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Integrated Powertrain Control to meet future CO_2 and Euro-6 emissions targets for a diesel hybrid with SCR-deNO_x system

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Abstract— **A new concept is introduced to optimize the performance of the entire powertrain: Integrated Powertrain Control (IPC). In this concept, the synergy between engine, driveline and aftertreatment system is exploited by integrated energy and emission management. As a result, fuel efficiency and drivability can be optimized simultaneously within the boundaries set by emission legislation. This is essential to meet both future CO_2 targets and ultra low emission limits.**

As a first step towards IPC, the potential of the proposed approach is demonstrated for a series hybrid diesel passenger car. The studied powertrain is based on a VW 1.2l TDI engine, which is equipped with a urea-based SCR-deNO_x aftertreatment system. For three different energy management strategies, chassis dynamometer results are presented over a European NEDC test cycle. Additional simulations demonstrate the potential of integrated energy and emission management, especially during low temperature conditions. Projections show that 130 g/km CO_2 and Euro-6 NO_x emission targets can be simultaneously met for the studied C-segment vehicle.

I. 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.

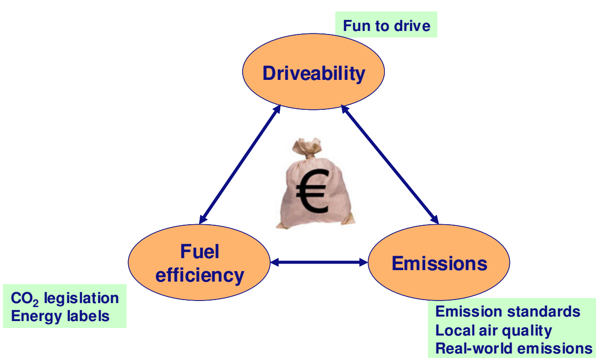

Figure 1: Illustration of the powertrain optimization problem

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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]:

- ***Further reduction of emission limits towards near zero impact levels (see Table 1)***: *e.g.*, compared to the current NO_x Euro-4 emission standard, additional NO_x reductions of 28% and 68% have to be realized to meet Euro-5 and Euro-6 targets, respectively. As a result, the control system has to maximize system performance, including transients;
- ***Cold start emissions for diesel vehicles*** will be monitored by type approval authorities. This places requirements on the control system to provide acceptable light-off times from -7°C;
- ***Durability targets will be doubled (see Table 1)***, requiring increased robustness of the control system to compensate for component deterioration;
- ***Emission limits during real-world driving conditions*** may be introduced in the future. This will require improved functioning of the control system, including on-board monitoring, under an extended range of driving conditions.

In addition to these emission limits, the target of 130 g CO_2/km is likely to be legislated for passenger cars from 2012; this target will need to be met by technical measures alone. Considering historical CO_2 emission trends, this is generally seen to be an immense challenge, see Figure 2.

Table 1: (proposed) European emission legislation for diesel-powered passenger cars. Test cycle: New European Driving Cycle (NEDC), see, *e.g.* ,[2].

EU	Euro-3 (2000)	Euro-4 (2005)	Euro-5 (2009)	Euro-6 (2014)
NO_x (mg/km)	500	250	180	80
PM (mg/km)	50	25	5	5
Durability (km)	80 000	80 000	160 000	160 000

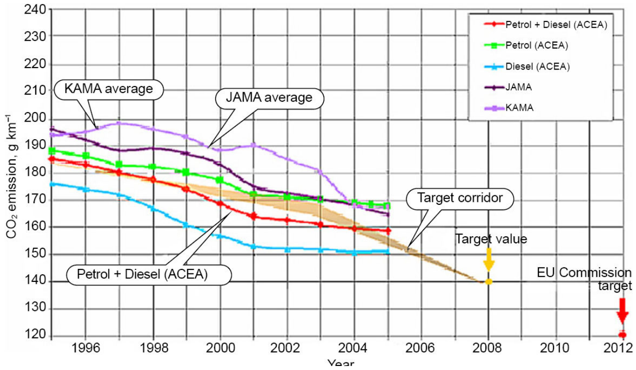

Figure 2: Overview of CO_2 emission trends and targets [3]

This paper is organized as follows. First, a new concept is introduced that deals with the powertrain optimization problem. The potential of this concept is demonstrated for a promising application: a series diesel hybrid powertrain. Second, the studied powertrain and control strategies are discussed. For these control strategies, experimental results are presented over a European NEDC test cycle. In addition, simulation results are presented for the engine with SCR system. Finally, conclusions are summarized.

II. Integrated Powertrain Control

To meet the more and more stringent requirements on pollutants, CO_2 emission and drivability, it becomes increasingly important to optimize the performance of the *entire* powertrain. This holds for test cycles as well as for real-world driving conditions. More precisely, the synergy between engine, driveline and aftertreatment system has to be maximally exploited, during all operating conditions. Therefore, a system approach is required: *Integrated Powertrain Control (IPC)*. Due to the increased complexity of powertrains, this is not straightforward.

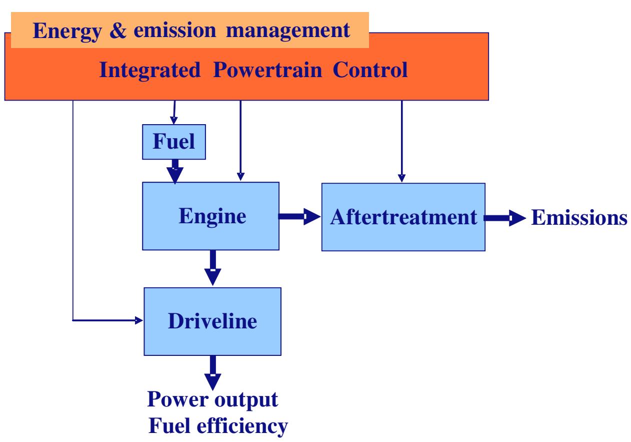

Figure 3: Illustration of Integrated Powertrain Control concept

As illustrated in Figure 3, the powertrain performance can be expressed in terms of the desired power output, fuel efficiency, and emissions. Consequently, the ultimate goal is to provide a solution to the coupling of 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 and storage in the powertrain (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 gas conditions (flow, temperature and emission levels) that lead to minimal tailpipe emissions for a given configuration. This will also make the powertrain more robust for variations during real life applications; *e.g.* varying ambient conditions and changed performance of components, while also reducing calibration effort.

IPC systems are supposed to be based on a model-based approach. In that case, IPC systems can deal with the high degree of interaction and complexity in powertrains. With this approach, the optimal performance of the total powertrain can be realized; requirements on emissions, fuel efficiency and power output can be systematically and simultaneously be dealt with. This cost-efficient optimization process is also expected to reduce development and calibration time (and thus costs). Furthermore, the model-based approach opens opportunities to monitor system performance using so-called virtual or soft sensors. It is expected that supervisory control and model predictive control concepts will play an important role in IPC systems.

In the literature, there are only a few examples found in which energy and emission management are combined. In a hybrid driveline, the storage and usage of regenerative braking 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 (TWC) to improve cold start performance and optimize combined engine/transmission efficiency [5]. Furthermore, diesel applications are known in which the temperature of the aftertreatment system is controlled by engine measures: post-injection events [6,7,8] or by a throttle in the intake [9]. Combined diesel and hybrid systems for emissions reduction have been shown to halve Euro 4 levels in passenger cars [10]. In [20], fuel economy and NO_x engine out emissions are optimized.

However, no results of active control of engine out temperature and emissions to optimize aftertreatment performance are found for hybrid diesels. As a first step towards IPC, the potential of the proposed integrated approach is demonstrated for TNO's Hybrid Carlab. A detailed system description is given in the following section.

III. System description

To realize low fuel consumption in combination with low NO_x emissions, a series diesel hybrid powertrain equipped with a SCR-deNO_x system is investigated in this paper. This system is based on TNO's Hybrid Carlab. In the simulation study, this diesel hybrid system is extended with a SCR system model, as illustrated in Figure 5.

In urea-based Selective Catalytic Reduction (SCR) technology, an ammonia forming reagent is injected in the exhaust upstream of the catalyst. Ammonia reduces nitrogen oxides (NO_x) over the SCR catalyst into harmless products: nitrogen and water. This aftertreatment technology is widely accepted for diesel truck applications in Europe. Furthermore, it is expected to be one of the preferred solutions for future US truck and large passenger car applications. This technology is characterized by high peak NO_x conversion efficiencies (> 90%), allowing the engine to be calibrated for high fuel efficiency. Detailed information on SCR systems can be found in *e.g.*, [11,21,22].

Application of hybrid technology allows further improvement in the vehicle's fuel efficiency. In addition, hybrid powertrain applications have the following potential benefits:

1. ***Assistance in thermal management of aftertreatment systems***: in the studied system, the SCR system performance during low-temperature conditions has to be optimized, such that NO_x conversion is maximized. This plays a crucial role to meet future emission targets, especially during cold start. Hybrids can vary the engine's operating point or can be used in combination with an electrical-assisted heating device to increase SCR catalyst temperature [5,12,13]. In this study, the first option is investigated;
2. ***Reduced engine-out emissions***: due to regeneration of braking energy, the power demand of the engine is reduced. This leads to a reduction in CO_2, NO_x and particulate emissions [16];
3. ***Relax transients***: this will reduce NO_x and particulate emissions, particularly for engines equipped with EGR [16];
4. ***Improved flexibility***: especially for a series hybrid, the decoupling of engine speed and vehicle speed provides an extra parameter for optimizing the NO_x-fuel consumption trade off.

Figure 4 shows TNO's Hybrid Carlab. In this technology demonstrator, a series hybrid diesel powertrain based on a standard VW 1.2L TDI engine is installed [14]. This engine is Euro-3 compliant with low fuel consumption (3l/100km), when applied to an A-segment vehicle. Key parameters are shown in Table 2, whereas the system configuration is sketched in Figure 5.

The powertrain consists primarily of a traction motor, generator set and battery. The generator set is a combination of a 1.2L direct injection diesel engine with VTG turbocharger, coupled to a permanent magnet generator; this combination provides a combined maximum efficiency of greater than 35%. The NiMH battery delivers 320V nominal with a capacity of 10Ah. This gives a total energy capacity of 3.2kWh, providing a zero emission driving range of more than 10 km.

While this system is of similar configuration to that proposed by GM for the Chevrolet Volt, some differences are noticeable [19]. The Hybrid Carlab has a slightly more powerful drive motor, but a much smaller battery pack due to the different zero emission development goals.

Figure 4: Photograph of TNO's Hybrid Carlab

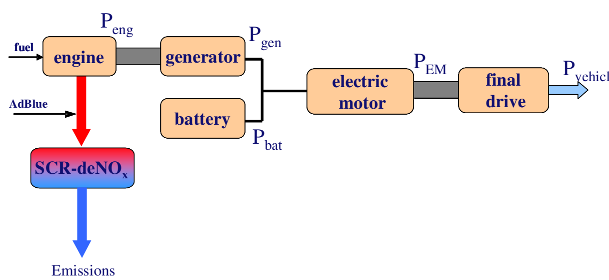

Figure 5: Scheme of the studied powertrain system

Table 2: Component specifications for the Hybrid Carlab

Generator set		
Engine	1.2L I3 TDI-PD	
Generator type	Surface permanent magnet	
Power	36	[kWe]
Battery		
Type	NiMH	
Capacity	10	[Ah]
Voltage	320	[V]
Peak power	50	[kW]
Electric motor		
Type	Induction	
Peak power	150	[kW]

The main emission control measures on the standard engine are cooled EGR and an oxidation catalyst. The Hybrid Carlab is a vehicle, which is two segments above that of the original engine application; therefore, to meet future emissions requirements, either redevelopment of the engine would be required or aftertreatment can be used. TNO decided to apply an SCR system in order to optimize NO_x-CO_2 trade-off with the convenience of an add-on system.

While SCR systems show excellent conversion efficiencies under normal operating conditions, performance issues still remain at low exhaust temperature, such as during cold start. This will become extremely important in the future according to future requirements. Besides experiments, simulations are done to study the impact of SCR systems. For the studied powertrain, a model was already available in Matlab/Simulink. This model was mainly based on the series hybrid model in the QSS toolbox [15]. It is fitted to the Hybrid Carlab using available data for the different components. Furthermore, the proportional control strategy is implemented in simulations. This model was extended with (see also Figure 5):

- Engine maps for NO_x emissions and exhaust gas temperature T_{exh};
- A thermal SCR catalyst model:

$$mc_p \frac{dT_{cat}}{dt} = hA\left(T_{exh} - T_{cat}\right);$$

- Description of chemical SCR catalyst behavior; this is based on available experimental data for a Vanadium SCR catalyst. This data describes the stationary relation between catalyst temperature, space velocity and NO_x conversion (see also [22]). Space velocity (in hr^{-1}) is defined as:

$$sv = \frac{3600 \cdot Q_{exh}}{V_{cat}}$$

The exhaust volume flow (in m^3/s) is approximated by:

$$Q_{exh} = \eta_v V_d \frac{N}{120}$$

with volumetric efficiency η_v, displacement volume V_d (in m^3) and engine speed N (in rpm).

IV. Control Strategy

In this study, three energy management strategies have been examined. These strategies are implemented and tested on a chassis dynamometer for a cold MVEG cycle:

A. Control of optimal engine operating point (*thermostat*)
B. Optimal work line control for minimal CO_2 emissions (*proportional*)
C. Optimal thermostat control for minimal NO_x emissions (*low NO_x*)

Strategy A and C are examples of work point control, whereas strategy B is an example of work line based control.

In simulations, a warm MVEG test cycle is run with the hybrid system with SCR catalyst. It is noted that the initial SCR catalyst temperature is 20 °C. Main focus is on a thermal management strategy for the SCR catalyst. This strategy is compared with the proportional strategy B.

A. Thermostat control

Thermostat control is the simplest form of series hybrid control. If the battery is below a given SOC level, the generator set is started at a fixed work point until the target SOC is reached after which the generator set is again shut off. The generator set's work point is selected at the highest efficiency point. For the Hybrid Carlab, the set points are 16.4kW power at 2000 rpm and 60% SOC. To provide sufficient drivability, coordinated control of the generator set is performed at high power request levels.
The thermostat control algorithm has the advantage of reducing total friction and pumping loss of the generator set together with high generator set efficiency. The disadvantages include high battery throughput and loading, leading to reduced durability.

B. Proportional control

Proportional control is a more advanced strategy, sometimes called load-follower. Below a given power request, electric driving is achieved by switching the generator set off. Above this point, the power delivered by the generator set is controlled proportional to the power request along a predetermined best-efficiency work line: *generator set map-based optimization* (Figure 6).

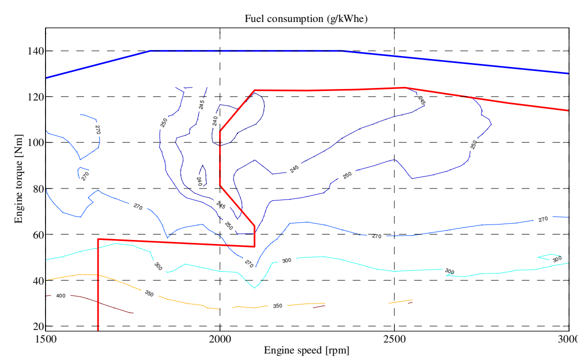

Figure 6: Generator set map with work line for strategy B (in red)

The desired generator set rotational speed is realized by a PI controller. This leads to significantly lower battery loading, but also lowers the average generator set efficiency although generator set behavior becomes more natural. The power request set point is determined by two factors (see Figure 7):

- Proportional control on battery SOC relative to a given set point (*SOC control*);
- Requested drive power based on accelerator pedal mapping ($P_{vehicle}$).

For the Hybrid Carlab, the generator set is switched on above 15 kW power request and the SOC target is 57%. These values are selected based on component capability and energy management considerations for electric driving considering component efficiencies.

C. Low NO_x control

Looking at the engine's NO_x emission characteristic, a significant reduction in NO_x emissions is possible by adapting the thermostat control to maintain engine operation in the EGR area. This reduces generator set efficiency not only due to the EGR, but also by reducing engine load. Practically, this is achieved by lowering the engine operating point to 10 kW at 1650 rpm.

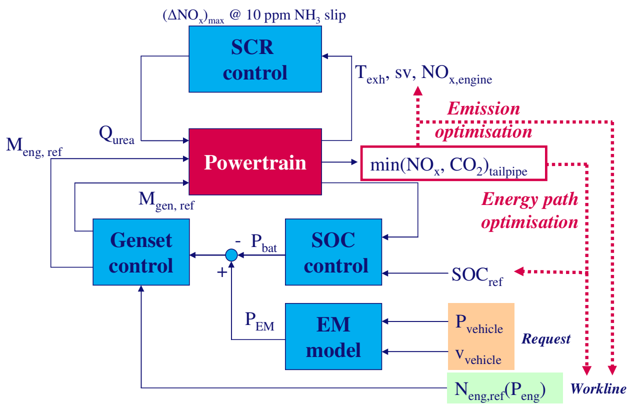

Figure 7: Scheme illustrating proportional control with thermal management strategy (Strategy D)

D. Thermal management

In the simulation study, it is examined to further optimize the NO_x-CO_2 trade-off by hybrid-assisted thermal management. The proportional control is used as a reference. For the configuration with SCR system, the applied work line in the proportional control strategy is adapted, such that the SCR catalyst temperature is maximized. Increased catalyst temperatures lead to higher NO_x conversion rates of the SCR system. As a result, this allows to calibrate the engine for higher NO_x emissions and lower fuel consumption. Furthermore, this relaxes the requirements on the remaining part of the test cycle.

V. RESULTS

A. Chassis dynamometer results

For the series hybrid powertrain, the experimental results over a cold MVEG cycle are listed in Table 3. For reference, the results for the equivalent standard (non-hybrid) diesel-powered vehicle are listed.

Table 3: Chassis dynamometer results for the studied energy management strategies

MVEG (cold)	***VW 1.9l TDI***	***Hybrid powertrain***		
		Thermostat	***Proportional***	***Low NO_x***
CO_2 (g/km)	177	128	122	131
NO_x (g/km)	0.45	1.09	0.973	0.35
PM (g/km)	0.020	0.013	0.025	0.045

These results illustrate that the NO_x-CO_2 trade-off can be strongly influenced by the hybrid powertrain in combination with the selected control strategy. With the proportional strategy, the CO_2 emissions are minimized at the penalty of high NO_x emissions. The effect of battery throughput and generator set efficiency on total vehicle efficiency is clearly noticeable on the CO_2 emissions.

B. Simulation results

To meet future NO_x emission targets, the hybrid powertrain may be equipped with an SCR system. This is modeled in Matlab/Simulink. It can be concluded from Table 4 that the developed model shows reasonable agreement with measurements for the proportional control strategy. Differences in performance, especially NO_x emissions, were expected, since the model is fitted using engine dynamometer data. For instance, cooling on engine and vehicle is different.

Table 4: Overview of simulation results for the studied strategies and configurations

MVEG (hot)	***Hybrid powertrain***		
	Proportional no SCR	***Proportional w. SCR***	***Thermal Management w. SCR***
CO_2 (g/km)	122	122	130
NO_x (g/km)	1.47	0.57	0.48
SCR NO_x conversion		61%	72%

For the proportional control strategy, it is seen that engine out NO_x emissions can be further reduced by approximately 60% by applying an SCR system. This can be achieved without the additional fuel penalty compared with the low NO_x strategy. To further enhance SCR system performance, a thermal management control strategy is developed, which mainly focuses on increasing catalyst temperature. This is done by changing the engine operating point using the hybrid system. With this strategy, exhaust gas temperatures can be increased by approximately 50 ^oC, as illustrated in Figure 8. Consequently, NO_x conversion increases from 61% to 72%.

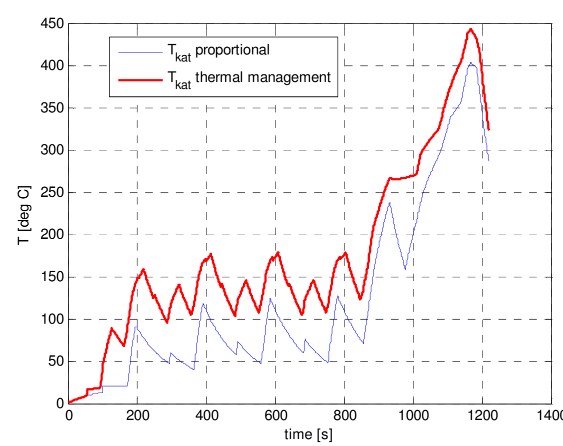

Figure 8: Impact of control strategy on catalyst temperature

Due to the high engine out NO_x level, tailpipe NO_x emission is still relatively high. A summary of results and future emission targets is given in Figure 9. Generally speaking absolute NO_x levels in simulations were too high. Consequently, the SCR result is a projection using the NO_x conversion rates found in simulations. Furthermore, it is shown that, with the NO_x reduction levels made possible by the advanced thermal management control, Euro-6 Type 1 test emissions levels should be achievable when applied to a Euro-4 base engine.

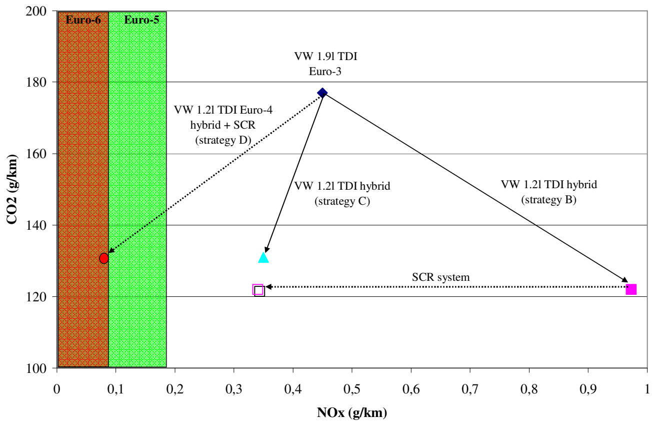

Figure 9: Overview of results for different control strategies (dashed lines are projections)

VI. CONCLUSIONS

- Powertrain control requires a system approach to deal with increased complexity and to meet future performance targets: *Integrated Powertrain Control (IPC)*. This approach has to combine energy and emission management;

- To improve the cost-benefit ratio of hybrids in diesel applications, besides improving fuel efficiency and torque output, the potential to reduce emissions has to be further exploited. Enhancing thermal management of aftertreatment systems by adaption of the engine's operating point or electrical-assisted heating is promising;

- The IPC concept is applied to a diesel hybrid powertrain application with a urea-based SCR-$deNO_x$ system. The hybrid powertrain is applied to enhance SCR system behavior during low temperature conditions by adapting the engine operating point. Results demonstrate that the traditional trade-off between NO_x emissions and fuel consumption can strongly be affected by the applied control system. Initial simulation results indicate that Euro-6 emissions in combination with 130 g CO_2/km can be comfortably met in a C-segment vehicle, without special vehicle or engine measures. Note that the base engine was targeted for Euro-3 when applied in the A-segment.

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