Towards Integrated Powertrain Control: exploiting synergy between a diesel hybrid and aftertreatment system in a distribution truck

Darren Foster, Robert Cloudt and Frank Willems

Abstract—With the increasing demands on driveability, fuel efficiency and emissions, it becomes essential to optimize the overall performance of future powertrains. Therefore, a system approach is required. In this study, the Integrated Powertrain Control concept is presented, which exploits the synergy between engine, driveline and aftertreatment system. To illustrate the benefits of this concept, the combination of a diesel engine, hybrid driveline and DPF system is studied for a distribution truck. Focus is on minimizing the required energy and components for DPF regeneration. For electric DPF heating, electric heating for DOC light off, and idle-stop cases, the impact on fuel consumption and on DPF temperature are determined during DPF regeneration. It is shown that the operating envelop of the DPF can be extended, even to idle.

I. INTRODUCTION

With growing concerns about 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.

![Figure 1: Challenges of automotive industry](image)

Diesel engines are an attractive option due to their relatively high fuel efficiency, good driveability and reliability. To a large degree, future developments of these engines will be driven by legislation. Based on the upcoming Euro-5 and Euro-6 emission legislation, the following trends are foreseen [9, 17]:

- **Further reduction of emission limits** (see Table 1): During the last decade, European emissions targets are drastically reduced. This means that minimization of engine out emissions and maximal emission reduction in the aftertreatment system becomes increasingly important. Special attention should be paid to low temperature operating conditions; emission standards also include limits for combined cold and hot test cycles.

- **Attention moves from test cycles to real world conditions**: besides tests for type approval, future legislation will also include requirements for On-board Diagnostics (OBD) and for in-use compliance. More precisely, emission limits during real-world driving conditions and on performance degradation during useful life will be introduced. As a result, acceptable variations in engine and aftertreatment performance become considerably smaller.

In the near future, also stricter legislation in the field of local air quality (green areas in cities), CO₂ emissions and noise will be introduced.

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<td>80</td>
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<tr>
<td>PM</td>
<td>50</td>
<td>25</td>
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Table 1: Illustration of (proposed) European emission legislation for both heavy-duty (HD) and light-duty (LD) diesel applications.

Diesel engines require additional measures to meet these future emission targets; e.g., NOₓ storage catalysts, urea SCR systems or Diesel Particulate Filter (DPF) systems. Simultaneously, significant CO₂ emission reductions are required. This is driven by the EU proposal for passenger cars (130 g CO₂/km in 2012) and by increasing fuel costs for heavy-duty applications. Especially, for DPF systems there are the following challenges (Figure 2):

- **Reliable DPF regeneration control to avoid damage of the filter**: the filter can be (locally) damaged during regeneration due to high temperature levels or high
temperature gradients. To avoid this, the soot load of the DPF is limited and sophisticated regeneration strategies are developed. For more details, see e.g. [2, 3].

- **DPF regeneration during all driving conditions;** this often requires additional measures, such as a throttle or a vaporizer, to realize the desired pre-DPF temperature.
- **Reduced fuel consumption associated with DPF regeneration;** the total fuel consumption penalty is the combination of:
  1) **Additional fuel consumption due to increased engine back pressure;** DPF flow resistance increases with increased soot load. This soot load is mainly determined by the DPF flow resistance, DPF filtration efficiency and engine out soot emission;
  2) **Additional fuel consumption related to measures to increase the pre-DPF temperature for DPF regeneration.** This is mainly determined by the operating conditions (exhaust flow and temperature).

The main objective is to find the regeneration frequency that minimizes the trade off between these effects [10]. More information on DPF systems and other aftertreatment systems can be found in [4].

To meet future requirements, it will become increasingly important to optimize the performance of the entire powertrain system: **Integrated Powertrain Control.** In this paper, the potential benefits of exploiting the interaction between a diesel engine, hybrid driveline and DPF system in a distribution truck are studied. As a first step, this is an interesting application; its typical use allows frequent energy recovery using regenerative braking energy. However, its low-load duty cycle makes it a challenging application for DPF systems, since exhaust temperatures will be relatively low. Furthermore, these distribution trucks require zero noise and emission driving in specific areas in the near future.

**Figure 2:** Illustration of challenges for Diesel Particulate Filters.

This paper is organized as follows. First, the Integrated Powertrain Control concept is discussed and several examples of this approach are given. Then, the studied system and possible benefits of diesel hybrids are discussed in Section III. In Section IV, the results for the specified cases are presented and discussed. Finally, conclusions are drawn and directions for future research are suggested.

**II. INTEGRATED POWERTRAIN CONTROL**

Current control systems in powertrains often concentrate on optimizing the performance of a subsystem; e.g. fuelling or EGR control for the engine, urea dosing for the SCR system [18]. However, with the more and more stringent requirements on pollutants, CO₂ emission and drivability, it becomes increasingly important to optimize the performance of the **entire** powertrain: Integrated Powertrain Control (IPC). Due to the increased complexity of powertrains, this is not straightforward.

As illustrated in Figure 3, the powertrain performance can be expressed in terms of the desired output, fuel efficiency and emissions. Consequently, the ultimate goal is to combine both energy and emission management in the IPC concept. Before this is realized, first developments are foreseen in both areas. Energy management will develop from separate control of the driveline, auxiliaries, and advanced cooling systems into a total energy management concept that covers all forms of energy flow (thermal, mechanical, electrical, etc). In parallel, emission management will evolve to a level that engine and aftertreatment systems are fine tuned at any instant; in that case, the engine generates the desired exhaust flow conditions (flow, temperature and emission levels) that lead to minimal tailpipe emissions. This will also make the powertrain more robust for variations during real life applications; e.g. ambient conditions and changed performance of components.

**Figure 3:** Illustration of Integrated Powertrain Control concept.

In summary, the main goals of the IPC concept are:

1) **Deal simultaneously with emission, fuel efficiency and drivability requirements;** use of synergy between subsystems to optimise total powertrain performance;
2) **Reduced development and calibration time through cost-efficient optimization of complex systems;**
3) **Increased robustness for system variations and disturbances.**

It is expected that concepts as supervisory control, model-based control and model-predictive control will play an important role in IPC systems.
Up to now, there are only a few examples in which the synergy between subsystems is exploited to enhance the overall system performance. In a hybrid driveline, the storage and usage of regenerative energy is controlled to generate the desired power output. Examples are known wherein the hybrid driveline is used to accelerate heat up of the three way catalyst to improve cold start performance and optimise combined engine/transmission efficiency [7]. Furthermore, diesel applications are known in which the temperature of the aftertreatment system is controlled by post-injection events or by a throttle in the engine. Combined diesel and hybrid for emissions reduction have been shown to half Euro 4 levels in passenger cars [19]. In this paper, the potential of an application is analysed, in which energy and emission management is combined. A detailed system description is given in the following section.

III. SYSTEM DESCRIPTION

In this work, a city distribution truck is studied in which a 4 l diesel engine and a parallel hybrid system are installed.

A. Potential benefits of diesel hybrids

Currently, hybrid drivelines are applied to reduce the fuel consumption of petrol engines. Interest is increasing in the application of hybrid technology to diesel engines, with increasing production and product announcements [5, 6]. Hybrid drivelines have also been applied to improve petrol engine emissions [7]. Diesels can also benefit from hybridization through:
1) Elimination of engine idle;
2) Reduced power demand through regenerative braking;
3) Reduction of emissions by reducing dynamics and optimizing the aftertreatment environment;
4) Shifting the engine working point can also lead to reduction of both fuel consumption and emissions for particular applications.

B. DPF system

To meet stringent upcoming emission standards, hybrid distribution trucks are equipped with a Diesel Particulate Filter (DPF). A scheme of the studied system is given in Figure 4. To oxidize the soot that is trapped in the filter (so-called DPF regeneration), diesel (‘HC’) is injected and vaporised upstream of the DPF system. Oxidation of the injected diesel in an oxidation catalyst (DOC) leads to the heat up of the exhaust flow and of the DPF.

Alternatively, engine-based measures, such as throttling and post injection can be used for DPF regeneration. Depending on the details of the application, regeneration measures can have the following disadvantages:
- Increased fuel consumption due to DPF regeneration;
- Regeneration possible only under restricted conditions;
- Additional components required;
- Possible side effects such as oil dilution (in the case of post-injection).

Figure 4: Scheme of studied hybrid distribution truck application.

C. Considered cases

In this study, the focus is on the capability of hybrid functionality to improve DPF regeneration by using electric heating while avoiding the above shortcomings. Three strategies to increase DPF temperature for PM regeneration were evaluated:

A. Electric DPF heating using energy from regenerative braking; HC injection is avoided by exclusive use of electrical heating of the DPF. For given levels of regenerative braking (which are vehicle and drive pattern dependent), the operating conditions under which this approach is feasible is determined along with the impact on component dimensioning. Note that this approach can have a significant effect on the behaviour and fuel saving capability of the hybrid driveline. For a description of various electrically heated applications, see [11]-[14].

B. Electric DOC heating to ensure HC oxidation under all driving conditions; regenerative braking energy is used for electric heating of the DOC only. HC is injected for DPF heating as in the baseline strategy. While this approach does not avoid HC injection, it allows HC oxidation under an extended range of conditions, also when the DOC would normally be under light-off temperature due to cold start or low exhaust temperature without the need for throttling.

C. Effect of idle-stop; during idle operation, the exhaust flow can cool down the DPF, which would increase the energy required for regeneration. By switching off the engine during idling, the DPF retains temperature prior to a regeneration event. This effect needs to be investigated.

The advantages and disadvantages of each case are summarised in Table 2.

Note that all techniques described are not exclusive to hybrid vehicles; conventional vehicles with appropriate functionality can also implement the above measures, albeit with restricted capabilities. The main differences are due to installed electric power and charge acceptance of the battery.
D. Approach

To investigate the potential and limitations of the proposed hybrid-assisted DPF regeneration strategies, simulations are performed with an exhaust line model comprising an 11.5 litre DOC/DPF combination. The DOC and DPF models are taken from the TNO SimCat library. This library also contains models of SCR catalysts, NH\textsubscript{3} oxidation catalysts, and urea decomposition in the exhaust pipe. Due to the modular approach, various configurations of aftertreatment systems can be studied. The one-dimensional models are based on first principle modelling, including mass and energy balances. For more information on the DPF system model, see [8].

The DPF model is mainly based on [15] and [16] and has the following features:
- Prediction of filtered soot mass in DPF;
- Prediction effect of filtered soot mass on $\Delta p$ over DPF;
- Soot oxidation via passive (with NO\textsubscript{2}) and active (with $O_2$) soot regeneration;
- Impact of soot oxidation on local filter temperature.

Diesel fuel injected upstream of the DOC is assumed to completely oxidize in the DOC. The exhaust gas temperature and flow are read from engine maps. The appropriate engine operating point is determined from the vehicle traction diagram. Regenerative braking energy was determined using TNO’s Hybrid Toolkit.

Table 2: Overview of considered cases.

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<thead>
<tr>
<th>Case</th>
<th>Comments</th>
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<tr>
<td>A</td>
<td><strong>Advantages</strong>&lt;br&gt;+ Low regeneration based fuel consumption&lt;br&gt;+ Eliminates vaporizer, throttle&lt;br&gt;+ Regeneration range extended&lt;br&gt;<strong>Disadvantages</strong>&lt;br&gt;- High power requirements on hybrid system&lt;br&gt;- Possible conflict with existing hybrid functions&lt;br&gt;- High power rating for heater</td>
</tr>
<tr>
<td>B</td>
<td><strong>Advantages</strong>&lt;br&gt;+ Reduction in regeneration based fuel consumption&lt;br&gt;+ Eliminates throttle&lt;br&gt;+ Regeneration possible under all conditions&lt;br&gt;+ Lower level of conflict with hybrid system&lt;br&gt;<strong>Disadvantages</strong>&lt;br&gt;- Medium power rating for heater&lt;br&gt;- Regeneration specific componentry still required</td>
</tr>
<tr>
<td>C</td>
<td><strong>Advantages</strong>&lt;br&gt;+ Higher DPF temperature at start of regeneration reduces regeneration energy requirement.&lt;br&gt;<strong>Disadvantages</strong>&lt;br&gt;- Heat-up of DPF is slower when DPF temperature is lower than exhaust temperature.</td>
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IV. RESULTS AND DISCUSSION

A. Electric DPF heating

To study the feasibility of full electric DPF regeneration, the steady-state DPF temperature was simulated for several constant vehicle speeds (Figure 5). The DPF is assumed to be equipped with an integrated electrical heating element that heats up the DPF substrate uniformly.

![Figure 5: Steady-state DPF temperature for several stationary operating conditions as function of the electrical power supplied to the DPF (25 °C ambient, no HC injection).](image)

The accomplished stationary DPF temperature is dependent on the ambient temperature, supplied electrical power, exhaust flow and exhaust temperature. Table 3 gives an overview of the simulated vehicle operation modes, exhaust gas flow and temperatures. The accomplished DPF temperatures are adversely affected by low exhaust gas temperature and high exhaust gas flow. For the simulated modes, 50 km/h in 4\textsuperscript{th} gear is worst-case. Efficient convection causes much heat removal from the DPF brick.

Table 3: Simulated vehicle operation modes.

<table>
<thead>
<tr>
<th>Vehicle Speed (km/h)</th>
<th>Gear</th>
<th>Exhaust Flow (kg/h)</th>
<th>Pre-DOC Temperature (°C)</th>
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<tr>
<td>80</td>
<td>6\textsuperscript{th}</td>
<td>264</td>
<td>367</td>
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<tr>
<td>Idle</td>
<td>Neutral</td>
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</table>

During a typical regeneration, the DPF temperature is controlled at 600 °C for a period of several minutes [2]. If this temperature is taken as a threshold, the results in Figure 5 imply that at least 18 kW of electrical heating power is necessary for full electric, operating point independent DPF regeneration. This demand for electrical power is well within the limits of the hybrid system, but may interfere with hybrid functions requiring high power level (e.g. boost). These power levels are too high for a conventional vehicle electrical system.

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Figure 6 shows the simulated additional fuel consumption penalty associated with DPF regeneration using a vaporizer at constant vehicle speed. This is done for different regenerative braking energy levels. Typical regenerative braking levels of 50 Wh/km lowers the fuel penalty by 18%. Alternatively, the DPF lower regeneration limit is reduced by 5 km/h from 80 km/h to 75 km/h for a fixed fuel consumption penalty.

The penalty at 250Wh/km reaches almost zero for typical real-world work points. 250 Wh regenerative brake energy is approximately equivalent to a single braking action from 80 to 0 km/h for this application. This requires 150 kW of installed electrical power (rating of electric machine and battery). Dynamic driving behaviour would require a boost power restriction in order to maintain the energy balance, leading to reduced drivability. Additionally, at this rate of battery throughput, battery life would be expected to suffer significantly, as more than 80k cycles (100% depth of discharge) would be required during vehicle life. However, an adaptive boost strategy may prove useful to maintain full performance while reducing throughput.

![Figure 6: Fuel penalty during DPF regeneration as function of vehicle speed and regenerative braking energy.](image)

Cooling of the DPF between constant speed driving periods should also be avoided to help minimize energy requirements. The idle-stop strategy may assist in this regard.

### B. Electric heating for DOC light-off

The second use of electrical energy in the aftertreatment system is the use of an electrical heater at DOC entrance, in order to ensure DOC light-off under all conditions. The DOC light-off temperature is typically about 200 °C.

During continuous engine operation the DOC will be continuously above light-off temperature. Situations in which electrical heating is advantageous are cold start situations and periods of uninterrupted idling.

Simulations have shown that a heater of 1.9 kW in front of the DOC is able to maintain the DOC at light-off temperature (at 25 °C ambient). With the DOC at 200 °C, 0.71 L/h diesel needs to be injected to reach a stationary DPF temperature of 600 °C at idle. When more electric power is available, it can be used to heat up the DPF substrate. Further electric heating of the DOC above 200 °C is not efficient as the HC oxidation maintains temperature in the oxidation catalyst.

Figure 7 shows a trade-off between the electrical power and HC injection quantity. The trade-off is based on reaching a steady-state DPF regeneration temperature of 600 °C at idle.

A 1.9 kW heater seems feasible from a power consumption point of view. However, a higher rated heater is desirable when cold climate is encountered, and for quicker DOC heat-up during cold-start conditions. When the heater power stays well below 3 kW, it can also be applied on a conventional vehicle; the advantage of electrical heating is not restricted to a hybrid vehicle in that case. On a conventional vehicle, electrical exhaust heating will compete with a throttle valve as a means of increasing the exhaust gas temperature, both from a fuel consumption and cost perspective.

### C. Effect of idle-stop

A hybrid control strategy will apply idle-stop to save fuel and reduce emissions. Idle-stop has potential benefit for DOC/DPF temperature, as the cooling idle exhaust flow from the engine is omitted in case the DOC and DPF are at temperature.

![Figure 7: DPF regeneration trade-off for steady-state idle (T_{amb} = 25 °C, DOC light-off requires 1.9 kW).](image)

Figure 7 shows a trade-off between the electrical power and HC injection quantity. The trade-off is based on reaching a steady-state DPF regeneration temperature of 600 °C at idle.

Figure 8 demonstrates the effect of idle-stop on the post- DPF temperature during a dynamic US FTP heavy-duty test.
cycle. The hot FTP cycle is preceded by a cold start FTP cycle and a 20 min. hot soak. The FTP test cycle is simulated since it contains considerable periods of idling.

The idle-stop strategy tends to prevent cool down in situations where the conventional strategy lets the engine idle. The effect is most significant after a period in which the temperature has reached its maximum (after the freewheel phases in the FTP test cycle). In general, the course of the DPF temperature is smoother in case of idle-stop. This helps in performing a well controlled DPF regeneration.

In situations where the catalyst and DPF temperature are below the exhaust gas temperature (e.g. at cold start), it is recommended to not use idle-stop functionality and let the engine idle to heat up the substrates. Information on the catalyst and DPF temperature should be integrated with powertrain control.

V. CONCLUSIONS AND FUTURE RESEARCH

Due to ever increasing requirements on fuel efficiency, emissions and drivability, the complexity of powertrains is expected to increase further in the future. In order to deal with this complexity level, integrated powertrain control is needed to ensure system robustness and reduce the required development resources.

Integrated powertrain control also allows synergistic optimization between powertrain sub-systems to meet future performance requirements. The potential of synergy between a diesel engine, hybrid driveline and DPF aftertreatment has been examined. For this application, three cases have been examined to determine the effects on a heavy-duty hybrid distribution vehicle:

1. By using regenerative braking energy for electric DPF heating, the fuel penalty associated with DPF regeneration can be completely avoided when using an 18 kW heater. However, this would lead to excessive battery throughput. Under realistic driving conditions, this fuel penalty can be reduced by 18%.

2. By electric heating of the DOC only, the DPF regeneration range can be extended down to engine idle without other additional measures. An electrical power of 1.9kW suffices, which is also within the capability of conventional vehicles.

3. An idle-stop strategy prevents cool-down of a hot DPF, especially after high load driving. Improvements of up to 50°C have been shown. This can be advantageous to reduce the energy required for regeneration and reduce thermal cycling.

Further research is recommended into the effects of the presented strategies on other hybrid functions, along with demonstration of the combined effectiveness on actual driving cycles. Other strategies representing even tighter integration between powertrain systems should also be evaluated for potential. For Integrated Powertrain Control, research will concentrate on the development of total energy concepts and advanced emission management for diesel engines with both an SCR and DPF system for emission control and CO\textsubscript{2} reduction. For this application, hybrid-assisted thermal management is of special interest.

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REFERENCES