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Hybrid-assisted DPF Regeneration in Distribution Trucks

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Abstract

TNO Automotive is developing an Integrated Powertrain Control (IPC) concept for powertrain controls that focuses on integration of the engine, aftertreatment and parallel hybrid electric system. One of the first steps is the focus on hybrid assisted Diesel Particulate Filter (DPF) regeneration. For inner-city distribution trucks the legislation on particulate matter is becoming more stringent. This means that diesel particulate filters will be increasingly applied to inner-city distribution trucks. The fact that these trucks often operate at idle- and part-load poses a great challenge to the successful regeneration of the DPF. Based on a simulation study, the capability of hybrid-assisted DPF regeneration is shown, along with the additional requirements placed on the hybrid components.

Keywords: catalyst, emissions, HEV, truck

1 Introduction

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

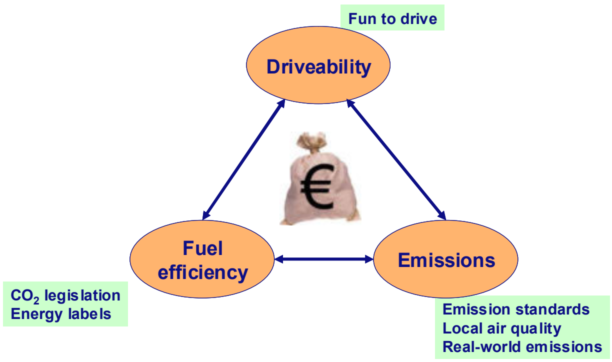

Figure 1: Illustration of the powertrain optimization problem

Diesel engines are an attractive option due to their relatively high fuel efficiency, good drivability and reliability. To a large degree, future developments of these engines will be driven by legislation. Based on the upcoming emission legislation, the following trends are foreseen [1, 2, 3, 4]:

- ***Further reduction of emission limits towards near zero impact levels (see Table 1)***: *e.g.*, compared to the current NO_x Euro-V emission standard, an additional NO_x reduction of 80% has to be realized to meet Euro-VI targets, next to a 50% reduction in PM. A similar reduction is required in the US. This requires the application of complex and expensive engine or aftertreatment measures;
- ***Cold start to be introduced in Europe*** for the type-approval cycle;
- ***Robustness*** will play an increasing role, especially with the introduction of aftertreatment technologies that need to be regenerated under all conditions and must achieve durability requirements;
- ***Emission limits during real-world driving conditions*** will require improved functioning of the control system, including on-board

Table 1: (Proposed) emission legislation for diesel-powered heavy duty engines.

Emission Step	**Euro-IV (2005)**	**Euro-V (2008)**	**Euro-VI (2012)**	**US 2007**	**US 2010**
Cycle	ETC	ETC	ETC	FTP	FTP
NO_x (g/kWh)	3.5	2	0.4	1.5	0.27
PM (g/kWh)	0.02	0.02	0.01	0.013	0.013

monitoring, under an extended range of driving conditions.

- ***Future emissions requirements are likely to include vehicle-level testing*** which will allow the full potential of powertrain level technologies, e.g. hybrid, to be apparant even at type approval time.
- ***CO_2 and emissions pricing in certain countries, through MAUT and the Clean Vehicles Directive*** which can lead to a market pull for environmentally friendly solutions.

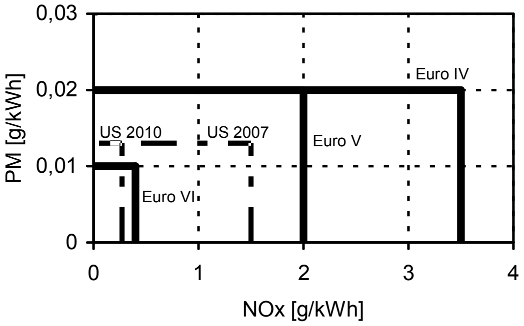

Figure 2: European and US emission legislation limits for type-approval

Additional to emissions reductions, there is a strong drive to reduce CO2 emissions from transport due to environmental concerns, and to reduce fuel consumption from a resource and operational cost perspective. Despite the highly efficient nature of the diesel engine, efficiency improvements have stagnated in the last years (Figure 3, [5]). Hybridisation is one technology that can provide improvements to this situation, albeit at a significant on-cost.

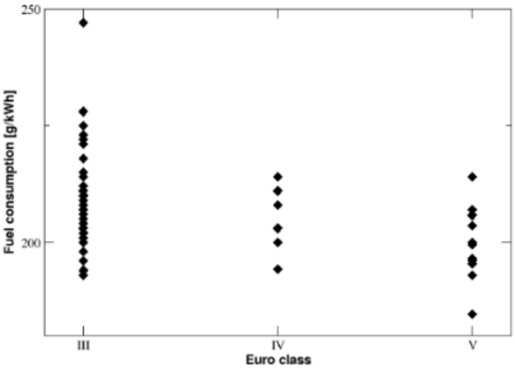

Figure 3: Progression in heavy duty vehicle fuel consumption

While hybridisation of powertrains in the heavy duty segment can provide emissions and efficiency benefits under real-world conditions, this is not reflected in the type approval procedure, which is currently engine based. Therefore, hybridisation also needs to explicitly show indirect benefits which improve cost benefit for the customer. In this way, environmental benefit can be coupled with improved competitiveness for the industry as a whole.

Tighter coupling of the powertrain subsystems will be increasingly important to satisfy these future requirements while providing the maximum cost effectiveness for the entire value chain. To this end, TNO utilises the Integrated Powertrain Control strategy (Figure 5). With the advent of hybrid powertrains in heavy duty applications, this coupling can be established in a natural way. [6]

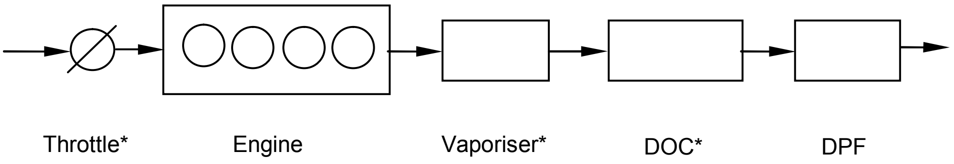

Figure 4: DPF system configuration (asterisk indicates DPF regeneration components)

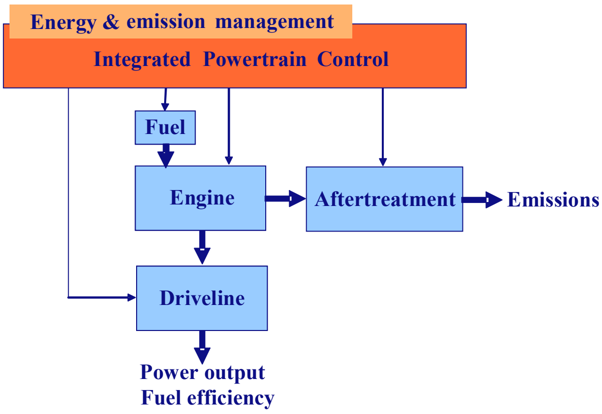

Figure 5: Illustration of Integrated Powertrain Control concept.

2 Diesel Particulate Filters

2.1 Conventional DPF Regeneration

A diesel particulate filter (DPF) is installed in the exhaust system to capture particulate matter (PM) from the exhaust gasses. During normal operation, the filter is loaded and its back-pressure increases. To release PM from the DPF, filter regeneration is applied. Therefore, additional heat is supplied to the DPF and after oxidation, PM is released from the DPF as carbon dioxide.

With the advent of Euro V and US 2007, the NOx-PM tradeoff requires fitment of a DPF in order to achieve the required emissions level if EGR is used for NOx reduction [3]. By applying an SCR system, the requirement for a DPF may be avoided.

A typical heavy duty powertrain with DPF is shown in Figure 4. In order to regenerate the DPF, additional components are required, in addition to the DPF itself:

- Vaporiser, for introducing fuel into the exhaust stream. This may also be performed by post-injection without additional hardware.
- Diesel oxidation catalyst (DOC), to oxidise the introduced fuel to heat the exhaust gases up to the DPF regeneration temperature.
- Throttle valve, to raise exhaust temperatures high enough to ensure proper conversion rates of the DOC, prior to DPF regeneration.

These components are required to generate sufficient temperature in the DPF to allow oxidation of the PM loading present in the DPF, even under extreme climates (e.g. -20°C).

In order to regenerate the DPF, the temperature of the DPF on-gas must reach 600°C. As the engine out exhaust gas temperature of a heavy duty diesel engine does not typically reach these levels, this is performed by introducing fuel into the exhaust upstream of the DOC using a vaporiser or post-injection, leading to extra fuel consumption. However, under 200°C, the DOC does not function. If the exhaust temperature is under this value, it can be increased by throttling the engine. This can lead to undesirable side effects, such as increased pumping loss, oil entrainment and increased PM emissions, in addition to the additional hardware.

2.2 Hybrid Vehicle DPF Regeneration

To improve the cost/benefit of the complete powertrain system, synergy may be found between the hybrid and DPF sub-systems. Various opportunities are present, e.g.:

- Reduced loading of the DPF, and thereby reduced regeneration frequency and back pressure. This leads to lower fuel penalties and increased reliability.
- Cost reduction in the base powertrain system, by eliminating components dedicated to the

regeneration of the DPF or by relaxing specifications on PM reduction measures.

Hybrid systems are generally used to control the total drive torque while optimising the energy flows in the powertrain. This leads to an SOC and torque based control; typical specifications of a heavy duty hybrid system is shown in Table 2 [7]. However by relaxing the SOC constraint, the hybrid control system may be used for other purposes, e.g. thermal management of the aftertreatment system. An example is utilising an electrically heated catalyst [6]. This may also be achieved by increased engine load directly by forcing battery charge. Battery charge is then later returned to the powertrain, in a Charge to Boost strategy (Figure 6). This strategy is essentially energy neutral, with the exception of the losses on the electrical path. As the maximum exhaust temperature is not high enough to regenerate the DPF, the focus of the hybrid control is to obtain DOC light-off without external measures.

Once DOC light-off is complete, regeneration of the DPF can commence through starting fuel injection in the exhaust upstream of the DOC. The required temperature of 600°C may then be reached.

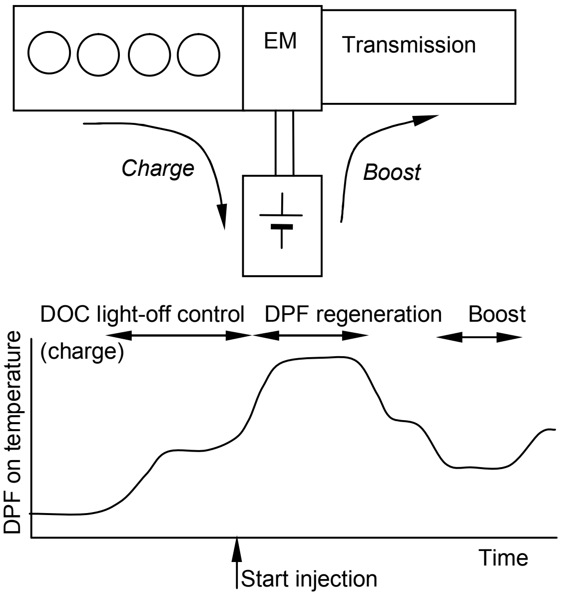

Figure 6: Principles of hybrid-assisted DPF regeneration

Table 2: Typical sizing HD hybrid system

EM Torque	800	[Nm]
EM Power	120	[kW]
Battery Energy	1.2	[kWh]

3 Development Process

Complex interactions are present when the hybrid system is being used to control catalyst light-off. Of critical importance is the capability of the system to support the new control regime. In order to understand the correlation between catalyst heating, hybrid power and hybrid storage capacity, TNO developed a special tool, including a simplified inverse catalyst thermal model to evaluate this impact. This also provides an initial calibration for the control system.

Utilising a phenomelogical model of the DOC from TNO's detailed SimCat model library for the oxicat [8], further detailed analyses are then performed to refine the calibration parameters.

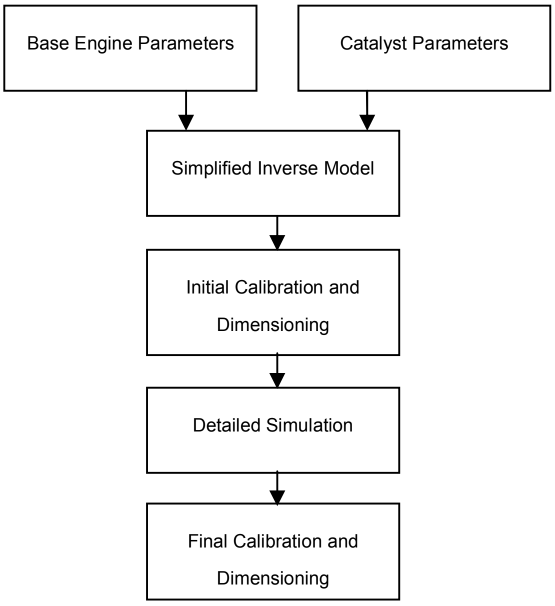

Figure 7: Development process steps

4 Control System

The hybrid DPF regeneration control forms a part of TNO's modular hybrid control system. This control consists of a temperature-based electrical power control and a hardware layer which allows decoupling of the control from the specific powertrain configuration (Figure 8). Closed-loop DOC temperature control is implemented using the existing installed sensors.

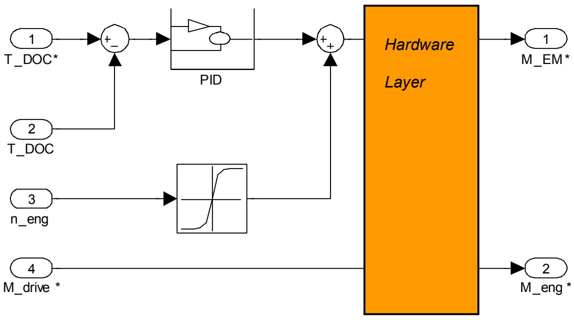

Figure 8: Control system implementation

5 Simulation Results

To calibrate and evaluate the performance of the control system, along with the impact on the dimensions of the hybrid system, a simulation study was performed using a 13L heavy duty 6 cylinder diesel engine together with an oxicat (15L volume).

5.1 Regeneration from idle @ 20°C

For the baseline case without hybrid light-off control, the exhaust temperature of the engine is insufficient for DOC light-off. Increasing the engine load by 500 Nm using the hybrid system allows light-off to be achieved within 180s (Figure 9); this is 35% of the available engine torque at idle speed. In this process, 1.5 kWh of mechanical energy is taken from the engine, which gives 1.2 kWh of battery throughput assuming 80% efficiency of the electric machine.

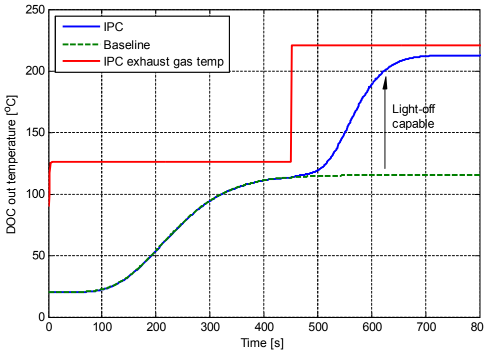

Figure 9: Exhaust and DOC temperature, regeneration from idle @ 20°C. Control is started at 450s.

5.2 Regeneration FTP cycle @ 20°C

The standard configuration shows a light-off time for the DOC of 666s on the FTP cycle from a cold start at 20°C. Prior to this time, the aftertreatment system is not capable of regeneration without external measures.

By implementing the IPC strategy, the light-off time is reduced by 64% to 240s (Figure 10, 11). In order to achieve this, 74 kW is required from the electric machine along with 1.4 kWh battery throughput.

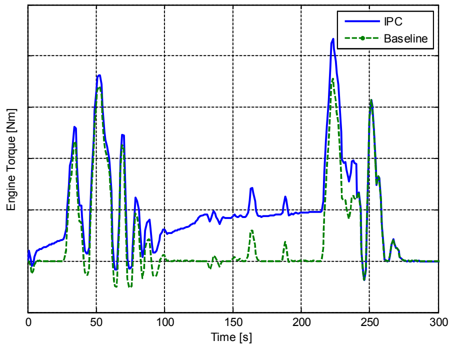

Figure 10: Engine torques with and without hybrid assisted regeneration, FTP cycle @ 20°C

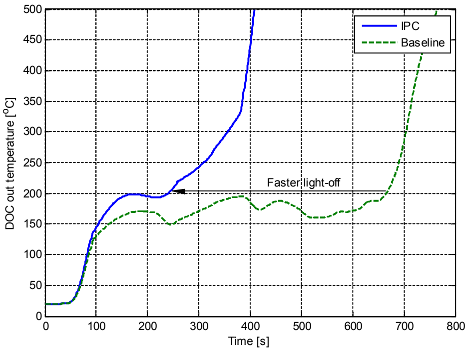

Figure 11: DOC temperature with and without hybrid assisted regeneration, FTP cycle @ 20°C

5.3 Regeneration from idle @ -20°C

In the standard configuration, the engine exhaust temperature is insufficient for DOC light-off at idle. By increasing the engine load to 700 Nm, the exhaust temperature is increased sufficiently (214°C) to provide catalyst light-off within 160s (Figure 12). For this, the electric machine must absorb 44 kW and 1.9 kWh mechanically. The battery is not fully exposed to this load due to efficiency of the electric machine. With an efficiency of 80%, the battery charge action corresponds to approximately 1.5 kWh.

As idle at -20°C represents worst case conditions, regeneration of the DPF should be possible under all conditions by using the proposed control.

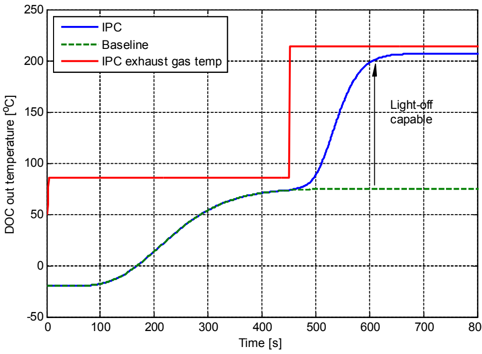

Figure 12: Exhaust and DOC temperature, regeneration from idle @ -20°C. Control is started at 450s.

5.4 Regeneration FTP cycle @ -20°C

Under -20°C conditions, the increased engine load due to the IPC strategy is noticeably higher than for the 20°C case.

On the simulated FTP cycle, light-off of the DOC occurs after 689s (Figure 13, 14). With the hybrid control, this is reduced to 244s. The power required from the hybrid system is in this case 104 kW, with an energy of 2.2 kWh (charge).

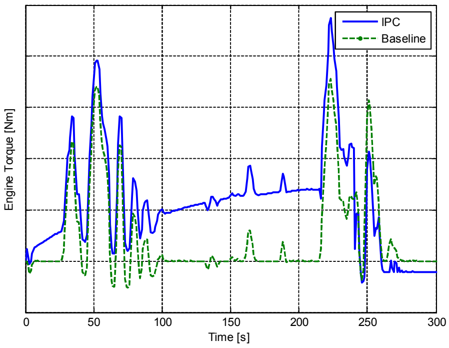

Figure 13: Engine torques with and without hybrid assisted regeneration, FTP cycle @ -20°C

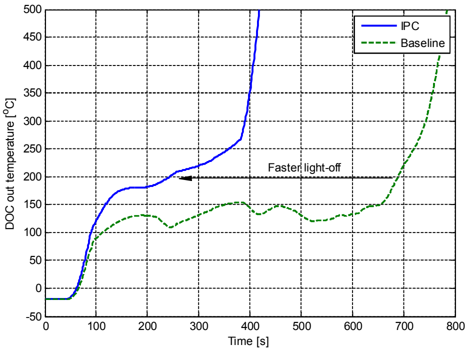

Figure 14: DOC temperature with and without hybrid assisted regeneration, FTP cycle @ -20°C

The results and system requirements per case are shown in Table 3.

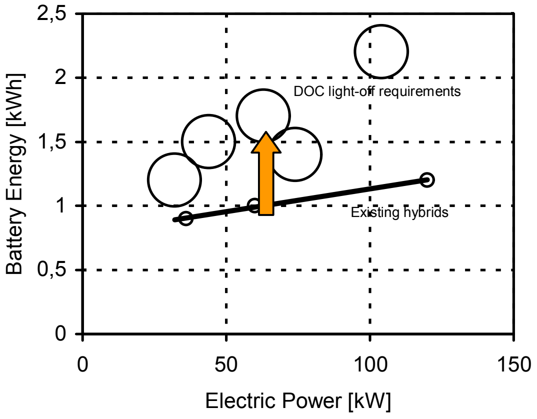

Figure 15: Increased requirements due to DOC light-off control. Battery energy based on estimated usable energy assuming 50% SOC window

When comparing the specifications of typical heavy duty hybrid systems (mostly targeted at city bus and distribution applications, Figure 15 [7], [9], [10]), it may be seen that the power of the electric machine required for DOC light-off falls within the current application range. However, the requirements on the battery are increased; the useable battery capacity needs to be increased by a factor 1.3–2.

6 Conclusions

In order to meet current and future heavy duty emissions legislation, fitment of a DPF provides an effective solution. However, DPFs require periodic regeneration. In order to achieve the temperatures

Table 3: Summary of DPF regeneration capability and requirements

Case	Regeneration capability					
	Baseline	Hybrid	LTR (1)	Torque	Power	Energy
Idle, 20°C	No	Yes	-	500 Nm	32 kW	1.2 kWh
FTP, 20°C	Yes	Yes	64%	485 Nm	74 kW	1.4 kWh
Idle, -20°C	No	Yes	-	700 Nm	44 kW	1.5 kWh
FTP, -20°C	Yes	Yes	65%	700 Nm	104 kW	2.2 kWh

(1) Light-off time reduction

required for this process, additional hardware is required.

Hybrid powertrain technology is recognised as one of the few technologies capable of providing a further step increase in powertrain efficiency, albeit at high cost price. But current emissions legislation is based on engine test only, whereby direct synergies between the hybrid system and the emissions measures for improved cost/benefit can not be exploited. Opportunities for cost reduction have therefore been sought in the DPF regeneration hardware.

By implementing the Integrated Powertrain Control concept to the regeneration of a DPF, simulations have shown that:

- On the FTP cycle, the DOC light-off time may be reduced by 65%.
- Under idle conditions, regeneration is possible down to -20°C, without additional measures.

This control approach has an effect on the requirements placed on the hybrid powertrain hardware. While the powers required are within the range of hardware implemented in the heavy duty segment, the requirements on the battery capacity are increased, by up to a factor 2. Depending on the application, such strategies may be a driver for the powertrain dimensioning and due attention needs to be paid to battery throughput and durability consequences. Addressing these issues will aid the introduction of environmentally friendly product with an attractive cost level for the end customer.

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