Towards integrated powertrain control: thermal management of NG heated catalyst system

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Towards Integrated Powertrain Control:

Thermal Management of NG Heated Catalyst System

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Abstract — Towards Integrated Powertrain Control: Thermal Management of NG Heated Catalyst System — *The conversion efficiency of catalytic converters is mainly defined by the temperature range wherein they are operating. Traditionally, ignition retard has been used to reduce the light-off time of the catalyst. This is however associated with a fuel penalty. With increasing vehicle electrification, external heating facilities present an alternative, especially for hybrid vehicles. Nevertheless, system complexity of hybrid vehicles prevents engineers to evaluate possible heating technologies with respect to traditional solutions.*

This paper evaluates the application of an electric heated catalyst on a hybrid vehicle equipped with a natural gas (NG) engine. The effect of system sizing on light-off time and fuel penalty is determined, using Integrated Powertrain Control (IPC) analysis techniques. By means of a case study, the IPC concept is explained by comparing the fuel penalty for electric heating with that of ignition retard. In this process, a mix of simulation and test data were combined, forming the foundations for future control developments of a suitable light-off strategy.

INTRODUCTION

With growing concerns about the environment and energy security, the automotive industry faces enormous challenges to find an optimal, cost-efficient balance between driveability and fuel efficiency within the boundaries set by emission legislation, as illustrated in Figure 1, see also [1, 2].

A major driver is the proposed European legislation on CO_2 emissions, along with the future stringent emissions requirements. In order to achieve these requirements in a cost effective and timely manner, TNO is actively researching, together with partners, the potential of Integrated Powertrain Control (IPC).

In this paper, IPC is studied from a thermal management perspective. Since the conversion efficiency of catalytic converters is temperature dependent, fast catalyst heating offers an effective manner to minimize the catalyst light-off time and hence, reduce exhaust emissions from cold start. Various implementations exist for catalyst heating. However, deciding which technology should preferably be used is far from trivial.

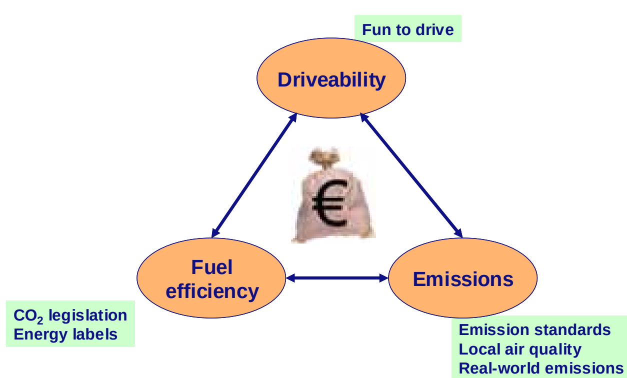

Figure 1: Challenges of automotive industry

This paper will demonstrate how IPC contributes to thermal management by selecting a suitable light-off approach. By means of an illustrative example, two heating methods are analyzed: engine calibration through ignition retard versus the electrically heated catalyst. Both solutions come with an additional fuel penalty and it will be shown how IPC offers an effective tool to make a fuel-efficient trade-off between both heating concepts.

This paper is build up as follows. Section 1 provides a short introduction to IPC and further details the scope of this paper. The impact of a suitable light-off strategy for emission control is explained in Section 2. The case study in Section 3 demonstrates how IPC deals with deciding on the light-off strategy from a fuel consumption perspective. Finally, the conclusions are stated in Section 4.

1 INTEGRATED POWERTRAIN CONTROL

The IPC concept involves a complete approach for analysis, simulation, testing and control. Emission and energy management are seen as integral and connected aspects of the vehicle powertrain system. Optimisation is performed across sub-system boundaries within vehicle functions. Whereas energy management minimizes the primary energy usage of the vehicle, emission management optimizes the exhaust gas emissions. Thermal management encompasses the thermal aspect of energy management, including exhaust and coolant enthalpies. Consequently, thermal management relates to energy management in view of reducing fuel consumption, but it also relates to emission management for reducing exhaust gas emissions. It is clear that all these optimization tasks cannot be solved independently. Moreover, a unified framework is needed to deal with all vehicle requirements and simultaneously satisfy constraints on fuel economy, emissions, driveability, reliability, and hardware costs. This is represented graphically in Fig. 2.

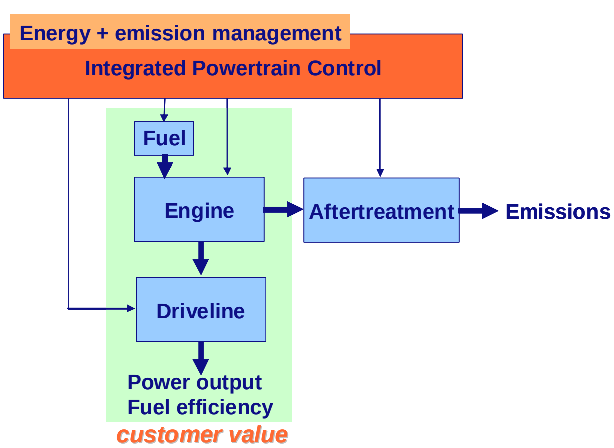

Figure 2: Interaction of IPC with vehicle powertrain

Hybrid powertrains provide additional freedom for optimisation of energy flows in the vehicle through the possibility of recovering and buffering large amounts of energy. While this functionality is often used for reducing fuel consumption and increasing vehicle performance, it may also be applied to reducing emissions. However, the emissions-fuel consumption trade-off of such techniques need to be compared with conventional measures to identify potential performance improvements and the suitability of such techniques for future CO_2 and emissions requirements.

2 EMISSION CONTROL

Generally speaking, the raw engine-out emissions for a stoichoimetric Otto engine are relatively high. In order to achieve low levels of emissions as demanded by stringent emission legislation, a Three Way Catalyst (TWC) is generally applied, which proves particularly effective with appropriate engine mixture control.

2.1 Light-off Temperature

The conversion efficiency of a TWC heavily depends on the temperature of the catalyst. At ambient temperature (e.g. after cold start), the catalyst activity is low leading to a high level of slip. To achieve a good conversion efficiency, the catalyst temperature needs to be above light-off temperature, i.e. the point where the catalyst reaches 50% conversion efficiency. In this work, the focus is on natural gas (NG) engines with emphasis on total hydrocarbon (THC) light-off temperature, typically around 300^{o}C. Above this temperature, the catalyst shows high conversion efficiency, leading to an extremely low level of additional tail-pipe out emissions. Absolute emissions depend largely on the time t_L [s] to reach this light-off temperature. Figure 3 shows a typical light-off profile for an NG TWC, measured at a constant engine operating point with λ=1.02 fixed.

A stock catalytic converter has a light-off period in the order of 1-2 minutes [3] and especially the THC conversion efficiency remains low during the heating phase. By means of a suitable light-off strategy, the light-off period can be reduced and consequently emissions will reduce. The conversion of CH_4 is significantly lower compared with that for HC and CO, which requires special attention for NG engines.

Additionally, the cold start phase of engine operation has a significant influence on fuel consumption, typically 10-15% [4] on the standard European drive cycle. This implies that special attention for the light-off strategy is an important factor for containing fuel consumption low while achieving further emissions reductions. Conversely, a dedicated light-off strategy can also be used to keep tail-pipe emissions fixed whereas the catalyst volume (and cost) decreases. IPC will be a necessity to develop a strategy which includes all these requirements simultaneously.

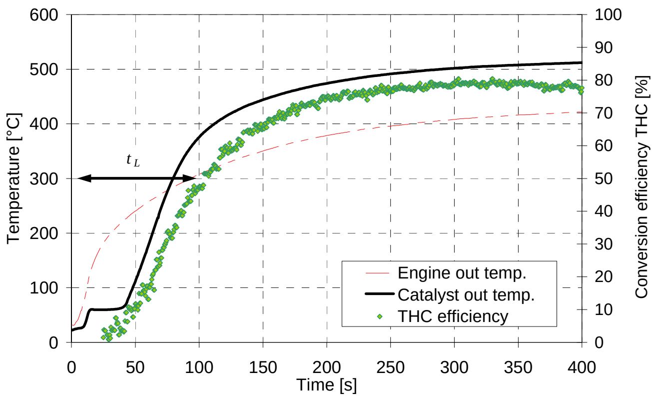

Figure 3: Typical light-off profile of a TWC at λ=1.02

2.2 Light-off Strategy

The goal of the light-off strategy is to reduce light-off time while minimizing emissions and fuel consumption. Offering additional heat to the TWC brings the catalyst faster to its light-off temperature and less tail-pipe emissions are produced for THC, NOx and CO. After reaching light-off temperature, the net emission reduction can be approximated by considering the average massflow before and after light-off time t_L. Suppose the average mass flow of emission x∈{THC, NOx, CO} during the light-off period is given by $\dot{m}^x{}_{pre\_L}$ [g/s]. Similarly, the average mass flow after light-off period is denoted by $\dot{m}^x{}_{post\_L}$ [g/s]. With an improved light-off strategy, the catalyst reaches its light-off temperature at $t_{LH} < t_L$ [s] and the emission reduction is approximately equal to (see also Fig. 4):

$$m^x{}_H \approx (\dot{m}^x{}_{post\_L} - \dot{m}^x{}_{pre\_L})(t_L - t_{LH}) \ \text{[g]} \qquad (1)$$

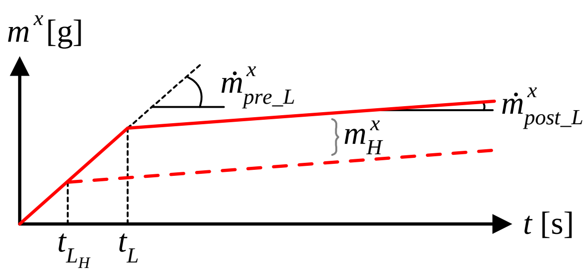

Figure 4: Emission reduction with reduced light-off time

To achieve this reduction in light-off time, a multitude of measures are possible, including:

- Insulation of exhaust, e.g. double-walled tubing,
- Close coupled catalyst,
- Exhaust gas temperature control
- Electrical heating.

Exhaust temperature control is commonly performed by ignition retard combined with close coupled catalysts. By retarding the ignition, exhaust temperature is increased which leads to faster heat transfer to the catalyst, reducing light-off time. This method has been shown to be highly effective [5]. One disadvantage is the increase in fuel consumption that results due to lower engine efficiency.

An alternative for ignition retard to increase the exhaust gas temperature is electrical heating of the catalyst. Heating methods fall apart into two categories:

- Direct heating, where the catalyst substrate is used as a heating element.
- Indirect heating, where the heating element is placed upstream of the catalyst. Exhaust gases are heated, leading to indirect heating of the catalyst.

A hybrid electric vehicle offers various mechanisms to supply the electric energy needed for catalyst heating:

- Directly by the electric generator in the powertrain.
- From the battery, using regenerative braking energy.
- From the battery, using energy that is recharged by the generator.

Nevertheless, all these charging methods lead to fuel penalties compared to a hybrid powertrain without EHC, as regenerative energy used by the EHC cannot be used for other fuel-saving functions from a hybrid vehicle (e.g. boost functionality).

In order to evaluate the effectiveness of catalyst heating by means of ignition retard as well as EHC, TNO has developed IPC-tools to quantify the fuel penalty regarding both heating methods. This will be illustrated by a case study in the next section.

3 CASE STUDY

The focus of this study is on comparing engine ignition retard with electric catalyst heating from an IPC perspective for an NG stoichiometric Otto engine in a hybrid vehicle application.

Measurements with an NG engine and a TWC are used to obtain insight into the heating behavior of the catalyst. These measurements included the effect of adjusting the ignition retard. For investigations into the effect of the EHC, simulations were used. The catalyst was simulated using TNO's catalyst model, SimCat [6]. Exhaust data from the measurements were used to fit this catalyst model. SimCat entails a physical model description of the catalyst where consecutive segments split up the catalyst in axial direction. Each segment includes a temperature model and a conversion efficiency model.

The temperature model is based on energy balances for the gas and solid phase. The efficiency model calculates the catalyst activity in terms of HC, CO and NOx emissions. The temperature model and the efficiency model are interconnected according to Fig. 5.

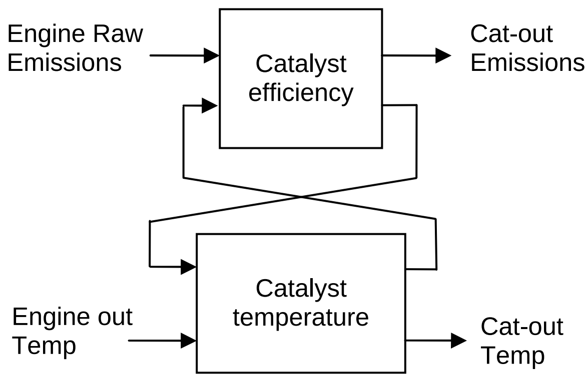

Figure 5: Simcat TWC model overview

3.1 Ignition Retard

To investigate the trade-off between fuel consumption and light-off time for ignition retard, tests were performed on a 5 cylinder, 2.3L NG MPFI engine running on Dutch NG. The engine workpoint was kept constant at 2 [bar] BMEP, 2000 [rpm] and λ=1.02. Exhaust gas temperature, catalyst temperature and fuel consumption were measured at the retard values ϕ [degrees of crankshaft angle (CA)] shown in Table 1. Retard was set as an offset relative to the standard ignition advance of 25 degrees before top dead centre (BTDC), in order to take into account the default engine calibration during warming up process. The measured engine out temperatures are shown in Fig. 6.

Test	Ignition retard [re 25°CA BTDC]
1	0
2	11
3	22
4	28

Table 1: Ignition retard measurements

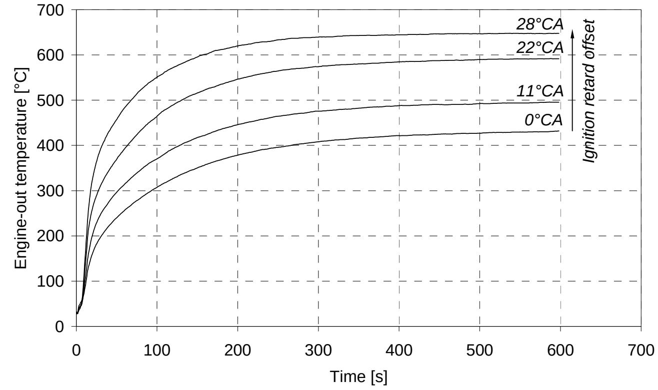

Figure 6: Temperature increases with ignition retard

As indicated in Fig. 7, ignition retard has a significant effect on the light-off time. However, a significant increase in fuel consumption was also observed, up to 50% (see Fig. 8).

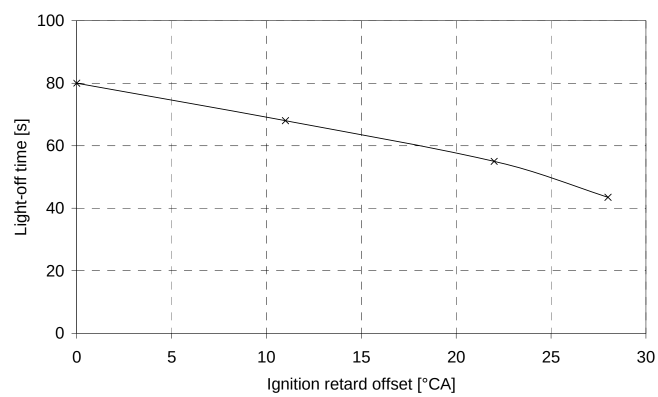

Figure 7: Light-off time reduction with ignition retard

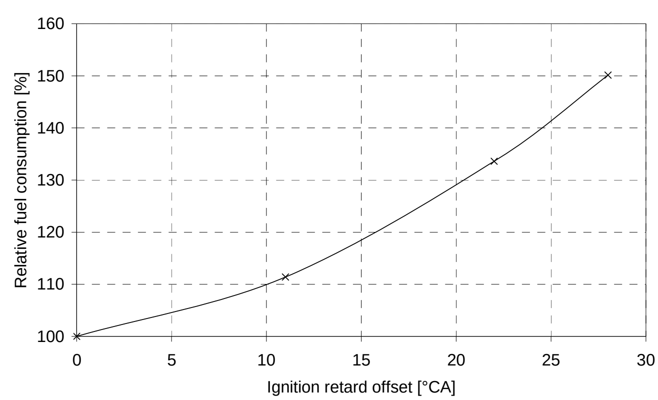

Figure 8: Measured fuel penalty for ignition retard

According to the measured fuel massflow $\dot{m}$ [g/s], the additional fuel penalty from ignition retard can be characterized by the following formula:

$$\psi = \dot{m}(\phi) - \dot{m}(\phi = 0) \quad \text{[g/s]} \tag{2}$$

By assuming that ignition retard is only active during light-off period, the additional fuel penalty can be approximated by:

$$F_R(\phi) \approx \int_0^{t_L(\phi)} \psi(\phi)dt \quad \text{[g]} \tag{3}$$

This fuel penalty $F_R(\phi)$ is shown in Fig. 9. In the next section, a similar figure will be drawn for EHC. All this information enables IPC to make a fair comparison between the fuel penalty from both heating mechanisms.

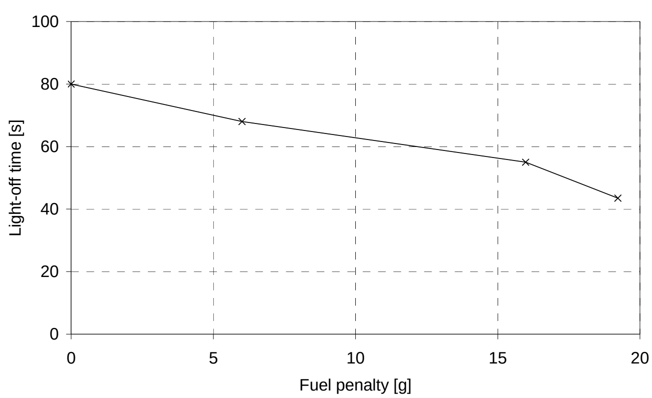

Figure 9: Fuel penalty F_R from ignition retard

3.2 Electrically Heated Catalyst

To evaluate the potential of the EHC, the catalyst was simulated using SimCat. This catalyst model includes energy balances for the gas phase as well as the solid catalyst bed (substrate with washcoat). This allows for simulations with both direct as well as indirect heating. Nevertheless, this paper presents only results using direct heating. More specifically, the electric heating is only applied to the first segment of the Simcat model. This is a cost effective solution where relative few heating power is required to reach light-off temperature. Since only a small mass volume is heated, the catalyst reaches light-off temperature very quickly and this enables fast startup of exothermal reactions (mainly from HC oxidation) to assist with heating up the remainder of the catalyst, see also [7]. Note that the catalyst model includes energy balances for both the gaseous phase and the solid phase. These energy balances describe the heat transfer from convection, conduction and reaction heat, whereas thermal energy from electric heating emerges in the solid phase.

The light-off time as a function of electrical power is shown in Fig. 10. At relatively modest powers (considering hybrid vehicle applications), a light-off time similar to that for ignition retard appears. Below approximately 35 seconds, significant increases in power are required for little gain. This would be the case for an engine which already uses other measures to make significant improvements to the light-off strategy (‘add-on EHC’ application). Care would be required to maintain driveability under these conditions due to availability of electrical power for e.g. boost functions.

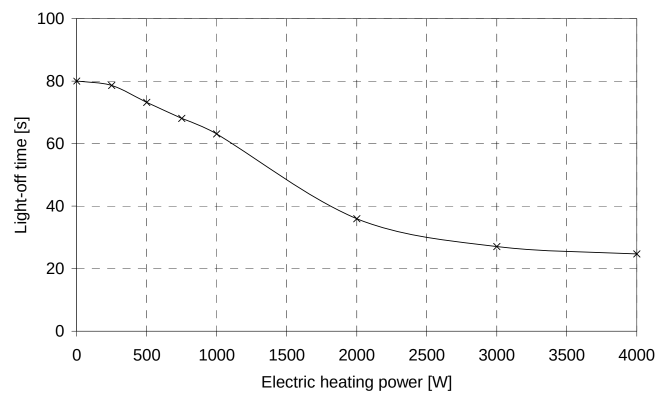

Figure 10: Light-off time reduction with EHC

Similar to the situation with ignition retard, the light-off data is translated into a fuel penalty diagram. The method for this is briefly summarized in Fig. 11 and is explained below.

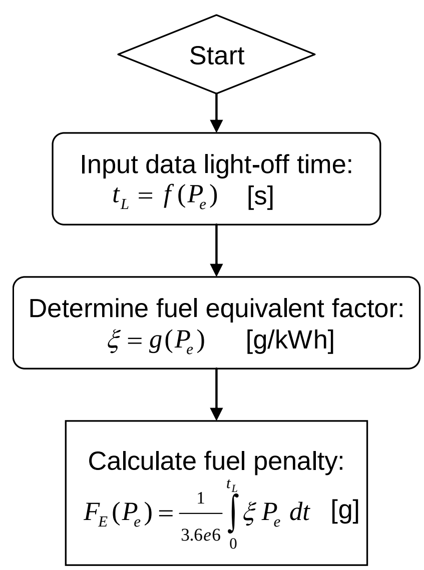

Figure 11: Calculation steps for EHC light-off data

After obtaining the light-off input data from Fig. 10, the fuel equivalent factor ξ needs to be estimated. This equivalence factor describes the additional fuel consumption of the combustion engine when it supplies power to the electric machine to recharge the battery for electric power P_e [W] taken by the EHC. The assumptions made necessary about the conversion efficiency from fuel to electric power are shown in Fig. 12. For this case study, the efficiency parameters have been selected according to the values indicated in Table 2. Similar approaches introducing a fuel equivalent factor have been presented in for example [8,9].

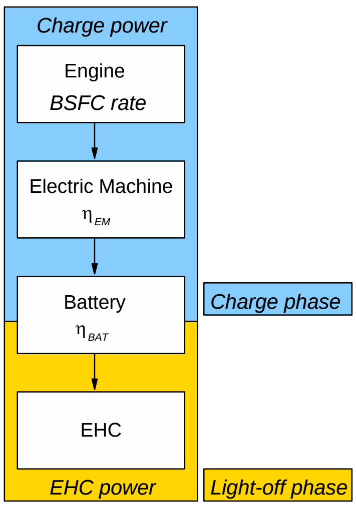

Figure 12: Energy path for the EHC function

The electric power request during the light-off period is translated into a momentary fuel cost using the fuel equivalent factor ξ. By integrating these fuel costs during light-off time the actual fuel penalty F_E emerges. According to the data shown in Fig. 9 and Table 2, the resulting fuel penalty is visualized in Fig. 13.

Component	Value
Battery efficiency η_{bat}	96%
Electric machine efficiency η_{EM}	80%
Engine BSFC rate[1]	202 g/kWh

Table 2: Selected component efficiency

[1] Defined as the change in fuel consumption [g/h] for a change in engine workpoint [kW], at constant engine speed, see also [8].

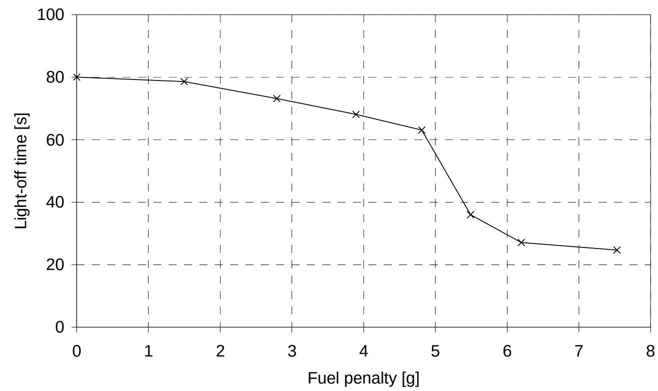

Figure 13: Estimated fuel penalty for EHC

According to the applied method, it follows that all energy available from regenerative braking will be used for hybrid vehicle operation and not for EHC. If energy comes available from regenerative braking, the equivalence factor ξ requires an update and hence, the curve in Fig. 13 looks different.

3.3 Comparison

By analyzing the results from Fig. 9 and Fig. 13, the IPC concept offers a systematic tool to compare the impact of ignition retard as well as EHC on fuel economy.

It may be concluded that:

- Ignition retard provides a significant reduction in light-off time, but also leads to an increase in instantaneous fuel consumption of up to 50%. This is equivalent to 17 [g] fuel consumption penalty for 30 [s] reduction in light-off time.
- Electrical heating is also an effective measure for reducing light-off time. In this case study, the fuel penalty is lower than for ignition retard. For a light-off time reduction of 30 [s], a fuel penalty of approximately 5 [g] is indicated requesting a heating power of 1.5 [kW]. Compared to the fuel penalty from ignition retard this is a reduction of 70%.
- Fast light-off with low penalty is possible with the EHC due to high catalyst activity just after cold start, in the presence of HC engine-out emissions, leading to exothermic HC conversion. This additional heating effect helps to reduce heating power requirements.
- Electrical heating is effective at lower power levels, while increasing the heating power at higher levels provides negligible benefits. The advantage of an add-on EHC in light-off time is significantly reduced for a given power level if the engine already has excellent light-off characteristics. Note that if the light-off time is already short (e.g. retard is applied), high power is required to achieve small gains. This conclusion is supported by other results [10].

- The attractiveness of EHC will be strongly dependent on the system costs compared with the benefit for given applications.

Finally, also a comparison with emission reduction as presented in Section 2 needs to be done such that IPC not only decides on thermal management, but also includes emission management and possibly also includes energy management. This is a topic for further research.

4 CONCLUSIONS

Due to increasing environmental requirements placed on modern road vehicles, it becomes ever more important to balance the requirements for efficiency, emissions and costs. This leads to ever increasing system complexity, new analysis techniques and better system control. In order to address this challenge, TNO is developing an approach under the framework of Integrated Powertrain Control.

For stoichiometric Otto engines, light-off time is critical for low emissions, but reducing light-off time is associated with a fuel penalty. The fuel consumption impact of two techniques for reducing the light-off time of a TWC for a hybrid vehicle with an NG engine were studied and compared, using a mix of test and simulation: ignition retard and electrical heating.

Further work will be focused on validating the presented results under drive cycle conditions. Furthermore, refinements of the tools and technology are required for TNO's Integrated Powertrain Control approach in order to further benefit from synergy between thermal-, emission- and energy management.

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