Electrically Heated Catalyst (EHC) Development for Diesel Applications

Muhammad Tahir Nazir 1) Miles Brammer 2) Robert Scholz 3) Florian Zote 4) Frank Bunar 5) Friedemann Schrade 6)

1)-6) IAV GmbH, Carnotstrasse 1, 10587 Berlin, Germany (Email: tahir.muhammad.nazir@iav.de)

Received on July 2, 2015
Presented at the SAE Annual Congress on May 20, 2015

ABSTRACT: A model-based approach for the design and development of electrically heated catalyst (EHC) systems is presented. Based on experimental analysis of the EHC heat-up and catalytic behaviour, a detailed physico-chemical EHC model is developed. Within a total system simulation environment, different heat-up measures are compared for SULEV30 compliance. The simultaneous reduction of HC, NO\textsubscript{x} and GHG is revealed to be challenging, HC being the limiting factor for engine based thermal management. Regarding total energy consumption, a combined EHC and late PoI approach is favoured to meet emission limits. The developed operation strategy is presented in detail and confirmed by experimental findings.

KEY WORDS: Vehicle development, environment, deNO\textsubscript{x} catalyst, computer aided engineering, fuel economy, exhaust system, Electrically Heated Catalyst, SULEV30, heat and temperature management, full vehicle simulation [B2]

1. Introduction

The statutory requirements for Diesel passenger car applications in the leading markets has led to an increase in the complexity of exhaust aftertreatment (EAT) systems and the emergence of numerous competing technological solutions. In the US, the Californian SULEV30 emission regulation specifies a stringent decrease in emission limits, especially for NO\textsubscript{x} (Nitrogen Oxides), and the introduction of additional regulation for greenhouse gases (GHG), which represent a significant challenge for Diesel powertrain development and aftertreatment system design.

Currently, the Diesel oxidation catalyst (DOC) plays a key role for the simultaneous abatement of CO and HC and the formation of NO\textsubscript{2} for downstream NO\textsubscript{x} reduction (deNO\textsubscript{x}) systems such as SCR (Selective Catalytic Reduction). DOC performance is kinetically limited by the low exhaust temperatures associated with fuel-efficient Diesel combustion, especially in city driving conditions and cold start phases. Conventional heat-up measures are realised by a change in combustion strategy or the use of late post injection (late PoI) once DOC light-off has been reached, at the expense of additional fuel consumption and HC emissions.

With the technological trend towards the electrification of the powertrain, the use of electrically heated catalyst (EHC) systems becomes an alternative\textsuperscript{1). This offers the possibility to decouple the catalyst heat-up from the Diesel combustion by using the energy recuperated and electrically stored during deceleration phases. Furthermore, the PGM loading and the sizing of the DOC can be optimized by increasing the temperature level in the EAT system using electric energy from the battery, instead of relying on the exothermic heat release from the catalyst. This can lead to potential cost reductions and can be used to offset the initial higher costs of an EHC system\textsuperscript{1). In addition, the combination of EHC with other thermal management technologies will allow a flexible and efficient heat-up strategy which can potentially be adjusted to adapt over component lifetime.

In this work, a model-based approach for the design and the operation strategy development of EHC systems is presented. Using lab-based experimental analysis of the EHC heat-up and catalytic behaviour, a detailed physico-chemical EHC model is developed in \textit{axisuite}. This is integrated into a total system simulation environment \textit{Velodyn} with sub-models for vehicle, engine, electric system and EHC control software. For the developed vehicle model, incorporating an eDOC-SCR/DPF-SCR exhaust system, various thermal management strategies are simulated and compared in terms of SULEV30 compliance; the simulation results are confirmed by experimental findings. Finally, in a simulation based study, the potential for further CO\textsubscript{2} reduction is evaluated for a combined EHC and late PoI thermal management strategy.

2. Background

2.1. SULEV 30 – Standards and Technical Challenges

In order to meet the future emission and fuel consumption requirements in the US market, a “Super Ultra Clean and Efficient Diesel”\textsuperscript{2, 3) powertrain concept needs to be defined. A major key technical challenge is to reduce exhaust gas emissions below the US NO\textsubscript{x} + NMOG fleet requirements (NMOG = non-methane organic gas). Figure 1 illustrates these legislative requirements in combination with LEVIII emission type approval categories\textsuperscript{4). By 2025, a competitive US diesel technology must comply with SULEV30 standards (NO\textsubscript{x} + NMOG < 30 mg/mi in FTP75 emission cycle). This means a significant emission reduction over current ULEV (LEVII) / Tier 2 Bin 5 tailpipe emission levels (ULEV = Ultra low emission vehicle; SULEV = Super ULEV).
For EAT system developments, a strong focus must be placed on periods of low exhaust temperatures. For US certification, this represents the cold start phase of the FTP75 emission cycle and the restart after the hot soak period in the third and final phase of the FTP75. Figure 2 illustrates the SCR deNO\textsubscript{x} performance in FTP75 for the aforementioned set-up, with a base calibration aimed at achieving the current EPA (Tier 2 Bin 5) and CARB (LEV II) emission level requirements. Obtaining higher deNO\textsubscript{x} efficiencies in these critical phases requires significantly improved low temperature performance from the EAT system as well as advanced thermal management.

![Fig. 1: NO\textsubscript{x} + NMHC fleet average standards and LEVIII FTP75 emission categories.](image)

### 2.2. Thermal management technologies

Providing sufficient exhaust gas temperatures necessary for the fulfilment of future legislation limits can be achieved in a number of ways. Which temperature levels are required, and for what purpose, is dependent on the specific EAT component combination in question. Generally, for current SCR technologies, maximum deNO\textsubscript{x} efficiencies require inlet gas temperatures to remain above approximately 200 °C\textsuperscript{9}, which cannot be ensured in the warm-up phase and during low load cycles (e.g. city driving) for high efficiency diesel engines.

Exhaust gas temperatures can be managed using both passive and active solutions. Passive heat measures involve reducing heat losses and thermal masses or storing excess heat energy, which is then released as the temperature drops. By using these fuel and emissions neutral measures, maintaining the required temperature levels in the EAT system can be improved, but their impact is limited.

Active exhaust gas thermal management devices such as EHC\textsuperscript{10} fully or partially Variable Valve Trains (VVT)\textsuperscript{6} or diesel fuel injectors with flexible and multiple injection functionalities, as well as external fuel burners, have been proposed. These technology options can offer modular and flexible thermal management strategies over various vehicle applications. Thus, the EAT system heat-up can be realised more and more independently from the ambient and driving conditions. Furthermore, active heating devices can be used to regulate the operation and performance of other EAT technologies, for example, LNT (Lean NO\textsubscript{x} Trap) or DPF (Diesel Particle Filter) at low engine loads. Generally, however, with the exception of the EHC in a hybridised powertrain environment, active heat technologies directly or indirectly increase fuel consumption.

For the purposes of this current study, the EHC was selected for further, experimental and model-based analysis due its flexibility of control and independence of subsequent catalytic activity. Furthermore, the benefit of using recuperated energy in a hybridised Diesel powertrain, as well as the likely trend towards more efficient and higher power board nets, makes EHC systems an attractive option for the near future.

### 3. EHC Characterisation and integration

This section provides a short summary of a study into the heat-up performance of an electrically heated catalyst, conducted as part of this research. Furthermore, aspects concerning the integration of an EHC into a vehicle environment are analysed and discussed.

#### 3.1. Component design and functionality

The investigated, prototype EHC consisted of a separate heat disc and support disc with metallic substrates of different cell densities (here: 160 / 600 cpsi) and wall thicknesses (here: 0.065 / 0.030 mm). The length of the heat disc was approximately 11 mm compared with a support disc of length 75 mm. The heat disc consisted of multiple, corrugated, metallic layers wound up in an Archimedean spiral in which sinus-shaped and straight layers alternate to form triangular channels.

The heat disc was mechanically supported by insulated retaining pins fixed to the support disc. Electrical power was applied to the heat disc only (see Fig. 3). The electrical power is a function of the resistance of the heat disc and the input voltage. Both the heat disc and support disc substrates were coated with precious metals for catalytic functionality.

![Fig. 3: EHC Assembly.](image)

#### 3.2. Measurements for heat-up characterisation

A preliminary evaluation of the heat-up behaviour of the heat disc was conducted using thermal imaging. The EHC was connected to a 12 V power supply under resting air conditions and
photographed using an IR thermal imager after approx. 10 s and 20 s of heating. From Figure 4 it can be seen that a temperature distribution is established with varying temperature uniformity due to small differences in the local electrical resistance of the disc structure. The current follows the path of smallest resistance (along the inner edge of the spiral matrix), such that the centre of the disc heats first, whilst some outer sections of the disc remain de-energised.

In addition, a three-dimensional evaluation of the heat-up characteristic of the entire heated catalyst was obtained by positioning thermocouples distributed over a perpendicular area at different radial and axial positions. The heat-up of the EHC was measured on a hot gas test bench for a range of gas temperatures and mass flow rates along hyperbolas of constant enthalpy, in order to assess the impact of the gas temperature at comparable power levels and inlet enthalpy flow rates. Using pulse width modulation (PWM), whereby the power was digitally modulated at regular intervals from full to zero, the effective total power input was varied from 25-100 %. Although it was found that, under stationary conditions, 100 % of the input power could be converted into an increase in gas enthalpy, it can be seen from Figure 5, that there is a delayed transfer of thermal energy from the disc to the gas phase, as electrical energy is first used to heat the solid itself. Also, it can be seen that the total temperature increase and the temporal temperature derivative through the heat disc scale approximately linearly with the electric power input.

Figure 6 shows the development of the local gas temperature relative to inlet temperature for selected thermocouple positions at the outlet to the heat disc for inlet conditions of 322 kg/h and 60 °C. It is clear that, directly after the heat disc, an inhomogeneous gas temperature distribution is established, resulting from the non-uniform power distribution observed in the thermography measurements. This effect was found to increase with decreasing mass flow rate and temperature.

Mixing effects in the support disc inflow region, as well as heat conduction through the metallic substrate, help to homogenise the spatial temperature distribution downstream of the heat disc. Nonetheless, local temperature differences remain; the potential impact on local emission reduction should be taken into account during the calibration of the EHC control strategy.

3.3. Integration of an EHC into a vehicle environment

Integrating the EHC into a vehicle environment requires the consideration of a number of factors including vehicle package, component design and electrical and control systems (Fig. 7). In terms of spatial requirements, due to its modular application, an electrically heated catalyst will integrate seamlessly into existing component cannings and will be of similar size to current catalyst technologies(1). Additional spatial requirements result from the associated electrical network, including cables to and from the battery to the heat disc, whose length and size are dependent on the power to be supplied. In addition, a high current relay or alternative controller is required, which is able to modulate the power supplied to the EHC according to the dedicated control strategy and to allow flexible and efficient operation. Furthermore, consideration must be made to prevent overheating of the modulator and possibly, also, the surrounding components, which may require additional clearances and control capabilities.

As well as challenges associated with the verification of the EHC electrical and thermal performance from an on-board diagnostic perspective, a key aspect for consideration is the provision of the required power. The maximum design performance for current EHC technologies is limited(5), whereby the actual output is inherently dependent on the overall system resistance. This is further limited by the power supplied by the vehicle’s electrical system at any given time: During engine and component warm up phases (e.g. cold start), a number of power consumers are active, including driver safety and comfort systems(5). This is especially a challenge for vehicles used in colder climates or with large numbers of power consumers; thus, the supply of electricity has to be prioritised.

Future trends away from current 14 V board net voltage levels towards higher conventional voltage levels of 48 V, or even more
if hybrid applications are considered, may lead to better overall efficiency levels. The trend towards hybridisation may also be of particular advantage to EHC application. Using electrical energy from recuperation enables the EHC to continue heating the exhaust gas and, ultimately, prevent a drop in emissions reduction performance, without additional engine or generator loads\(^{(1)}\). Depending on the heating power required and the availability of electrical energy, EHC heating could be supplemented by other heating measures, such as late PoI. Here, the EHC could be used to initiate component heating, with subsequent fuel injection being employed once sufficient component temperatures have been reached.

4. EHC heat control Strategy requirements

The functionality and requirements of a thermal management system consisting of an EHC and late PoI may be summarised as follows:

- Heating is required first and foremost in cold start phases and during long periods at low load (e.g. city driving) as well as in periods of deceleration to prevent catalyst light-out.
- The EHC can be applied to quickly increase the exhaust gas temperature, directly after engine start up, before the oxidation catalyst is in light-off.
- Once the oxidation catalyst reaches light-off, it is possible to use alternative or additional measures, such as late PoI, to regulate the exhaust gas temperature.
- The use of late PoI has to be calibrated to reduce any subsequent HC-penalty during operation and minimise oil dilution effects on the engine.
- Once the target downstream EAT components such as DOC and SCR have reached the required, stable operating conditions, the EHC and late PoI can be deactivated.
- The realisable EHC heating power is dependent on the available power from the board net at any given time.
- Engine based power supply to the EHC via the generator may lead indirectly to increased engine-out emissions and increased fuel consumption.

A control system which seeks to optimally balance the above listed factors will have to monitor various system parameters in order to decide when and how heating will be applied. These may include exhaust gas temperatures in and around the various EAT components, exhaust gas flow rates and component efficiencies. For example, whilst for a cold start situation the EHC might be the first choice for increasing exhaust gas temperatures, during transition to phases of low load driving, once the DOC has reached light-off, the use of late PoI may be more fuel efficient.

Furthermore, the optimum control strategy is dependent on the EAT layout and vehicle environment in which the EHC is integrated. For example, taking an electrically heated DOC (eDOC) system, different considerations are necessary for an eDOC-cDPF-SCR layout compared with eDOC-SCR/cDPF-SCR, as an SCR/cDPF (DPF with SCR catalytic coating) does not have the same oxidation capability as a cDPF (catalysed DPF), and thus is more sensitive to upstream HC levels.

Therefore an efficient and cost-effective method is required, for evaluating the impact of the complex interactions of the various possible control configurations under diverse operating conditions. Virtual calibration and testing in a full vehicle environment allows the comparison of multiple control options at an early design stage without the need for iterative and costly component testing.

5. Simulation Methodology

5.1. Total system simulation in Velodyn

In order to assess the impact on engine-out as well as tailpipe emissions of various combinations of electric heating with late PoI, it was necessary to simulate the total system by creating a full vehicle model, including both the engine and EAT components. For this study, a Simulink based simulation environment named Velodyne\(^{(7)}\) was selected as the integration platform as it offers the required flexibility of interfaces and the integration of various modelling approaches (Fig. 8). For the EAT component models, the simulation software axisuite\(^{(8,9)}\) was used.

![Fig. 8: Velodyn interface showing the total system simulation model with EHC](image)

5.1.1. System definition and boundaries

The virtual vehicle model was calibrated on a typical D-segment passenger car: A Euro V engine concept, consisting of a turbo-charged 4 cylinder diesel engine with common rail injection system and high pressure EGR. A data-based engine emission model was developed and an EAT layout was chosen as a result of previous simulation and optimisation work\(^{(5)}\). In the proposed layout, an eDOC was selected to quickly deliver the required light-off temperatures for HC conversion and to regulate the exhaust gas temperatures for subsequent emission reduction systems. NO\(_x\) and PM (particulate matter) reduction is achieved by a downstream SCR/cDPF and an active AdBlue dosing system. A second, under-floor SCR catalyst is located further downstream acting as an NH\(_3\) storage buffer, operating at lower exhaust gas temperatures and offering increased NO\(_x\) reduction performance. Copper-zelite based washcoat materials were selected for the two SCR components as they are notable for their high activity at low temperatures, low sensitivity to NO\(_x\) and high ammonia storage capacity.\(^{(9,10)}\) The selected EAT component volumes are typical for current passenger car applications.

5.1.2. System and component modelling

Since the focus of this paper is the virtual optimisation of an eDOC thermal management system, the modelling of the eDOC system and its integration in the full vehicle model will be described. Details of the EAT component, vehicle and engine modelling processes have been described elsewhere and shall not be discussed here\(^{(8,9,10)}\).

For the full vehicle model, a complete EAT system was modelled based on hydrothermally aged (HTA) eDOC, SCR/cDPF and SCR components measured on a synthetic gas test bench\(^{(7)}\). For the engine sub-model, a “hybrid” approach was used as presented in previous work\(^{(10)}\), whereby certain elements such as the air path and engine fluid circuits were modelled physically.
whereas others, such as the emissions and friction losses of the engine, were based on empirical data.

The electrical environment and control logic for the eDOC was integrated into the existing vehicle model. Losses via the cables and generator, as well as battery charge and discharge performance, were simulated and coupled back to the Diesel engine model in the form of increased generator loads. These, in turn, lead to increased engine loads, resulting in higher engine-out exhaust flow temperatures and corresponding emissions.

The temperature increase as a result of electric heating was calculated according to the schematic depicted in Figure 9. A first order low pass filter is used to recreate the delayed transfer of thermal energy to the exhaust gas, observed in the characterisation measurements (see section 3.2).

![Fig. 9: Schematic of the eDOC heating model](image)

The heating effect of the late PoI was accounted for using increased gaseous HC emissions entering the eDOC equivalent to the amount of injected fuel. The resulting exothermic reaction over the eDOC leads to the increased exhaust temperature and is dependent on the calibration of the eDOC kinetic model as well as the assumed HC split of the injected fuel. Figure 10 shows the validation of the combined heating effect of electric heating and late PoI in the heat-up phase of a cold start FTP75.

After integration of the eDOC heating model and basic calibration of the control software, the vehicle model was used to simulate the FTP75 certification cycle with different levels of late PoI and electric heating, in order to assess their impact on tailpipe NO\textsubscript{x} + NMOG levels as well as CO\textsubscript{2} emissions. For the purposes of the optimisation process, it was assumed that the incoming flow of the EAT components is uniformly distributed, therefore 3-D effects are not taken into account in this study.

![Fig. 10: Validation of the combined heating performance of the eDOC and late PoI for FTP75, Phase 1](image)

6. Simulation Results and Discussion

6.1. Basic heating strategy for the fulfilment of SULEV30

The FTP75 certification cycle consists of three phases, including a cold and a warm start phase, representing urban driving with frequent stops. It was selected for the basis of this study as it is characterised by low load driving, with an average speed of 34.1 km/h (21.2 mph), and therefore is also associated with low exhaust gas temperatures.

Using the full vehicle model coupled with the HTA EAT system layout, firstly, a base condition without active heat measures was simulated as a reference for further optimisation. It was calibrated in terms of EGR rates and transmission strategy to give the optimum deNO\textsubscript{x} performance for the investigated system. Whilst appropriate to achieve the ULEV50 targets, these measures are not sufficient for the SULEV30 NO\textsubscript{x} + NMOG target of 30 mg/mile (Figure 11, upper left, dark green circle). Based upon the observed gas temperatures, a target window between \( t = 60-100 \, \text{s} \) after cold start for the achievement of eDOC and SCR/DPF light-off temperatures was defined (Figure 11, right hand side).

As a next step, a combined strategy was assessed using electric heating and late PoI to meet the SULEV30 NO\textsubscript{x} + NMOG targets. Earlier work has shown that the use of only late PoI is insufficient for the investigated system, as it results in unacceptably high tailpipe NMOG emissions, despite lowering NO\textsubscript{x} emissions considerably\(^3\).

For this combined strategy, the electric heating was applied continuously for the first 160 s with a power supply of 2.3 kW. Late PoI with a quantity of 3 mg/stroke was activated between \( t = 40-140 \, \text{s} \) (Fig. 11, right hand side). A further 70 s period of electric heating was employed at the beginning of phase 3 (not shown) to re-boost the temperature upstream of the SCR/DPF after cooling during the engine soak period. This approach was suitable for meeting the SULEV30 targets, although at the expense of higher fuel consumption (Fig. 11, upper left, light green circle).

Finally, a third variation was considered in which only electric heating was active (same level and duration as above, no late PoI). This strategy was also found to be sufficient to meet the SULEV30 targets (Fig. 11, upper left, blue circle).

Comparing the electric heating only with the combined eDOC and PoI strategy, the trade-off between deNO\textsubscript{x} performance and the NMOG emissions associated with additional heating via PoI can be clearly seen (Fig. 11, upper left).
component age, can account for the differences in absolute emissions levels compared to the simulation results.

In terms of CO\textsubscript{2} emissions, it can be seen from Figure 11 (lower left) that for both simulation and measurement, whilst on a 'macro' level all three control strategies display similar weighted levels of CO\textsubscript{2}, on a 'micro' level, exhaust gas heating leads to increased CO\textsubscript{2} emissions due to additional fuel demands. Furthermore, as expected, the simulation results for electrical heating without PoI display a decrease in CO\textsubscript{2} emissions compared to with PoI, due to decreased fuel consumption. This 'micro' trend, however, was difficult to establish from the few measurement points presented here, highlighting the difficulty associated with reproducibility due to the previously mentioned factors such as driver influence and component ageing. Using total system simulation, it was possible to isolate these effects, thus enabling an optimisation on a micro level.

6.2. Virtual optimisation of an eDOC system for CO\textsubscript{2} and component ageing

It can be expected that, if the oxidation catalyst is at optimum operating conditions, late PoI is more fuel efficient than electric heating dependent on engine based power supply. This is because the electric heating exhibits losses at various stages of the supply chain, including in the engine, generator, through cables and also due to initial catalyst surface heating. Therefore, it should be possible to reduce fuel consumption and, thus, CO\textsubscript{2} emissions by partially substituting electric heating with late PoI. Thus, a virtual study into the micro optimisation of tailpipe CO\textsubscript{2} emissions by variation of the thermal management strategy was performed, taking into account the effect on NO\textsubscript{x} + NMOG emissions, with focus on the emissions in phase 1. In order to assess the impact of further ageing on the calibration of the thermal management strategy, an additional severely aged boundary condition was considered by adapting the existing HTA eDOC model.

For the virtual optimisation, the electric heating only strategy was taken as the starting point of the variation, having fulfilled the SULEV30 NO\textsubscript{x} + NMOG targets. As before, the eDOC heats for the first 160 s with a power supply of 2.3 kW, and again after the soak phase for a further 70 s. Between a period of t = 40-110 s, the level of electric heating was stepwise reduced and substituted with a stepwise increase in late PoI up to a maximum of 3 mg/stroke.

From Figure 12, it can be seen that, with increasing substitution of electric heating with late PoI, there is a non-linear reduction in CO\textsubscript{2} emissions for both the HTA and the severely aged eDOC condition, whereby the decrease in indirect fuel consumption via electric heating is increasingly offset by larger amounts of injected fuel burnt over the eDOC. In absolute terms, the differences are small, with a maximum weighted CO\textsubscript{2} reduction of approx. 2 g/mile over the entire FTP75 cycle (Fig. 12, lower left). However, taking into consideration the tailpipe emissions from phase 1 only, the impact is much clearer to see with a maximum of approx. 3.5 % reduction in CO\textsubscript{2} compared with the electric heating only strategy (Fig. 12, lower right).

With regards to NO\textsubscript{x} + NMOG it can be seen that increasing levels of late PoI lead to increasing NMOG emissions. Thus, within the constraints of this simplified heating strategy, a compromise between optimum CO\textsubscript{2} levels and NO\textsubscript{x} + NMOG emissions has to be met.

For the HTA eDOC layout, all of the considered variations stayed within the SULEV30 boundary limits. However, the simulation results for the severely aged eDOC show that, for the variations of 80 % and 100 % late PoI, SULEV30 emissions criteria can no longer be met (Fig. 12, upper left). This is because the severely aged eDOC is no longer able to oxidise the injected fuel with the same efficiency as for the HTA eDOC, resulting in higher HC slip. This demonstrates a particular challenge for the considered EAT layout, as there is no subsequent oxidising component downstream of the eDOC. Therefore, a higher ratio of electric heating to late PoI must be selected, at the expense of slightly increased CO\textsubscript{2} emissions, for the severely aged eDOC condition to remain SULEV30 compliant. The impact of the severely aged eDOC on tailpipe NO\textsubscript{x} emissions is small for the investigated system. However, it should be noted that the influence of further SCR/DPF and SCR component ageing is not considered here.

7. Summary and Conclusions

To meet SULEV30 requirements (NO\textsubscript{x} + NMOG target of 30 mg/mile), EAT system development must focus on periods of low exhaust temperatures, mainly represented by the cold start and restart phases of the FTP75. An attractive thermal management option is an electrically heated catalyst since it is independent of subsequent catalytic activity and beneficial in hybridised Diesel powertrains by using recuperated energy.

For a D-segment vehicle application with a high performance EAT system (eDOC-SCR/DPF-SCR), various thermal management strategies were developed with a total system simulation approach using a full vehicle model in Velodyne.

It was found that a base condition without active heat measures was not sufficient to reach the SULEV30 limits. Therefore, advanced thermal management based on electric heating and late PoI was required in the thermally critical phases. A thermal management strategy with electric heating only was sufficient to meet the SULEV30 limits. An alternative strategy with electric heating and additional PoI also met the requirements but trade-offs between deNO\textsubscript{x} performance and the NMOG emissions, as well as fuel consumption associated with additional heating via PoI, exist. The simulation results were confirmed by experimental findings.

The trade-offs were further investigated using simulation. An optimisation of tailpipe CO\textsubscript{2} emissions was performed by varying the levels of electric heating and late PoI. A 3.5 % reduction in
CO₂ for phase 1 of the FTP75 was achieved by targeted substitution of electric heating with PoI, as late PoI was more fuel efficient. For the HTA eDOC layout, all of the considered variations remained within the SULEV30 boundary limits.

However, for a more severely aged eDOC, variations with higher late PoI ratios breached the SULEV30 emissions criteria, due to an increase in HC slip, as the eDOC was no longer able to efficiently oxidise the injected fuel. Thus it was concluded that different thermal management strategies could be used for optimised emission performance over the system lifetime.

8. Outlook

The total system simulation approach presented here can be used to investigate the various boundary conditions for a given system and to virtually optimise and calibrate the thermal management strategy for a range of target emissions. This process ensures a more robust, efficient and cost-effective technology selection and system calibration. The results presented in this study demonstrate the promising application of electrically heated catalyst technology for the fulfilment of SULEV30 emission limits. The current concept is reliant on a high powered electric supply which lies above current market levels. However, through developments in the board net voltage supply, as well as with the future trend towards diesel hybridisation, these power levels may yet be realisable. Lower powered EHC concepts could be implemented in combination with reduced engine-out NOₓ emissions, e.g. with low pressure EGR, or additional heating measures such as VVT. However, this study has shown that the combination of PoI and electric heating has many benefits with regards to the management of exhaust gas temperatures and fuel consumption, giving flexibility over the lifetime of the vehicle, and enabling significant reductions in tailpipe Diesel emissions.

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