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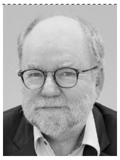

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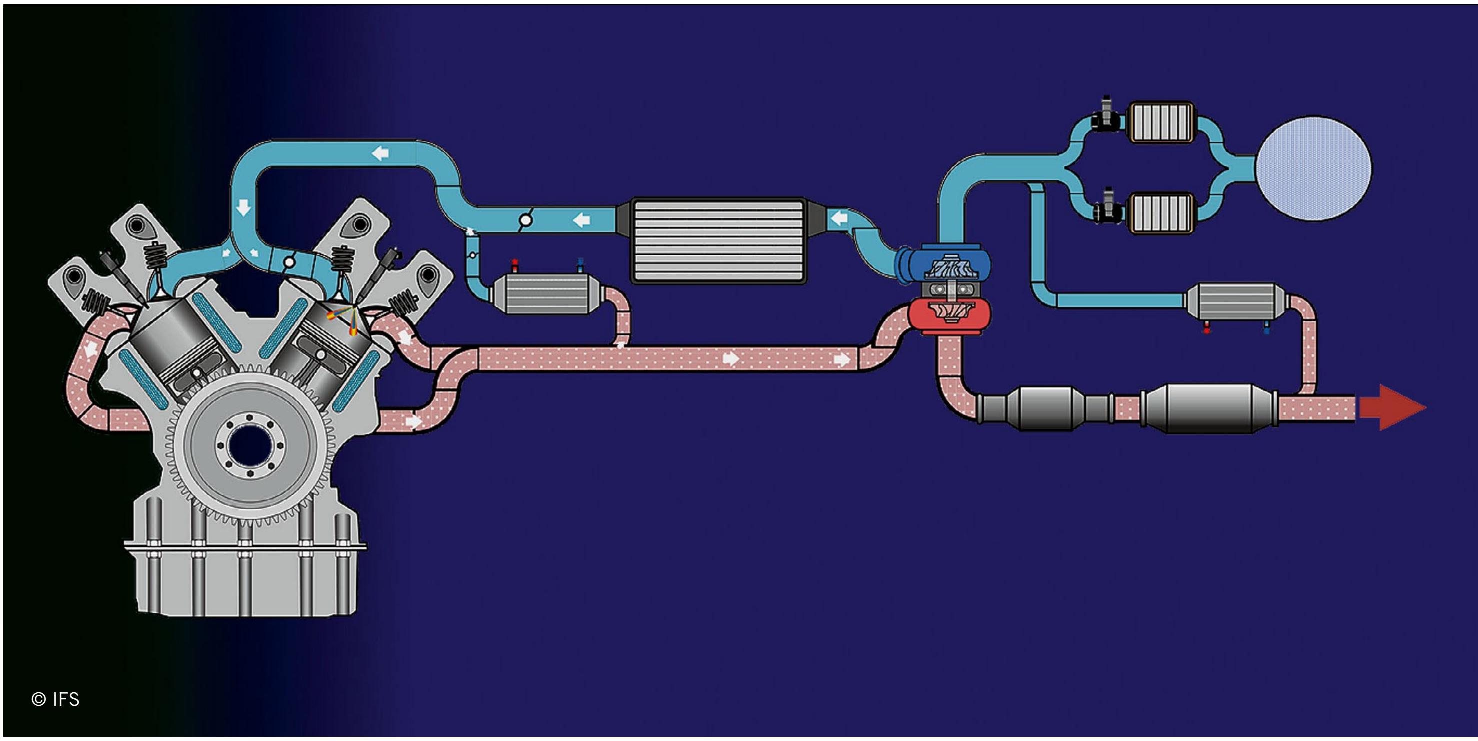
Electrification of the Partially Homogeneous Diesel Engine

The electrification of vehicle powertrains holds great potential for reducing emissions of both pollutants and greenhouse gases. As part of the FVV research project No. 1312, the combination of a partially homogeneous diesel engine combustion process and additional hybridization was investigated on a vehicle concept at the University of Stuttgart. The modified combustion process can benefit greatly from the increased on-board voltage of a hybrid powertrain.



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1 MOTIVATION

Partial Homogeneous Charge Compression Ignition (PHCCI) allows the soot-NO_x trade-off to be mitigated, but optimum operation can only be guaranteed in a narrow map range and with low torque gradients. The additionally increasing carbon monoxide (CO) and hydrocarbon (HC) emissions resulting from homogenized combustion are in direct conflict with the strict limit values [1]. The extra degree of freedom resulting from electrification of the powertrain can both extend the operating time in the partially homogeneous range and mitigate the torque gradients. The increased on-board voltage deriving from hybridization and the second energy storage unit enable the use of an electrically heated catalytic converter to reduce CO and HC emissions. The research project carried out at the Institute of Automotive Engineering (IFS) is intended to achieve not only a reduction in emissions but also a reduction in fuel consumption with the aid of an operating strategy specially adapted to the application, thus lowering the CO_2 emissions of the powertrain concept.

2 SIMULATION AND MODELING OF THE VEHICLE CONCEPT

To be able to determine the emissions of the drive concept experimentally, complete modeling and simulation is required. This will allow the mandatory torque/speed curves to be generated on the test bench. To ensure realistic load requirements, a so-called forward model is used, in which the torque requirement is calculated by a driver controller from the difference between the target and actual speed. A module is used to calculate various torque combinations between the Electric Machine (EM) and the Internal Combustion engine (ICE) during the driving cycle of this model that satisfy the load requirement set by the driver controller. In the operating strategy, an automated decision must be made as to which torque combination and in which gear the hybrid vehicle is operated. Not only must the battery's State of Charge (SoC) be simulatively determinable for this, but also for the electrically heated catalytic converter. The temperature model specially developed for this purpose can precisely simulate the exhaust gas temperature of the drive concept, which means that the time ranges and the electrical energy of the additional heating applied during these ranges can be determined [2]. From the torque-speed combination selected by the operating strategy, the speed of the vehicle is determined via transmission, differential, wheel and the longitudinal dynamics model and compared again with the required speed of the cycle in the driver controller, **FIGURE 1**.

Since the combustion engine in use has a map range with partially homogeneous combustion as well as a map range with diffusive diesel combustion, two optimization approaches are followed. In normal diffusive diesel engine operation, an Equivalent Consumption Minimization Strategy (ECMS) is used. The ECMS corresponds to a classic mathematical optimization algorithm that minimizes the vehicle's consumption in the application presented. For this purpose, a total consumption is calculated from the energy demand of the EM and the fuel consumption of the ICE. The previously calculated torque combinations can thus be assigned a cumulative consumption and the best point can be selected. A fuel consumption is attributed to the electrical energy P_{EM} by means of a conversion factor λ.

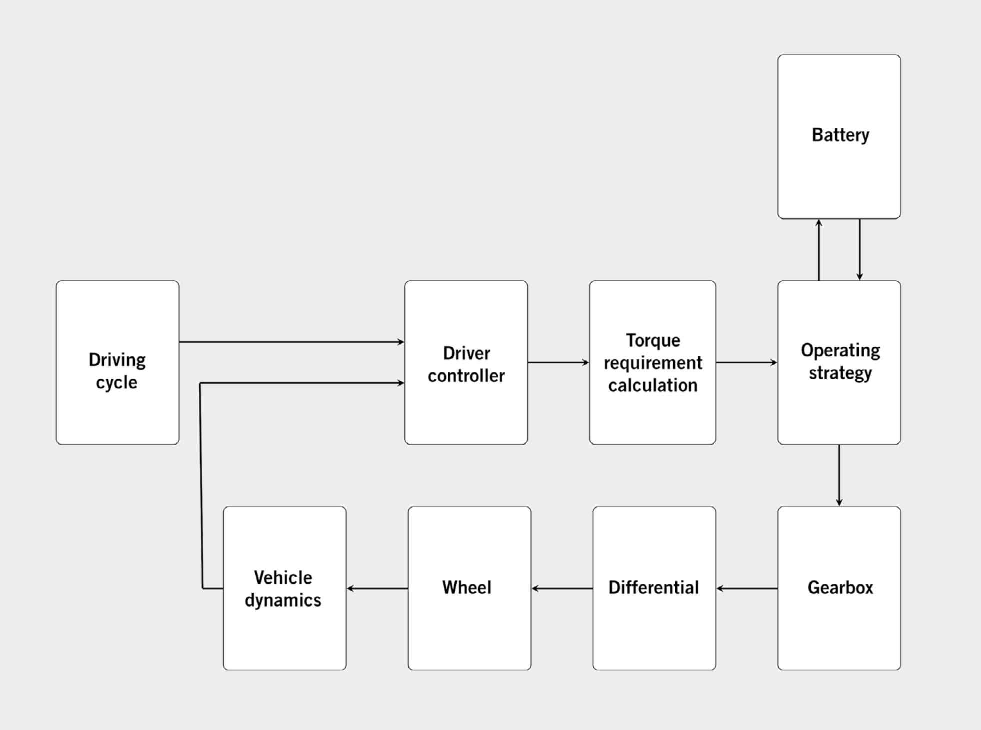

FIGURE 1 Schematic representation of the forward model (© IFS)

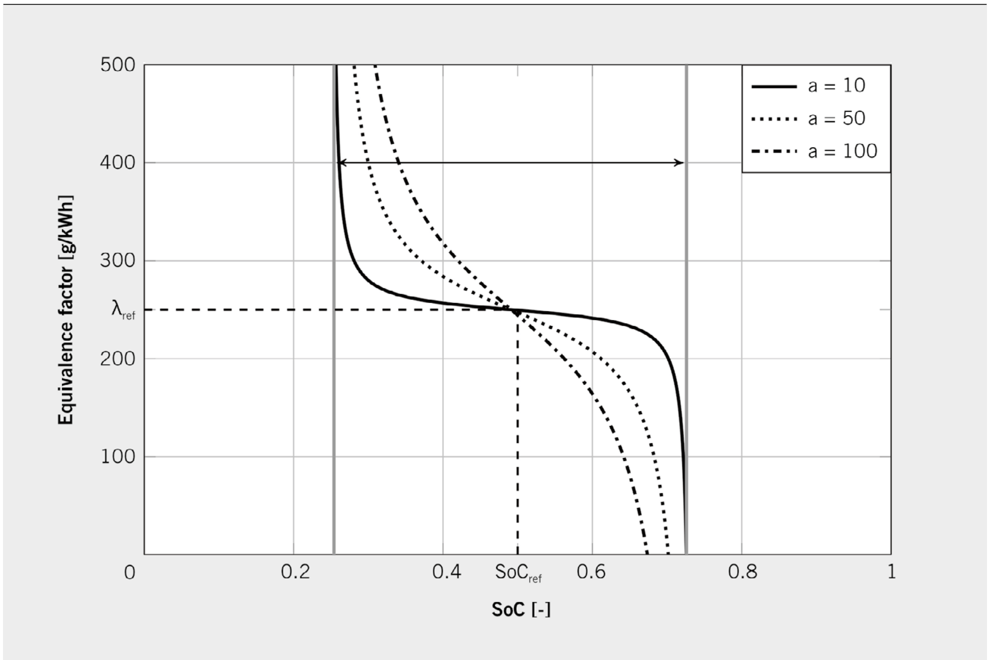

FIGURE 2 Equivalence factor modulated with tangent approach (© IFS)

Eq. 1 $\dot{m}_{total} = \dot{m}_{ICE} + \lambda \cdot P_{EM}$

A constant conversion factor leads to either too little utilization of the battery capacity or to a simulated discharge beyond the physically possible limits. In the developed simulation model, the proportionality factor is therefore modulated via a tangent function. If the battery charge approaches the previously defined limits, the factor tends towards plus or minus infinity. For the ECMS, it can thus be said that the operation of the EM becomes very cheap when the battery is almost full and very expensive when the battery is almost empty. The simulation shows a far improved utilization of the charge band due to the modulation as well as a consistent adherence to the charge limits. Eq. 2 shows the tangent function [3]. The constant SoC_{ref} stands for the reference battery charge, that means, 50 % SoC, and SoC_{sma} for the averaged battery SoC of the last 10 s. The factors λ_{ref}, K_p, α and b can be varied to influence the shape of the tangent function, where b defines the bandwidth in which the battery is used.

Eq. 2 $$\lambda(t) = \lambda_{ref} + K_p \cdot \left(SoC_{ref} - SoC_{sma}\right) - \alpha \cdot \tan\left(\frac{\pi}{b + 0.02} \cdot \left(SoC(t) - SoC_{ref}\right)\right)$$

FIGURE 2 shows the course of the conversion factor modulated by means of the tangent approach and the behavior at the limits as an example.

In the second approach of phlegmatization, the ICE is operated with the lowest possible emission of pollutants. With a load demand in the partially homogeneous range, that means, between 850 and 2400 rpm and a torque between 0 and 55 Nm, the torque demand is phlegmatized. The resulting lower gradients in the ICE's air path lead to reduced HC and CO emissions. If the requested torque is in a narrow band above the semi-homogeneous operating limit, the ICE is operated at a constant torque of 55 Nm and the EM applies the additional requested torque, which also ensures low emissions of pollutants.

Motor data		
Description	**Unit**	**Characteristics**
Design/cylinder bank angle	-/°	V6/72
Displacement	cm³	2987
Bore × stroke	mm	83 × 92
Cylinder spacing	mm	106
Connecting rod length	mm	168
Compression ratio	-	15.5 : 1
Rated power	kW	68
At speed	rpm	2400
Maximum torque	Nm	270
At speed	rpm	2200-2400
Catalyst data		
Description	**Unit**	**Characteristics**
Cell density	cpsi	400
Matrix diameter	mm	143
Outer diameter	mm	146
Matrix length	mm	90
Frontal area	cm²	160
Mantle wall thickness	mm	1.50
Foil thickness	µm	40
Active metal density	g/ft³	10
Heating power	kW	4.5

TABLE 1 Characteristics of the engine and electrically heated catalyst (© IFS)

3 RESULTS

The measurements are performed on a modified V6 diesel engine (OM642) with a research control unit. The air path has been extended to include a low-pressure exhaust gas recirculation section. The reduced compression ratio of ε = 15.5 benefits the partially homogeneous combustion, since a low cylinder pressure and temperature prevail in the compression phase, increasing the ignition delay time and the associated homogenization. The control unit implements partially homogeneous combustion for the lower load range (with an indicated mean effective pressure up to 4 bar and engine speeds from 850 to 2400 rpm). Above the PHCCI range, conventional diffusive combustion follows. Compared to diffusive combustion, the reduced exhaust gas temperature leads to higher HC/CO emissions in PHCCI combustion. To achieve the light-off temperature more quickly, the series catalytic converter is replaced by an electrically heated catalytic converter. Engine and catalyst data are listed in **TABLE 1**.

NO_x emissions are measured at the turbine outlet, while HC and CO emissions are measured at the diesel particulate filter outlet. The soot emissions are metered with an AVL Micro Soot Sensor, which is mounted between the turbocharger and the catalytic converter. The Hybrid Electric Vehicle (HEV) consists of a 48-V system with an EM, an electrically heated catalytic converter, PHCCI combustion in the lower load range and diffusive combustion in the load range above and phlegmatization of the ICE. The torque and speed profiles required for the test bench are generated by the powertrain simulation developed with the ECMS and phlegmatization operating strategies acting in parallel. The speed/torque profile of the ICE is reproduced on the test bench. The results of the measurements on the Worldwide harmonized Light-duty vehicle Test Cycle (WLTC) Class 3 for the HEV concept and for a conventional vehicle with diffusive diesel combustion are discussed below.

FIGURE 3 shows the comparison of the combustion engine operating points of the conventional vehicle and the HEV. The majority of the HEV's operating points are shifted into the PHCCI range due to EM assistance and phlegmatization. The high proportion of electrically assisted driving translates into a higher torque requirement for battery charging: Most operating points outside the PHCCI range are between 100 and 200 Nm. In contrast, there are only a few operating points in the torque range between 60 and 100 Nm. The conventional vehicle exhibits a significantly greater dispersion across the entire engine map.

The torque profiles in **FIGURE 4** show the influence of the EM and phlegmatization. For the case of the conventional vehicle, the ICE operates strongly transiently. In the HEV concept, the ICE can be phlegmatized with the aid of the EM and thus operated less transiently. The time interval between 1200 and 1350 s exemplifies the clear formation of plateaus in the torque profile. The ICE thus operates at the same torque level over a long period of time, which leads to less intervention by the pressure gradient control and thus to a smaller shift of the combustion into the expansion phase. In the lower diagram of **FIGURE 4**, the higher proportion of the PHCCI process compared to the diffusive one can be seen. The ICE can be operated in PHCCI mode for long periods of time without switching to diffusive mode.

TABLE 2 compares the specific emissions for NO_x, soot, CO and HC of the conventional vehicle with diffusive diesel combustion and those of the HEV concept. The evaluation shows that all four emission types could be significantly reduced in the WLTC. The usage of an electrically heated catalyst achieves drastic reductions in CO and HC emissions of 97.86 and 42.48 %, respectively. The EM and phlegmatization reduce emissions of soot by 74.89 % and NO_x by 14.71 %. If the NO_x emissions are considered without regarding the high-speed phases, the HEV concept emits 51.0 compared to 224.25 mg/km of the conventional vehicle. This corresponds to a reduction of 77.26 %.

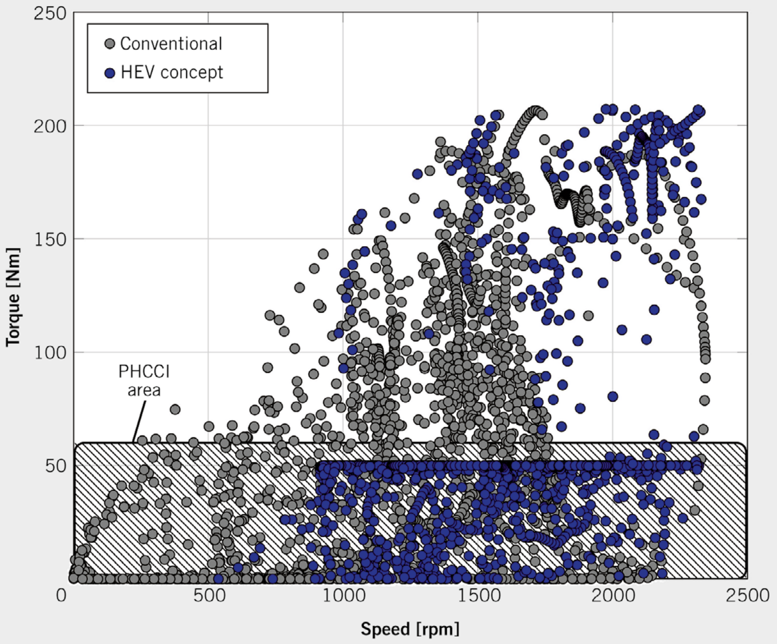

FIGURE 3 ICE operating points on WLTC: conventional vehicle versus HEV concept (© IFS)

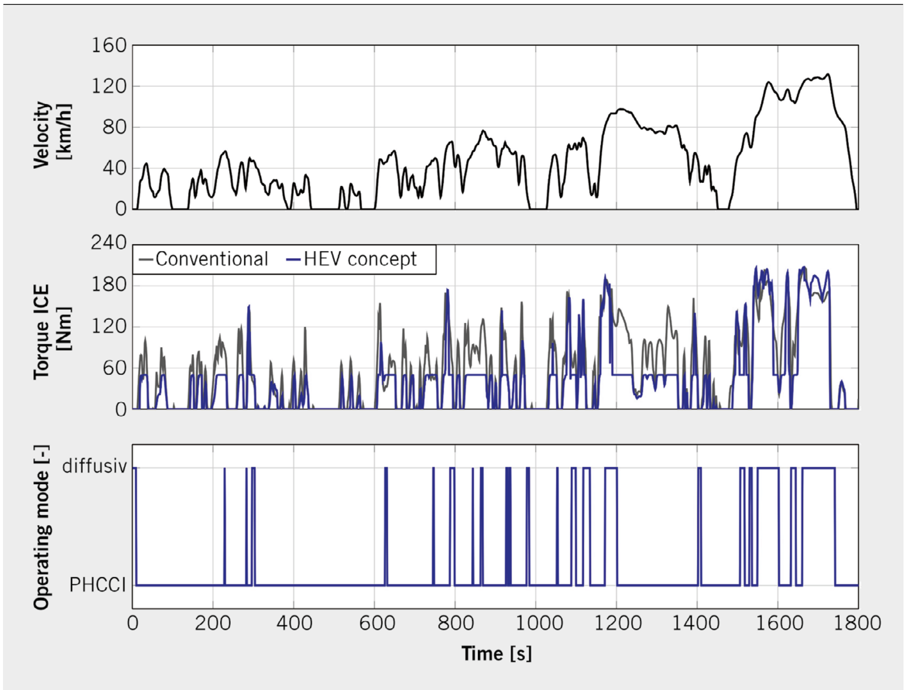

FIGURE 4 Velocity (top) and operating modes (bottom) of the ICE at WLTC with comparison of the torques of the conventional vehicle and the HEV concept (middle) (© IFS)

Vehicle concept	NO_x	Soot	CO	Total Hydrocarbons (THC)	Unit	Fuel consumption	Unit
Conventional vehicle	508.87	145.51	462.97	75.78	mg/km	6.65	[l/100 km]
HEV	434	36.54	9.93	43.59	mg/km	6.13	[l/100 km]
Change	-14.71	-74.89	-97.86	-42.48	%	-7.82	[%]

TABLE 2 Specific emissions and fuel consumption during WLTC (© IFS)

4 SUMMARY

The evaluation of the measurements at the WLTC show that phlegmatization reduces the torque demand on the ICE which also results in less intervention by the combustion control system. Torque plateaus form resulting in lower ICE load gradients. This reduces the cylinder pressure gradients and results in a less pronounced shift of the start of combustion toward the expansion phase. Furthermore, increased operating time within the partially homogeneous range can be observed due to phlegmatization.

The HEV concept with phlegmatization and electrically heated catalytic converter can achieve a significant reduction in all pollutant emissions compared to the conventional vehicle. Especially in low-speed areas, the HEV can achieve high reductions in soot and NO_x due to the high proportion of phlegmatization. By using the electrically heated catalyst, CO and HC emissions can be drastically reduced with low electric consumption. The HEV concept can not only reduce all emissions through the WLTC, but also plays its strengths especially in urban phases. Shifting NO_x emissions to high-speed phases is beneficial for the selective catalytic reduction system, as its necessary that hot operating temperatures are already reached during these phases. In addition, the fuel consumption of the HEV can be reduced by 7.82 % compared to the conventional vehicle, **TABLE 1**.

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THANKS

The research project (FVV project no. 1312) was performed by the Chair of Automotive Powertrain Systems of the Institute for Automotive Engineering (IFS) of the University of Stuttgart under the direction of Prof. Dr.-Ing. Michael Bargende as well as Prof. Dr.-Ing André Casal Kulzer and at the at the Chair in Automotive Mechatronics of the IFS under the direction of Prof. Dr.-Ing. Hans-Christian Reuss. Based on a decision taken by the German Bundestag, it was supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the AIF (German Federation of Industrial Research Associations e. V.) within the framework of the industrial collective research (IGF) programme (IGF No. 19784 N). The project was conducted by an expert group led by Dr. Achim Lechmann (IAV GmbH). The authors gratefully acknowledge the support received from the funding organizations, from the FVV e. V. and from all those involved in the project.

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