the exhaust emissions from the internal combustion engine in the warm-up phase of the considered driving cycle during chassis-dynamometer tests. In cold conditions, the emission rates of carbon monoxide (CO) and hydrocarbons (HC) were approximately four times higher than in hot condition. In reference,<sup>18</sup> the cumulative CO and HC emissions in the cold start and warm-up process accounted for approximately 80% of the total driving cycle emissions. In fact, low cylinder temperatures suppress the fuel/air mixture formation, with the result of poor in-cylinder combustion and high engine-out emissions. In addition, the exhaust temperature is low and insufficient for catalyst light off, which prevents a large amount of exhaust emissions from being treated. The diesel catalyst light-off temperature is approximately 200°C<sup>19</sup>; however, in reference<sup>20</sup> the DOC inlet temperature was below 130°C for the majority of the first 400 seconds of the new European driving cycle (NEDC) from cold start. In Maus' results,<sup>21</sup> the SCR took more than 1000 seconds to reach its light-off temperature after cold start. The catalyst can operate inefficiently even during portions of the NEDC from warm start.<sup>20</sup> The same study reports that cold conditions occurred more frequently during real road driving than in preprogrammed bench tests.

As indicated in references,<sup>22,23</sup> the NEDC does not represent realistic driving conditions due to its low longitudinal vehicle accelerations, significant constant cruising speed regions, and many idle events. In reference,<sup>24</sup> the measured fuel consumption in the NEDC was from 12% to 30% lower than in real driving conditions. The worldwide harmonized light vehicle test cycle (WLTC) was developed to overcome the NEDC issues.<sup>25</sup> Tsokolis et al<sup>25</sup> compared the carbon dioxide (CO<sub>2</sub>) emissions during the NEDC and WLTC by testing 20 vehicles; the CO<sub>2</sub> emission difference ranged from 4.7 g/km to 29.2 g/km, corresponding to 2.2% and 27.8% of the total emission. In the worst case, the CO<sub>2</sub> emission increase caused by cold start was 14% in the WLTC.<sup>26</sup> Also, the efficiency of the catalytic converters was poorer during the WLTC than in the NEDC,<sup>27</sup> as a result of lower exhaust temperatures.

Richer fuel/air mixtures,<sup>28</sup> variable valve timing,<sup>29</sup> retarded ignition,<sup>30</sup> heat storage devices,<sup>31</sup> and electrically heated catalysts (EHCs)<sup>32</sup> have been implemented for the thermal management of catalytic converters, with a light-off time reduction from 20 seconds to 300 seconds depending on the system. Kessels et al<sup>33</sup> investigated the effect of ignition delay on the catalyst light-off time and fuel consumption, and concluded that the fuel penalty was approximately 50% for decreasing the light-off time from 105 seconds to 19 seconds. Lee et al<sup>34</sup> applied enriched air/fuel mixture and secondary air injection to a naturally aspired engine. In the first 25 seconds

of the federal test procedure 75 (FTP-75), the cumulative pipe-out emissions worsened, although the light-off time was effectively decreased. In general, catalyst light-off time and fuel penalty have a trade-off relationship. Furthermore, also the engine power output may be affected.<sup>16,35</sup> To maintain the catalyst temperature after the engine is switched off, thus reducing the light-off time when the engine is restarted, investigations were carried out to integrate the catalytic converters into heat storage devices including phase changing materials, which recycle the exhaust waste heat.<sup>36</sup> Although these technologies do not introduce noticeable fuel penalty, they do not bring any benefit after the engine is shut off for a relatively long time, because of the inevitable heat losses. In general, catalyst heating methods associated with high fuel penalties should be avoided to meet the 2020 CO<sub>2</sub> targets.<sup>37</sup> A review of catalyst heating methods is provided by the authors in reference.<sup>16</sup>

Compared with other methods, EHCs are promising solutions for decreasing engine cold start emissions, due to the heat injection flexibility and independence from engine operation. In reference,<sup>21</sup> the three-way catalyst (TWC) light-off time dropped from 60 seconds to 15 seconds after adopting an EHC. In reference,<sup>38</sup> a motorbike engine catalyst reached its light-off temperature in 120 seconds through an EHC device with a 96 W heating power. Reference<sup>39</sup> compared the exhaust temperature profile for different EHC heating power levels, with results showing 60 seconds to reach 200°C with a 3 kW heater. Electrically heated catalysts are also convenient in hybrid electric vehicles (HEVs). Hybrid electric vehicle operation is characterized by much more frequent engine start-stop transitions than in conventional vehicles. This is caused by the electric motor torque contribution, which allows the engine to be switched off at low torque demands and vehicle speeds. Although this is beneficial to the overall fuel consumption, the frequent engine start-stop phases can lead to poor thermal catalyst conditions. Knorr et al<sup>39</sup> highlighted the potential CO<sub>2</sub> and other emission reduction benefits for HEVs equipped with EHCs. In particular, according to reference,<sup>39</sup> the EHC enabled CO<sub>2</sub> savings between 1% and 2% in the NEDC from cold start, with respect to other thermal management methods of the exhaust systems. Ning and Yan<sup>40</sup> combined catalyst preheating (before engine start) and postheating (after engine start) to reduce the light-off time, with a control strategy tuning mainly focused on decreasing the EHC switching frequency.

The state of the art of EHC control is still based on switching the device at a constant heating power level. This is a significant limitation as a large amount of engine operating points can be in the catalyst inefficient zone if the constant heating power is small, that is, the catalyst does not light off in a short time. On the other hand, in some conditions high values of the constant heating power can cause excessive exhaust temperatures and fuel penalty.

Despite the available literature on the topic, the very few studies proposing EHC controllers imposing continuously variable power levels do not assess them with experiments or experimentally validated engine models nor analyze the EHC fuel consumption implications. Also, there is a general lack of EHC performance indicators that simultaneously consider emission reduction and fuel consumption. This paper targets this gap by the following:

- Developing two EHC control strategies with continuous heating power modulation and assessing them with an experimentally validated engine simulation model. In particular, the effect of the exhaust target temperature of the EHC controllers on gas emissions and energy penalty is analyzed during the WLTC, which is used as reference driving cycle;
- Proposing an EHC performance indicator, that is, the specific emission reduction, which synthetically evaluates the trade-off between emission reduction and EHC-related fuel consumption penalty.

## 2 | SIMULATION MODEL

### 2.1 | Diesel engine model

A diesel engine model was established in Ricardo WAVE<sup>41</sup> and was used for the analyses of Sections 3 and 4. The main engine parameters are listed in Table 1; they refer to a benchmark diesel engine evaluated during the Horizon 2020 European project ADVICE. To simulate the engine cold start and warm-up process, the time histories of coolant and oil temperatures were set as boundary conditions. The other main input variables of the model are engine speed and fuel injection rate. The transient heat losses are calculated with a transient heat transfer model.<sup>42</sup> The

**TABLE 1** Main diesel engine parameters

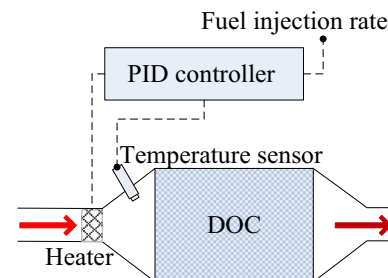
Item	Content
Diesel engine type	In-line, four-cylinder, four-stroke
Intake type	Turbocharger
Fuel injection type	Direct injection
Max power/kW	Approx. 100 kW @ 5500 rpm
Max torque/N m	320 N m @ 1500-4800 rpm
Stroke/mm	80.1
Bore/mm	79.7
Compression ratio	16
Valve number per cylinder	4

after-treatment system includes a DOC, a DPF, and an SCR. The detailed chemical reactions in the DOC and SCR are shown in references.<sup>43,44</sup> The electric heater was positioned at the DOC inlet to decrease the heat losses. The schematic diagram of the EHC configuration is shown in Figure 1. A controller was implemented to regulate the exhaust temperature before the DOC, which is the controller input signal together with the fuel injection rate, while the EHC heating power is the EHC controller output. The maximum EHC power output for the specific application was limited to 4 kW.

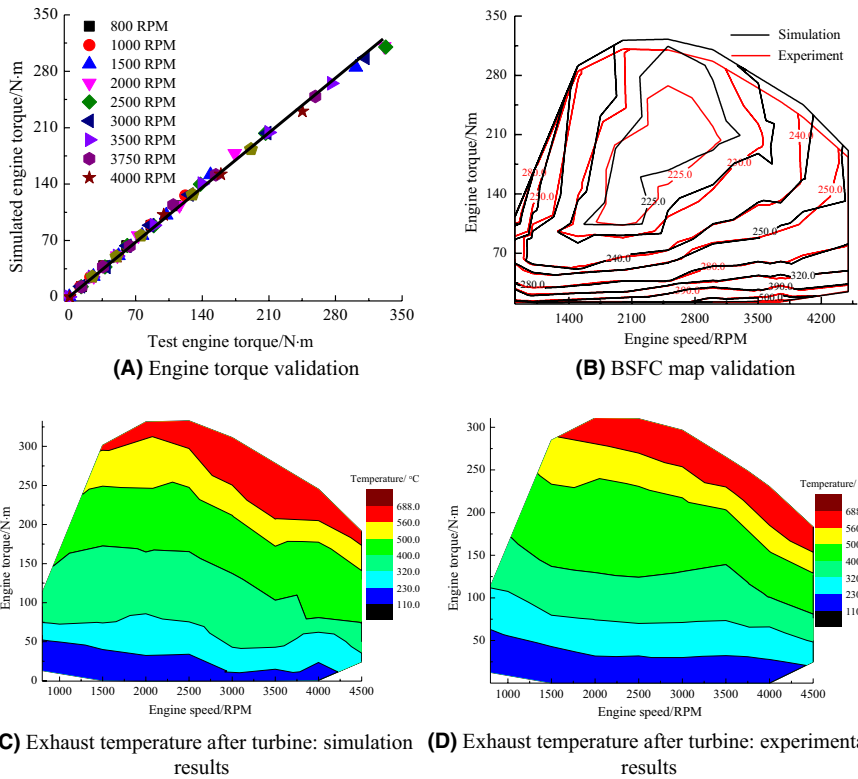
### 2.2 | Engine model validation

The case study diesel engine without EHC was experimentally evaluated on a dynamometer by the industrial partners of the ADVICE project in 63 steady-state operating points, which were used for the WAVE model validation. For example, Figure 2A compares the simulated and measured engine torque values for the same engine inputs, while Figure 2B overlaps the brake specific fuel consumption (BSFC) isolines from simulations and experiments. The optimal fuel economy is in the high load and medium-speed region, with a minimum BSFC of approximately 225 g/(kW h). Figure 2C,D shows the simulated and experimental steady-state exhaust temperature distributions after the turbine, which are closely related to the catalyst light-off time and efficiency. The iso-temperature characteristics have similar trends in the simulations and experiments, especially below 230°C.

Moreover, the engine was experimentally assessed on the dynamometer along the WLTC, and Table 2 reports the average exhaust emission values along the cycle. The experimental and simulated emissions are within a 25% error margin, which is a good approximation for this kind of variables. In particular, the analysis of the emission profiles showed differences mainly during fuel cutoff. In fact, because of the exhaust residuals in the exhaust pipes, the emissions in the experimental results are not zero during cutoff, while they are zero in simulation.



**FIGURE 1** Schematic diagram of the considered EHC configuration



**FIGURE 2** Examples of WAVE model validation results

In summary, the set of validation results confirms the good accuracy of the simulation model, which can be considered a reliable tool for predicting the EHC effects.

### 2.3 | Electrically heated catalyst control strategies

This study proposes the two EHC control strategies in Figure 3, targeting the reduction in the fuel consumption penalty associated with the EHC. Rather than being based on a fixed heating power, which is the main EHC solution from the literature (eg, see references<sup>30,45</sup>), the proposed algorithms include a proportional-integral (PI) controller that continuously adjusts the heating power based on the measured exhaust temperature and fuel flow rate. In particular, in the control strategy A the heater is active only when the exhaust temperature is lower than a target value, and at the same time, the fuel injection rate is nonzero. This prevents EHC energy consumption in fuel cutoff conditions, which normally occur when the accelerator pedal is released. In the control strategy B, the heater is always active as long as the exhaust temperature is lower than the target value; moreover, the target temperature can be set to different values, respectively,  $T_{\text{target}1}$  and  $T_{\text{target}2}$  in Figure 3, for fuel injection and cutoff conditions.  $T_{\text{target}1}$  and  $T_{\text{target}2}$  can vary with time, depending on the engine operation. In particular, in the implementation of the paper  $T_{\text{target}2}$  was set lower than  $T_{\text{target}1}$ , unless the cutoff duration was less than a specific value, in which case  $T_{\text{target}2}$  was set equal to  $T_{\text{target}1}$ . The PI controller gains were tuned

through a sensitivity analysis, targeting good temperature tracking performance without excessive oscillations. The same PI gains were adopted for all the EHC simulation results of this paper.

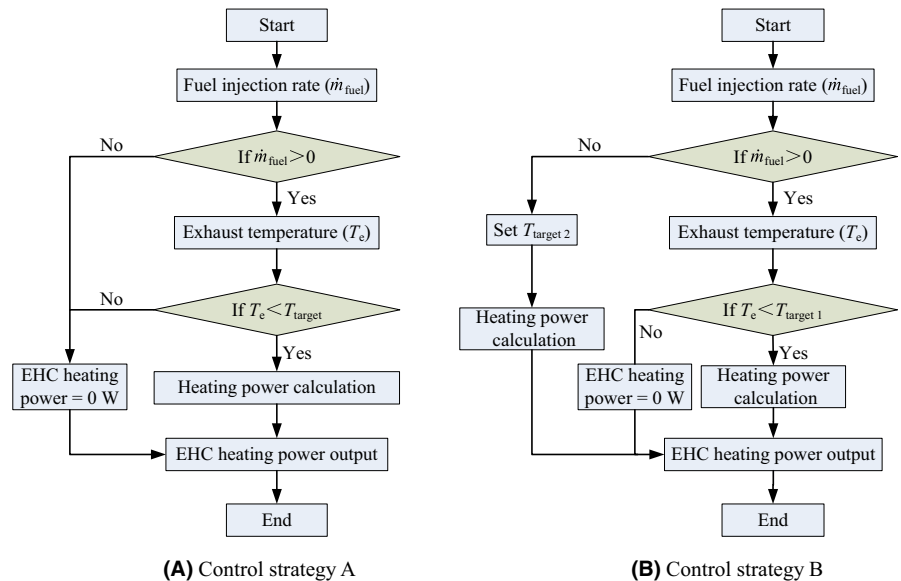
### 2.4 | Worldwide harmonized light vehicle test cycle characteristics

Differently from the NEDC, in the WLTC the vehicle is frequently accelerating and decelerating. Hence, the WLTC is considered representative of the vast majority of real-world vehicle driving situations. Based on the vehicle speed level, the cycle consists of four sections, that is, the low-, medium-, high-, and extra high-speed sections.<sup>26</sup> The cycle has a total duration of 1800 seconds, with 235 seconds of stops and 23.27 km of travelled distance. In a typical cold start condition, the warm-up process mainly happens in the low vehicle speed section. This paper analyses the effect of cold and warm start on the exhaust temperature, EHC performance, and energy consumption. The operating profile of the engine of the case study vehicle during the WLTC was derived from

**TABLE 2** WAVE model validation results: average values of exhaust emissions along the WLTC

Emissions	Experiment	Simulation
HC/g s <sup>-1</sup>	0.0024	0.0030
CO/g s <sup>-1</sup>	0.0084	0.0068
NO <sub>x</sub> /ppm	59.93	47.60

**FIGURE 3** Block diagrams of the proposed EHC control strategies



the experimental measurements provided by the industrial partners of the project, already used for the WAVE model validation in Section 2.2.

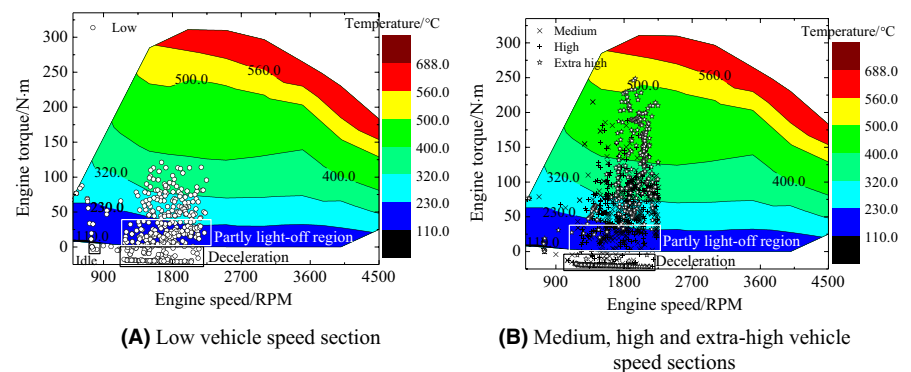
### 3 | EXHAUST TEMPERATURE AND EMISSIONS OF THE BASELINE CONFIGURATION

This section analyses the performance of the diesel engine without EHC, which is the baseline configuration. The engine operating points in the WLTC are presented in the steady-state exhaust temperature distribution contour plots of Figure 4A,B. In the low vehicle speed regions of the WLTC, both engine speed and torque are low, and the catalyst operates inefficiently as the exhaust temperature is insufficient. This is also a symptom of low cylinder temperatures, which exert a major influence on the engine-out emissions. In fact, low cylinder temperatures compromise the fuel/air mixture formation and combustion, thus increasing the HC and CO emissions and decreasing the nitric oxides ( $\text{NO}_x$ ) output. In the medium- and high-speed sections of the cycle in Figure 4B, most of the operating points are in the sufficiently high

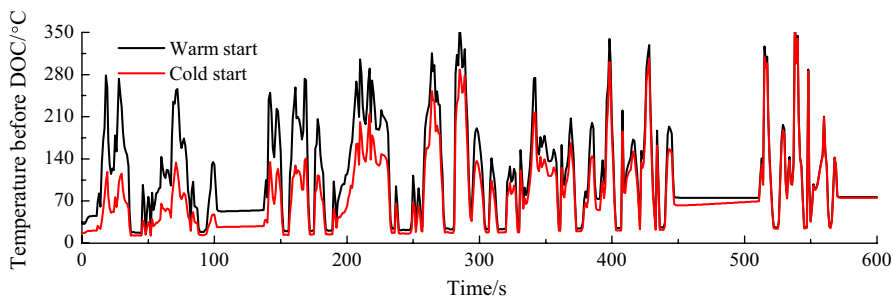
exhaust temperature region for effective catalyst operation. As a consequence, the low-speed section of the WLTC contributes to the majority of the pipe-out emissions and will be the focus of this study.

Both cold and warm start conditions were investigated. Warm start was defined as the situation in which the initial coolant and lubricating oil temperatures are  $75^\circ\text{C}$  and  $95^\circ\text{C}$ , respectively. Figure 5 shows the exhaust temperature profiles at the DOC inlet for the first 600 seconds of the WLTC (the low-speed section has a duration of 589 seconds). The exhaust temperature is very dependent on the engine operating condition and ranges from  $50^\circ\text{C}$  to  $350^\circ\text{C}$ . The difference between cold and warm start conditions decreases after 400 seconds and becomes negligible after 510 seconds. In the first 210 seconds of the cycle from cold start, the exhaust temperature is constantly below the catalyst light-off value. This light-off time is prolonged by the thermal capacity of the exhaust pipes and catalytic converter. Interestingly, also in warm start conditions a large proportion of engine operating points are in the inefficient catalyst region, which is consistent with Robinson's results.<sup>20</sup>

Figures 6 and 7 show the emissions in the same section of the cycle. As the particulate matter is not the focus



**FIGURE 4** Operating points during the WLTC reported on the engine torque characteristic as a function of speed, including the contour plots of the steady-state exhaust temperature before the catalyst



**FIGURE 5** Time histories of the exhaust temperature at the DOC inlet during a WLTC from warm and cold start conditions

of this study and can be significantly reduced by a DPF device, it is not reported in the figures. The average catalyst efficiency is approximately 50% in warm start conditions, while it is less than 20% for cold start, in which the catalysts are barely effective especially during the first 300 seconds. The inlet temperatures of the DOC and SCR are significantly different, because of the thermal capacity of the catalysts, which brings a smoother temperature profile at the SCR. To achieve low vehicle emissions, the inlet temperatures of both SCR and DOC need to exceed the light-off threshold.

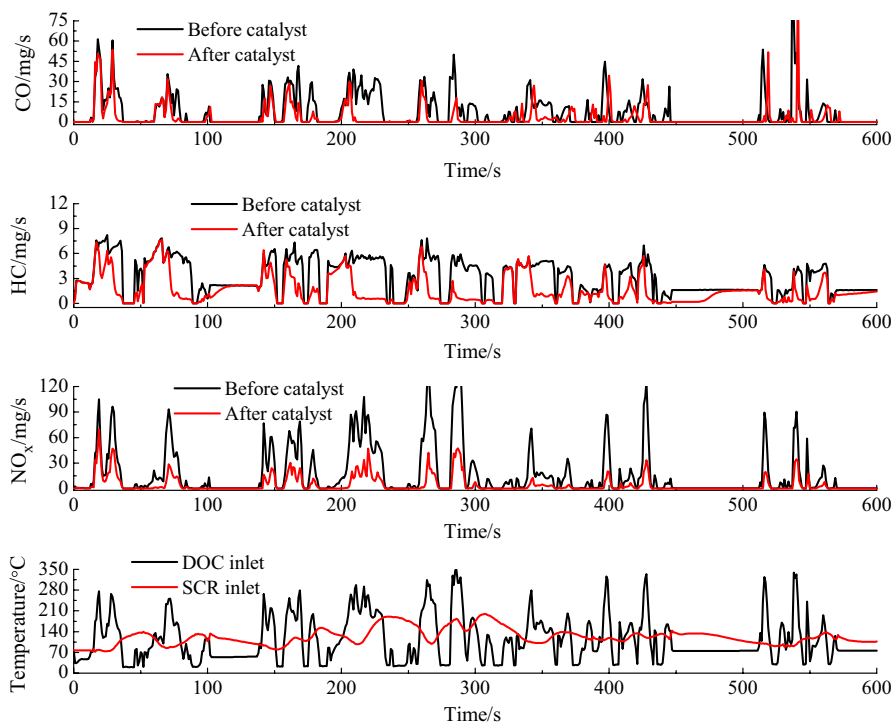
## 4 | ELECTRICALLY HEATED CATALYST RESULTS AND DISCUSSION

### 4.1 | Electrically heated catalyst performance with control strategy A

This subsection discusses the EHC performance with control strategy A. The target temperature at the DOC inlet and the

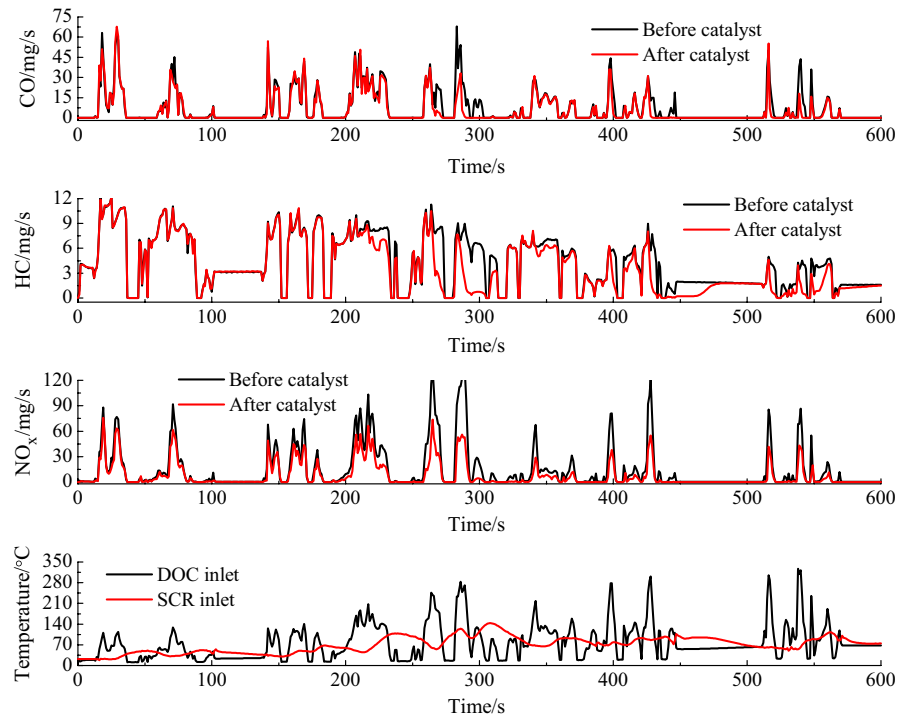
exhaust flow rate determine the EHC energy consumption and catalyst efficiency. Two target temperatures, 180°C and 200°C, were considered for the analysis.

Figures 8 and 9 show the gaseous emissions during warm start. For both target temperatures, the pipe-out emissions significantly drop after the EHC implementation. As previously discussed, the exhaust temperature profile at the SCR inlet is different from that at the DOC inlet because of the thermal capacity of the catalyst. This leads to low SCR efficiency in the initial part of the cycle. Moreover, the figures highlight that the emissions are particularly high when the fuel injection is re-initiated after cutoff, because of the thermal transient of the catalyst toward the target temperature after the heater is restarted. When the target temperature increases from 180°C to 200°C, the CO and HC emissions further decrease, but the NO<sub>x</sub> emissions barely change, because the SCR efficiency is primarily affected by the heating interruptions during cutoff. This is an important observation, as in modern diesel engines HC and CO emissions are usually less problematic, and most of the vehicles can satisfy the recent emission regulations, such as the Euro 6 regulations, with good margin even in real

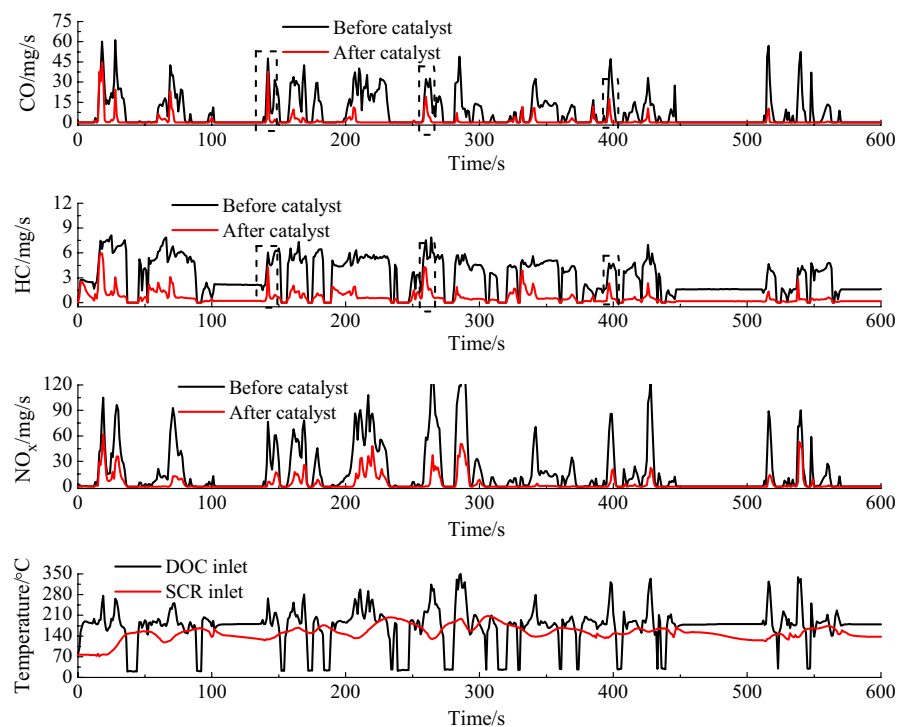


**FIGURE 6** Exhaust emissions during the initial 600 s of the WLTC from warm start conditions

**FIGURE 7** Exhaust emissions during the initial 600 s of the WLTC from cold start conditions



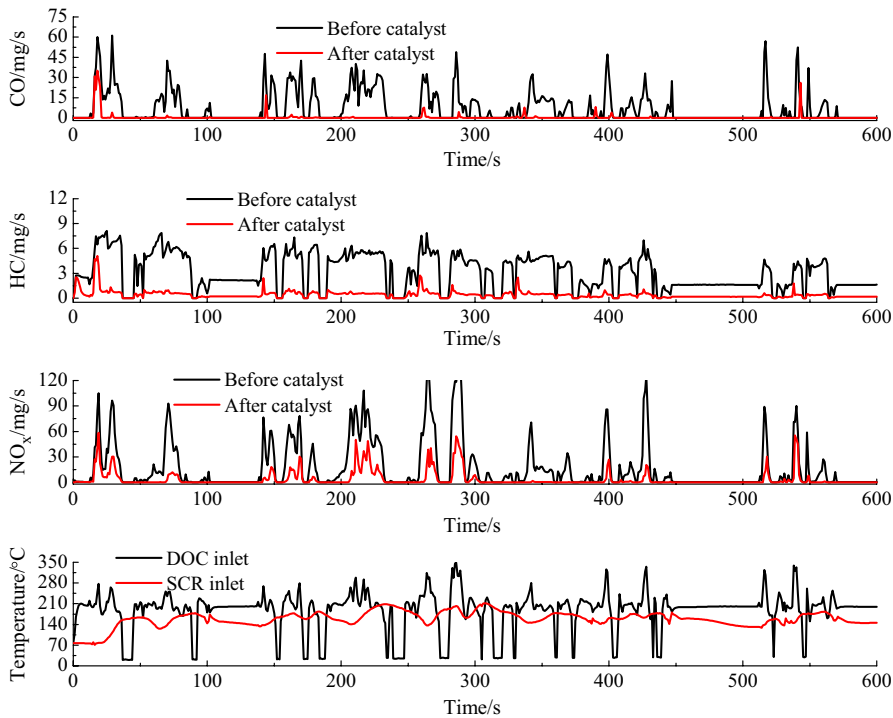
**FIGURE 8** Exhaust emissions during the initial 600 s of the WLTC from warm start conditions; EHC with control strategy A and a target temperature of 180°C



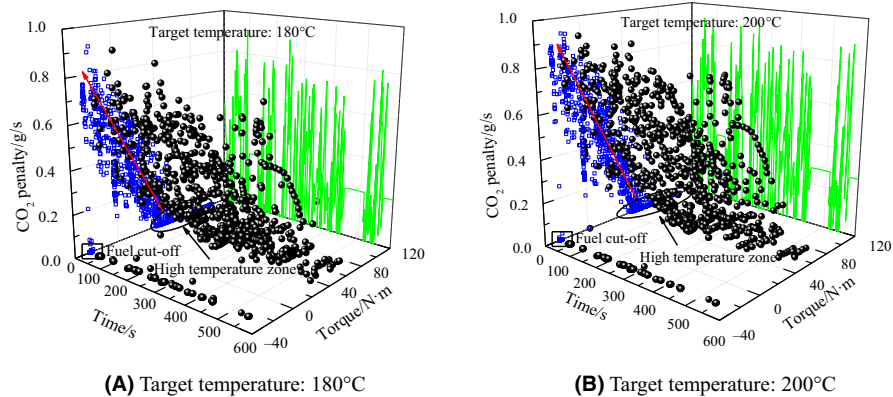
driving conditions. On the other hand, the  $\text{NO}_x$  emission reduction remains a challenge.

As the  $\text{CO}_2$  emission reduction is an urgent target for the automotive sector, this analysis also evaluates the  $\text{CO}_2$  penalty associated with the EHC application. The EHC energy consumption was converted into  $\text{CO}_2$  penalty based on the average thermal efficiency of the internal combustion engine during the WLTC and the average efficiency of the

alternator/rectifier, which was supposed to be 75%.<sup>46</sup> The results are shown in Figure 10, where the circles are the operating points of the internal combustion engine on the three-dimensional plot of time, engine torque, and EHC-related  $\text{CO}_2$  penalty. The figure also includes the projection of the same points on the  $\text{CO}_2$  penalty as a function of torque plane (see the squares) and on the  $\text{CO}_2$  penalty as a function of time plane (see the continuous line). Interestingly, the  $\text{CO}_2$



**FIGURE 9** Exhaust emissions during the initial 600 s of the WLTC from warm start conditions; EHC with control strategy A and a target temperature of 200°C



**FIGURE 10** CO<sub>2</sub> penalty associated with the EHC implementation from warm start conditions

penalty is almost inversely proportional to the engine torque and is nearly negligible for torque values in excess of 40 N m. The 20°C increase in the EHC target temperature greatly increases the CO<sub>2</sub> penalty.

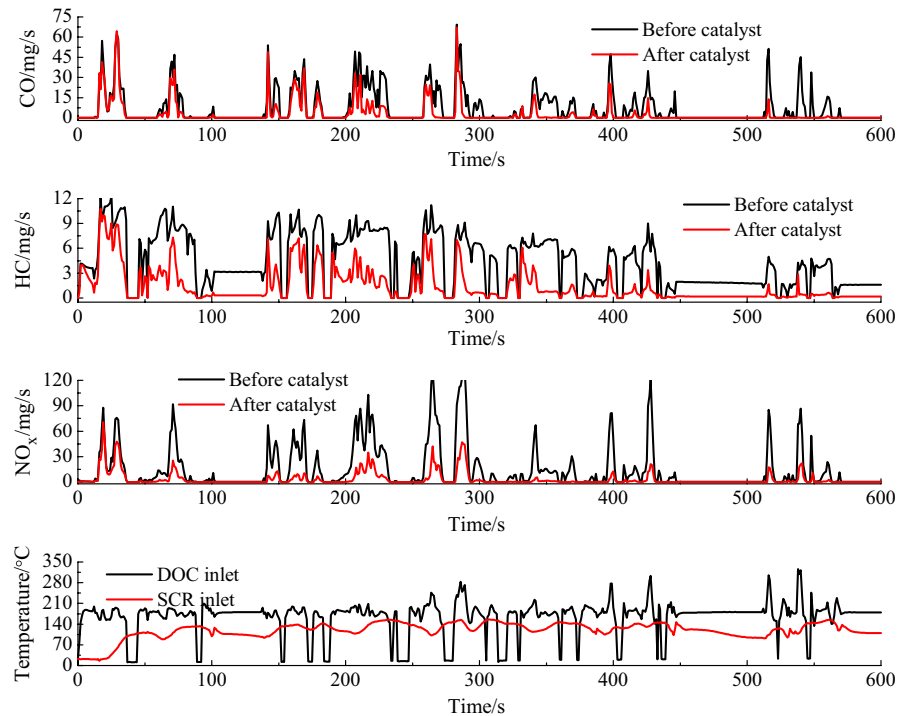
Figures 11 and 12 report the exhaust emissions for cold start conditions. Compared with warm start, the cylinders and tailpipes are characterized by lower temperatures. As a result, the achievement of the DOC target temperature takes longer (approximately 5 seconds) and requires higher heat injection. The pipe-out emissions significantly decrease after the application of the EHC. Also in this case, high pipe-out emissions are observed immediately after fuel cutoff, because of the catalyst thermal capacity and the heater deactivation during cutoff.

In summary, for both warm and cold start conditions, the catalyst light-off time is significantly shortened by the EHC, that is, by 20 seconds and 25 seconds for warm start with target temperatures of 180°C and 200°C, and by 254 seconds and 256 seconds from cold start with target temperatures of

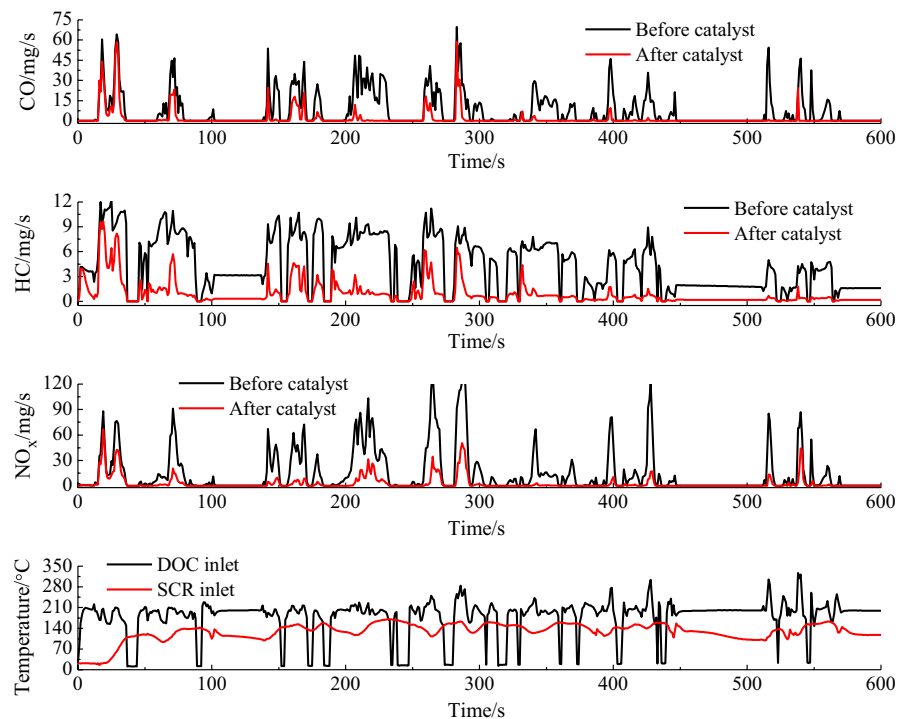
180°C and 200°C. This is aligned with the literature,<sup>28,47,48</sup> which reports that the EHC is generally better than other methods in terms of light-off time reduction. For example, with reference to alternative methods, in Cavina et al<sup>49</sup> fuel injection retarding increased the exhaust temperature by approximately 50°C with 15% fuel penalty in the first 300 seconds of the NEDC. In addition, the temperature increase was less than 30°C for a larger nozzle opening of the variable geometry turbine, which resulted in 5% fuel penalty. Mahadevan et al<sup>19</sup> demonstrated 67% catalyst light-off time and 63% HC emission reductions through hot air injection technology.

Figure 13 shows the CO<sub>2</sub> penalty for cold start conditions, in which many operating points in the initial part of the cycle require the maximum heating power from the EHC, especially for the case of the 200°C target temperature, with considerably increases the CO<sub>2</sub> penalty with respect to the warm start conditions. After 200 seconds, the EHC barely uses its maximum power output.

**FIGURE 11** Exhaust emissions during the initial 600 s of the WLTC from cold start conditions; EHC with control strategy A and a target temperature of 180°C



**FIGURE 12** Exhaust emissions during the initial 600 s of the WLTC from cold start conditions; EHC with control strategy A and a target temperature of 200°C

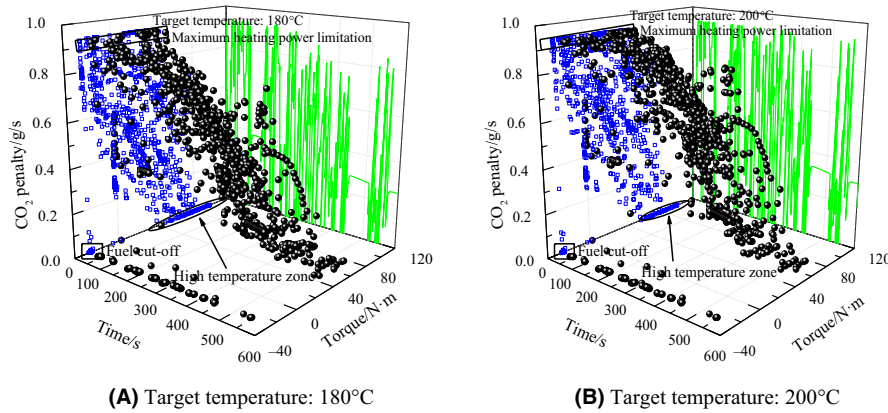


## 4.2 | Electrically heated catalyst performance with control strategy B

On the one hand, with control strategy A the DOC inlet temperature is low at the end of each fuel cutoff phase, and thus, the SCR catalytic efficiency is rather poor for the typically high NO<sub>x</sub> emission points immediately after

cutoff. On the other hand, if the target temperature remains constant during fuel cutoff, the energy penalty can be significant.

Control strategy B targets a balance between energy consumption and catalyst efficiency. For example, Figure 14 shows the DOC inlet temperature histories for the following: (i)  $T_{\text{target}1} = 190^{\circ}\text{C}$  and  $T_{\text{target}2} = 160^{\circ}\text{C}$  and (ii)



**FIGURE 13** CO<sub>2</sub> penalty associated with the EHC implementation from cold start conditions

$T_{\text{target}1} = T_{\text{target}2} = T_{\text{target}} = 200^{\circ}\text{C}$ . Case (i) still presents some criticalities after each cutoff phase, as the exhaust temperature tends to remain below the optimal values for non-negligible durations, because of the thermal dynamics of the system (see the ‘response delay’ region in the figure).

Figure 15 reports the exhaust emissions from warm start conditions for case (ii), which is directly comparable with control strategy A in terms of target temperature. The emission reduction is significant especially in terms of HC. As expected, the CO<sub>2</sub> penalty is very important during fuel cutoff because of the low exhaust temperature and decreases almost linearly with engine torque (see Figure 16). Similar trends were obtained for cold start conditions (see Figures 17 and 18), with longer vehicle operation at the maximum EHC heating power, in comparison with warm start conditions.

### 4.3 | Electrically heated catalyst performance summary along the whole worldwide harmonized light vehicle test cycle

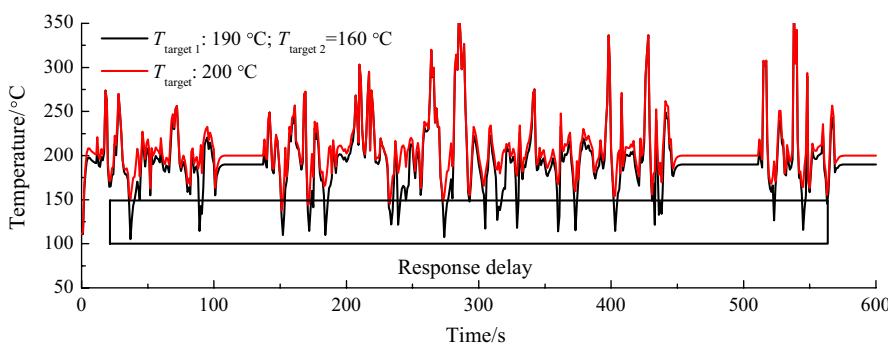
Table 3 summarizes the EHC performance benefit with control strategies A and B along the whole WLTC, for different target temperatures. For the baseline configuration, the exhaust emissions from cold start are almost twice as high as those from warm start. The pipe-out emissions significantly decrease with both control strategies after

adopting the EHC, which brings higher benefits in the cold start case than in the warm start one. Because of the heat loss of the exhaust pipes and the catalyst thermal capacity, the NO<sub>x</sub> percentage reduction is lower than that of HC and CO. For example, from warm start conditions with control strategy A with a target temperature of 200°C, the CO, HC, and NO<sub>x</sub> emissions are reduced by 88%, 74%, and 21%, respectively. Nevertheless, the NO<sub>x</sub> emission reduction is important especially from cold start, when control strategy B with a target temperature of 200°C brings a 65% NO<sub>x</sub> decrease, that is, from 4776.6 mg to 1662.7 mg.

In parallel, the CO<sub>2</sub> emission penalty (in percentage) of the vehicle with the EHC, with respect to the baseline case, ranges from 3.93% to 6.65% and from 6.49% to 9.35% for warm and cold start, depending on the considered control strategy and tuning. When limiting the analysis to the configurations with EHC, the CO<sub>2</sub> penalty associated with cold start varies from 2.56% to 2.70%, with respect to warm start.

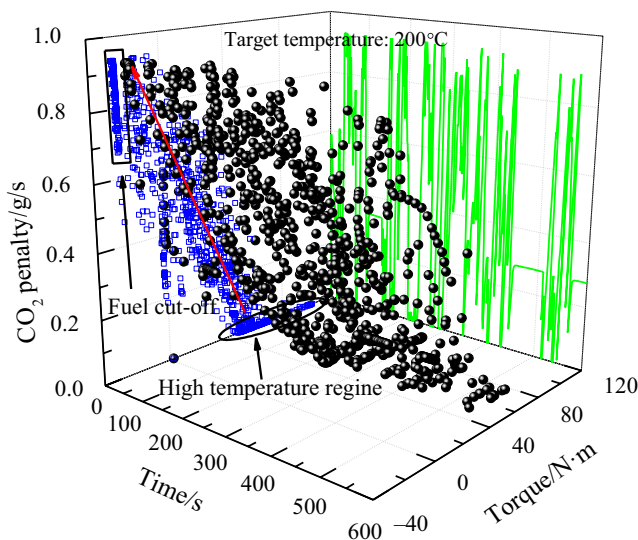
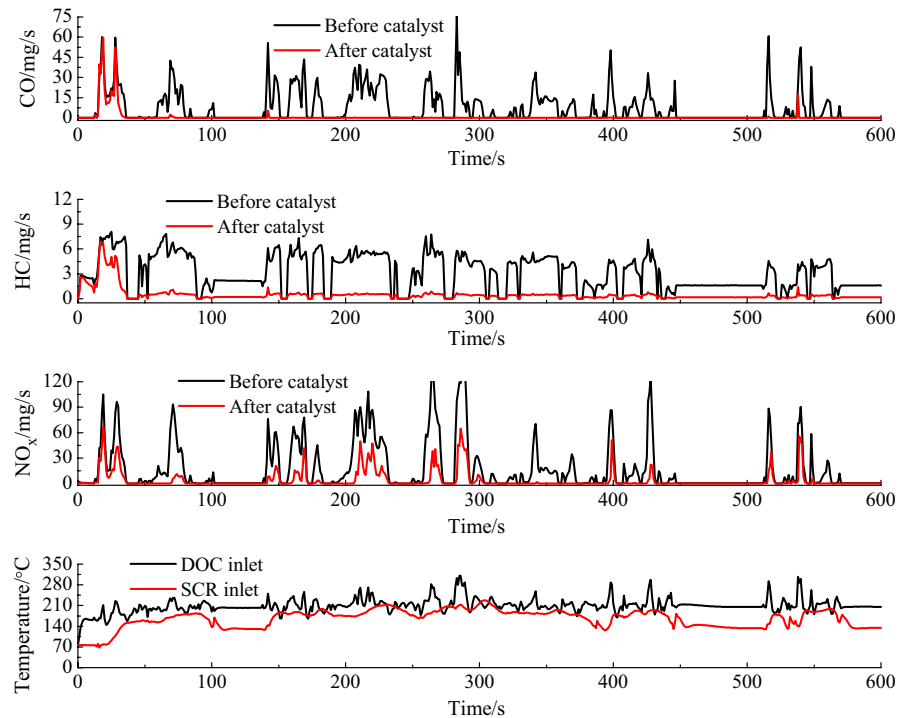
The specific emission reduction,  $\Delta_{\text{CO/HC/NO}_x, \text{spec}}$ , is defined as performance indicator of the EHC strategies and is calculated as the ratio between the emission reduction and the corresponding electrical energy consumption of the EHC:

$$\Delta_{\text{CO/HC/NO}_x, \text{spec}} = \frac{\Delta_{\text{CO/HC/NO}_x}}{E_{\text{EHC}}} = \frac{Em_{\text{CO/HC/NO}_x, N} - Em_{\text{CO/HC/NO}_x, A/B}^{180/200}}{E_{\text{EHC}}} \quad (1)$$



**FIGURE 14** Exhaust temperature at the DOC inlet for control strategy B

**FIGURE 15** Exhaust emissions and temperatures during the initial 600 s of the WLTC from warm start conditions; EHC with control strategy B and a target temperatures of 200°C



**FIGURE 16** CO<sub>2</sub> penalty from warm start conditions with control strategy B

where  $\Delta_{\text{CO/HC/NO}_x}$  is the emission reduction (in terms of NO<sub>x</sub>, HC, and CO depending on the subscript in the notation) of the vehicle with EHC with respect to the baseline vehicle;  $E_{\text{EHC}}$  is the total electrical energy consumed by the EHC heating device during the driving cycle;  $Em_{\text{CO/HC/NO}_x, N}$  is the cumulative pipe-out emission level (in terms of CO, HC and NO<sub>x</sub> mass) of the baseline vehicle, that is, with no heating (hence the notation N); and  $Em_{\text{CO/HC/NO}_x, A/B}^{180/200, C/W}$  is the cumulative

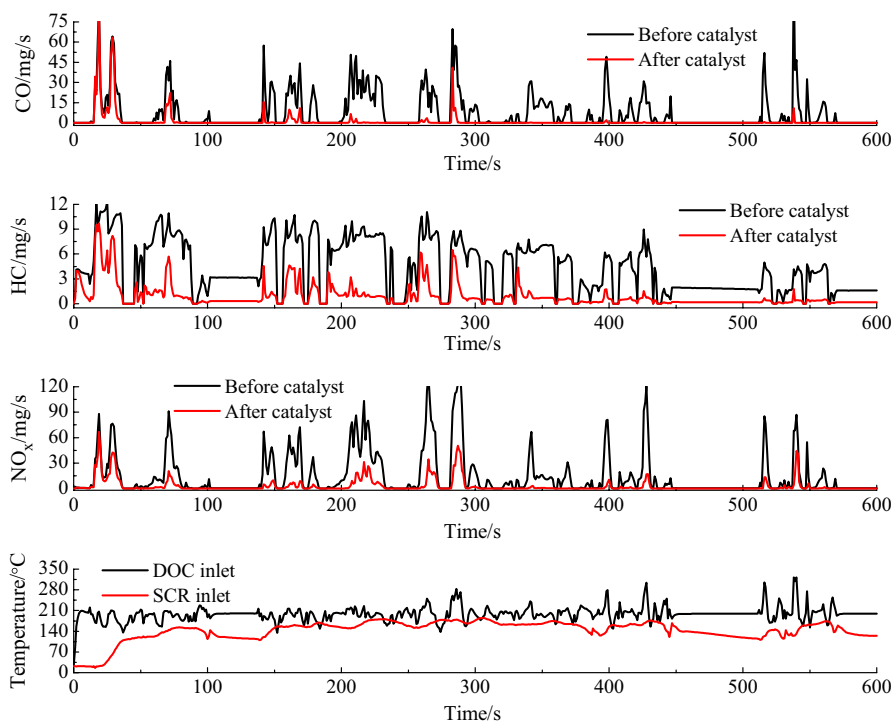
pipe-out emission level for control strategy A or B, with target temperature of 180°C or 200°C (hence the notations 180 and 200). In other words,  $\Delta_{\text{CO/HC/NO}_x, \text{spec}}$  measures the effectiveness of the EHC energy expenditure.

On the one hand, the performance indicator values show that in general control strategy A is more effective than control strategy B, especially in terms of CO and HC from warm start, and that the EHC has a valuable impact on the NO<sub>x</sub> emissions only from cold start. On the other hand, Figure 19 compares the pipe-out emissions during the WLTC with the limits imposed by the Euro 6b emission regulations. The CO emission is under the Euro 6b limit of 500 mg/km, independently from the EHC control strategy. As for the NO<sub>x</sub> emission, only control strategy B with 200°C target temperature meets the regulation and becomes the choice for the specific application.

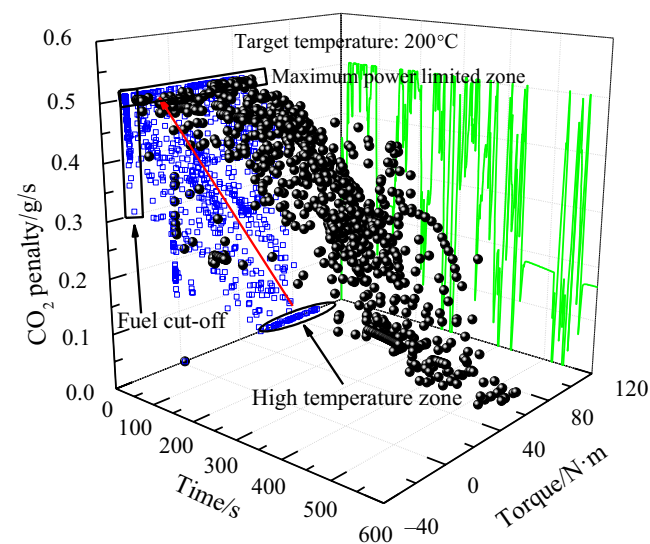
## 5 | CONCLUSIONS

This study implemented and experimentally validated a detailed diesel engine model, including an EHC system. Two control strategies were developed and assessed to decrease the exhaust emissions during the WLTC while limiting the EHC energy consumption. The main conclusions are as follows:

- For the case study vehicle, a large amount of engine operating points are located in low-efficiency zones of the catalyst during the cold start and warm-up phases, which causes



**FIGURE 17** Exhaust emissions and temperatures during the initial 600 s of the WLTC from cold start conditions; EHC with control strategy B and a target temperatures of 200°C



**FIGURE 18** CO<sub>2</sub> penalty from cold start conditions with control strategy B

significant exhaust emissions during the first 300 seconds of the cycle for the case without EHC. Moreover, in the low vehicle speed section of the driving cycle, a large proportion of the engine operating points is in regions characterized only by partial catalyst light off, even when the engine is already fully warmed up.

- The pipe-out emissions significantly decrease after the EHC implementation, especially for cold start conditions. For example, for control strategy A with a 200°C target temperature the reduction ranges from 62% for the NO<sub>x</sub> to 73% for

the CO. Nevertheless, the exhaust emissions are still high for control strategy A when fuel injection is recovered after short cutoff intervals. The problem is alleviated by control strategy B, which heats the catalyst also during cutoff. The system performance is also limited by the maximum heating power (4 kW) of the device and the significant heat loss in the tail pipes after cold start, which make the exhaust temperature lower than the target in the initial section of the WLTC.

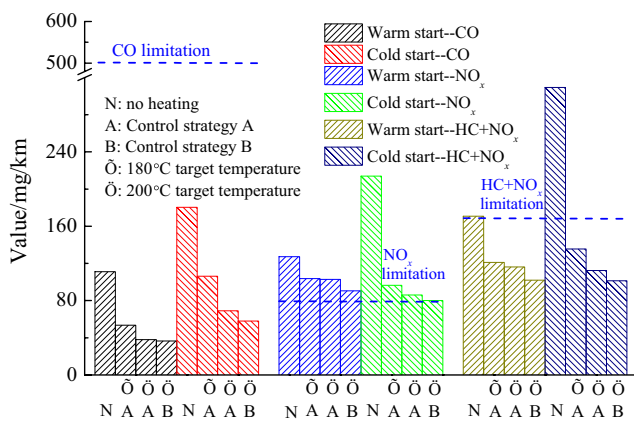
- During the whole WLTC, the CO<sub>2</sub> percentage penalty associated with the EHC ranges from 3.93% to 6.65% and from 6.49% to 9.35% for warm start and cold start conditions, respectively, while the specific NO<sub>x</sub> emission reduction ranges from 2.59 g (kW h)<sup>-1</sup> to 8.86 g (kW h)<sup>-1</sup>. The application of control strategy B with a 200°C target temperature meets the Euro 6b emission regulation along the cold start WLTC.

Future research will focus on NO<sub>x</sub> emission control and the effective regulation of the exhaust temperature before the SCR. This will include the following: (i) model predictive control based on the expected torque demand profile ahead, to switch on the heater based on the expected end of the fuel cutoff phases; (ii) application of a second heater located at the SCR inlet; (iii) evaluation of low thermal capacity catalysts to shorten the SCR light-off time; and (iv) extensive adoption of the newly defined EHC performance indicator for the comparison of different EHC strategies.

**TABLE 3** EHC performance for different control strategies and target temperatures along the whole WLTC

Target temperature/°C	Electrical energy penalty/ kW h	CO	HC	NO <sub>x</sub>	CO <sub>2</sub> penalty/g
		Cumulative pipe-out emission/mg			
N <sup>w</sup>	NA	1932.4	948.2	2757.9	–
A <sup>180,w</sup>	0.1728	594.4	340.8	2208.0	144.9
A <sup>200,w</sup>	0.2186	231.9	245.9	2190.5	182.5
B <sup>200,w</sup>	0.2915	198.5	201.7	1905.2	244.6
N <sup>c</sup>	–	3541.2	2155.5	4776.6	–
A <sup>180,c</sup>	0.2840	1819.9	844.9	2042.5	238.2
A <sup>200,c</sup>	0.3360	952.2	546.0	1800.3	281.2
B <sup>200,c</sup>	0.4101	696.3	427.5	1662.7	343.1
–	–	Specific emission reduction/g (kW h) <sup>-1</sup>			CO <sub>2</sub> increase percentage/%
A <sup>180,w</sup>	–	7.74	3.52	3.18	3.93
A <sup>200,w</sup>	–	7.78	3.21	2.59	4.95
B <sup>200,w</sup>	–	5.94	2.56	2.92	6.65
A <sup>180,c</sup>	–	6.06	4.61	9.63	6.49
A <sup>200,c</sup>	–	7.71	4.79	8.86	7.64
B <sup>200,c</sup>	–	6.93	4.21	7.59	9.35

Note: N, no heating; A: control strategy A; B: control strategy B; <sup>180</sup>: 180°C as target temperature; <sup>200</sup>: 200°C as target temperature; <sup>w</sup>: warm start; <sup>c</sup>: cold start.

**FIGURE 19** Pipe-out emission results with respect to the Euro 6b emission regulation

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## NOMENCLATURE

BSFC brake specific fuel consumption  
CO carbon monoxide

CO<sub>2</sub> carbon dioxide  
DOC diesel oxidation catalyst  
DPF diesel particulate filter  
EHC electrically heated catalyst  
FTP federal test procedure  
HC hydrocarbon  
HEV hybrid electric vehicle  
NEDC new European driving cycle  
NO<sub>x</sub> nitric oxides  
NTP nonthermal plasma  
PI proportional-integral  
PPC partially premixed combustion  
PPCI partially premixed compression ignition  
SCR selective catalyst reduction  
TWC three-way catalyst  
WLTC worldwide harmonized light vehicle test cycle

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