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"Build Your Hybrid" - A Novel Approach to Test Various Hybrid Powertrain Concepts

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Abstract

Powertrain electrification is becoming increasingly common in the transportation sector to address the challenges of global warming and deteriorating air quality. This paper introduces a novel "Build Your Hybrid" approach to experience and test various hybrid powertrain concepts. This approach is applied to the light commercial vehicles (LCV) segment due to the attractive combination of a Diesel engine and a partly electrified powertrain. For this purpose, a demonstrator vehicle has been set up with a flexible P02 hybrid topology and a prototype Hybrid Control Unit (HCU). Based on user input, the HCU software modifies the control functions and simulation models to emulate different sub-topologies and levels of hybridization in the demonstrator vehicle. Three powertrain concepts are considered for LCVs: HV P2, 48V P2 and 48V P0 hybrid. Dedicated hybrid control strategies are developed to take full advantage of the synergies of the electrical system and reduce CO_2 and NO_x emissions. Experimental testing of the demonstrator vehicle on a chassis dynamometer is used to evaluate the control strategy and demonstrate the capabilities of the "Build Your Hybrid" methodology. For the HV P0P2 hybrid configuration, a 3.5% benefit in fuel consumption and a 45% benefit in tailpipe NOx emissions are realized in WLTC compared to the conventional powertrain. For the 48V P2 and P0 hybrid configurations, initial results are available and the control strategy is presented.

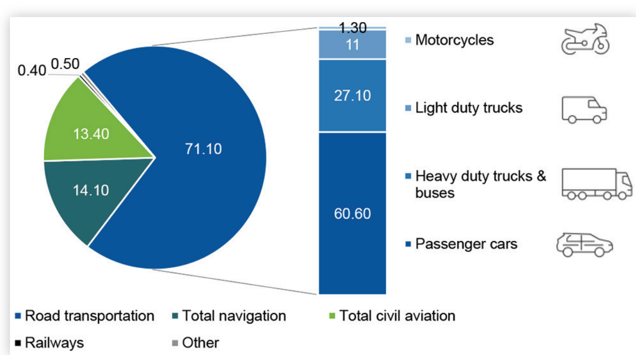
Introduction

In recent years, concerns about global warming and climate change have increased. According to the European Commission [1], road transport accounted for 71% of the total GHG emissions in the European Union (EU) in 2019, see Figure 1, with cars and vans accounting for 15 % of total GHG emissions [2]. As a countermeasure, the European Green Deal calls for a 90% reduction in GHG emissions from the transport sector by 2050 compared to 1990 levels. Additionally, the European Climate Law mandates a binding economy-wide GHG reduction target of at least 55% by 2030 compared to1990 levels in order to achieve climate neutrality by 2050. As part of this "Fit for 55 package", the revised CO_2 emission limits for cars and vans are as follows [2]:

- Cars: Reduce average CO_2 emissions from new cars by 15% by 2025, 55% by 2030 and 100% by 2035, relative to the 2021 target of 95 g/km
- Vans: Reduce average CO_2 emissions from new vans by 15% by 2025, 50% by 2030 and 100% by 2035, relative to the 2021 target of 147 g/km

For pollutant emissions, the European Commission has started the development of the next stage of Euro 7/VII emission standards. The new standards are expected to be implemented around 2025. The main focus will be to ensure that vehicles are "as clean as possible" under "all driving conditions" and over their entire useful life [3]. The new

FIGURE 1 Distribution of transport-related greenhouse gas emissions in the European Union in 2019 [1]



emission standards are likely to include another significant reduction in pollutant limits and a parallel extension of the current RDE test conditions with a focus on short trips and cold starts. While most EU6D vehicles already today achieve very low emissions when driving over medium distances (>12 km), ensuring the lowest emissions even when driving over very short distances is still a challenge.

To meet these stringent regulations, optimization of the powertrain is required. For example, alternative fuels can be used instead of conventional fossil fuels. Powertrain electrification is another important option that has been explored and introduced into production by many OEMs over the past decade. While full electrification seems feasible and the preferred choice for passenger cars, it may not be optimal for the heavier vehicles segment due to the required driving ranges and the diverse operating characteristics, e.g., for commercial and off-highway applications. A hybrid electric powertrain appears to be an appealing alternative for many of these vehicle segments.

One such interesting segment is the Light Commercial Vehicle (LCV) segment. LCVs are typically employed for freight and passenger transport within urban areas, but are also used in interurban and motorway operations. These diverse operation cases are often unsuitable for full electric powertrain concepts, limiting their large-scale introduction [4]. Therefore, in addition to full electric powertrains, hybrid powertrain concepts with a strong level of electrification are likely to be introduced on a larger scale. The introduction of hybrid powertrain technology increases costs, but also offers new opportunities for optimizing the internal combustion engine and its Exhaust gas After Treatment System (EATS).

There are various concepts for the powertrain of a Hybrid Electric Vehicle (HEV), depending on the hybrid topology and the level of hybridization. Based on the topology, HEV powertrains are divided into four categories - series, parallel, power split and mixed-mode hybrids. According to the level of hybridization, HEVs are also classified into micro, mild, full and plug-in HEVs. A detailed review of the different hybrid powertrain configurations is provided in [5].

The determination of an optimal powertrain configuration and component size is referred to as Design Space Exploration (DSE), which is usually formulated as a multi-objective optimization problem. The optimization problem usually considers the major mechanical and electrical components and the control strategy parameters. Due to the numerous possibilities for the HEV powertrain concept, the design space is ample and the computational effort for the optimization is correspondingly high. The typical optimization approaches for a large DSE, as described in [6], are brute-force, derivative-free [7, 8], and gradient-based algorithms [9, 10, 11]. In order to reduce the computational cost, a statistical optimization method using the Design of Experiments (DoE) is proposed in [12] to develop a powertrain concept. In [13], the HEV architecture is fixed and not varied for the powertrain optimization. This approach is not holistic and limits the scope of design optimization to the sizes of only specific components.

These simulation-based approaches to powertrain optimization are often based on assumptions and have drawbacks in reproducing the same behavior when validated under real-driving conditions [14]. This is especially true for exhaust gas emissions. For example, when dynamic programming is used for the control strategy during powertrain optimization, the different powertrains are compared with their best possible strategy in a drive cycle. However, this global optimal control strategy is usually hard to reproduce using the rule-based controller required for real-time implementation. Moreover, the optimality of the strategy is not guaranteed for other driving cycles. Also, the actual driving experience is missing. The alternative solution is to set up multiple demonstrator vehicles with different powertrain concepts and component sizes. This is associated with high costs, effort and time.

In this context, this publication introduces a novel "Build Your Hybrid" approach, which allows to experience and test various hybrid powertrain concepts. This approach is used to investigate different powertrain concepts for the LCV segment. For this purpose, a demonstrator vehicle with the internal codename SISAL was built.

SISAL Demonstrator Vehicle

The main targets of the demonstrator vehicle are:

1. Identification of optimized hybrid powertrain configurations for different customer requirements and operating characteristics in the LCV segment
2. Optimization of the operating strategies for diesel hybrid powertrains
   - Fast heat-up of the EATS for lowest cycle emissions
   - Transient emission reduction
   - Prevention of critical conditions for the EATS
3. Evaluation of CO_2 and pollutant emission benefits
4. Definition of a cost optimized internal combustion engine and EATS design for different levels of electrification

FIGURE 2 Diesel hybrid demonstrator vehicle to test various hybrid powertrain concepts

Powertrain Concept

The base vehicle for the demonstrator is a VW Crafter. It is a panel van 2017 model with a medium wheelbase (3.64 m) and a low roof. The VW Crafter is offered in many different configurations (front, rear and all-wheel drive). For the demonstrator vehicle, a rear-wheel drive configuration was selected to facilitate the packaging of the hybrid system. The base engine in this configuration is a 4-cylinder 2.0 L DI diesel engine with a power rating of 130 kW. The engine has a 2-stage boosting system, high-pressure Exhaust Gas Recirculation (EGR) and a close-coupled SCR-coated Diesel Particle Filter (SDPF). The engine is certified according to the heavy-duty EU VI D emission standard. An 8-gear automatic transmission with torque converter is installed.

Several hybrid powertrain configurations were analyzed during the initial phase of the project [4]. Finally, the P0P2 hybrid powertrain configuration, shown in Figure 3, was selected due to its high flexibility to operate in different hybrid modes. In addition, this powertrain configuration is compatible with the mass-production components already available in the market. The first electric machine is a Belt-driven Starter Generator (BSG) integrated into the front-end accessory drive in the P0 position. The second Electric Machine (EM) is installed between the internal combustion engine and the transmission in the P2 position with a separation clutch (C0) between the electric machine and the internal combustion engine. Only series components were used in the vehicle apart from the Inverter Power Unit (IPU) of the BSG and the power distribution box (PDU). The PDU serves as a junction box for the different series-production High Voltage (HV) cables. A more detailed description of the demonstrator vehicle set-up and the selected components can be found in [4] and [15]. The technical specifications of the components in the vehicle are provided in Table 1.

FIGURE 3 Powertrain layout of the hybrid demonstrator vehicle

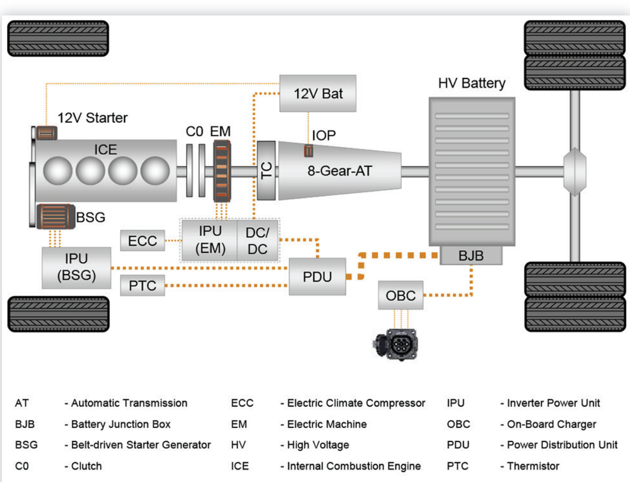


TABLE 1 Technical specifications of the components in the demonstrator vehicle

Diesel engine rated power	130	kW
Diesel engine maximum torque	410	Nm
P2 electric machine power (cont./peak)	60/95	kW
P2 electric machine torque (cont./peak)	200/350	Nm
BSG power (cont./peak)	15/30	kW
BSG torque (cont./peak)	30/60	Nm
Nominal system voltage	308	V
Usable energy	13.6	kWh
Nominal capacity	56	Ah

Hybrid Control Unit

The powertrain control system is implemented in the Hybrid Control Unit (HCU) on a dSPACE MicroAutoBox (MABX) II prototyping system. The HCU controls the auxiliary units and serves as a communication gateway for all newly added components. The software for the HCU is derived from generic software established at FEV. The software consists of modules that can be implemented depending on the hybrid topology, the components used, and the desired functional scope (e.g., cruise control, torque vectoring, and prediction algorithms). Depending on the interface to the components, only a few adjustments are necessary once the modules have been assembled.

Figure 4 gives an overview of all states and sub-states implemented in the HCU that are possible in the demonstrator vehicle. Besides the external charging, idle charging of the HV battery is possible via the internal combustion engine by the P0 and P2 electric machines in transmission mode Neutral. In transmission mode Drive, the powertrain switches to E-drive. When the internal combustion engine starts, the HCU switches between series and parallel hybrid operation depending on the state of the C0 clutch. Due to the lower power of the BSG, a series operation mode is not possible for high power demands.

FIGURE 4 Operating modes and HCU states

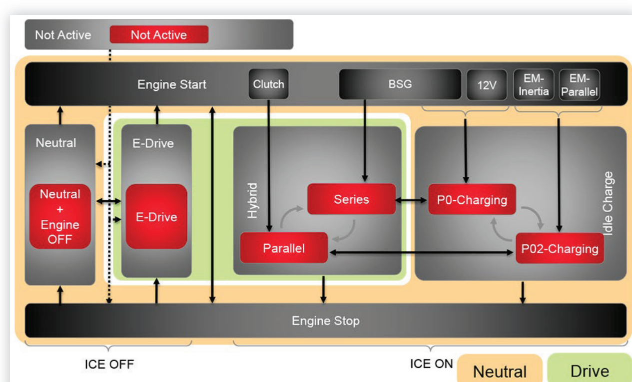


TABLE 3 Potential of fuel consumption and tailpipe NO_x emissions benefit for the considered hybrid powertrain configurations compared to the conventional powertrain.

	HV P0P2 hybrid	48V P2 hybrid	48V P0 hybrid
Fuel consumption benefit	High	Medium	Low
Tailpipe NO_x emissions benefit	High	Medium	Medium

the lower battery capacity is noticeable due to rapid discharging and charging of the battery. Therefore, the load shifting strategy for the internal combustion engine has a significant impact on NO_x emissions.

During the braking phases, the P2 E-machine recuperates energy with a maximum braking torque of 75 Nm. The actual and target SOCs at the end of the cycle are within 5% and is acceptable for charge-sustaining operation in the case of mild HEVs. Since the engine is used for a longer time in the 48V P2 hybrid configuration, a high SCR system temperature can be seen at the end of the low phase of WLTC compared to the HV P0P2 hybrid configuration. Despite reaching the light-off temperature early in the cycle compared to HV P0P2 configuration, the tailpipe NO_x emissions produced during this period will be higher due to reduced electrical support. However compared to a conventional powertrain, the 48V P2 hybrid configuration will have lower tailpipe NO_x emissions to the dedicate hybrid control functions.

The calibration of the control strategy in the 48V P0 hybrid powertrain configuration is still ongoing. Results will be part of future paperwork.

Based on the developed control strategies and initial results, a comparison of the three hybrid powertrain configurations with respect to the conventional powertrain is provided in Table 3. The HV P0P2 hybrid configuration offers a higher benefit in fuel consumption and tailpipe NOx emissions due to recuperation and masking of emission critical operation. Due to limited load point shifting, a medium benefit in tailpipe NO_x emissions is possible in the 48V P2 and 48V P0 configurations. Due to drag losses of the engine, recuperation is limited in the 48V P0 configuration resulting in a lower fuel consumption benefit.

Summary/Conclusions

Powertrain hybridization will play an important role in meeting the future CO_2 and pollutant emission legislation in the LCV segment. However, the optimal hybrid powertrain configurations for different customer requirements vary widely due to the diverse operating characteristics in the LCV segment. This paper introduces a novel "Build Your Hybrid" approach in which simulation models are implemented in a prototype control unit on a demonstrator vehicle to emulate different hybrid powertrain configurations. First, the powertrain configuration, hardware specifications, and the operating modes of the demonstrator vehicle are explained. A communication interface is established between the driver and HCU to switch between different topologies, levels of hybridization and driving modes.

Three different hybrid powertrain concepts are then selected for the LCV segment use case - HV P0P2, 48V P2 and 48V P0. The calibration of functions within the HCU, such as engine start and powertrain link, to operate the vehicle in the three topologies considered is described. By using the BSG for the start of the internal combustion engine in the HV P0P2 and 48V P2 powertrain configurations, the fuel consumption required to accelerate the engine to idle speed can be avoided. Dedicated HCU functions, like balanced load point shifting and low emission heat-up of the EATS, are developed in to minimize CO_2 and NO_x emissions. These functions are fully calibrated for the HV P0P2 hybrid configuration, and the control strategy is evaluated using WLTC measurements in charge-sustaining operation. Compared to a conventional powertrain, an advantage of 3.5 % in fuel consumption and 45% in tailpipe NO_x emissions is achieved. However, the actual potential for reducing fuel consumption is even higher and could not be achieved here due to the limitations of the vehicle braking system, which always also activates the foundation brakes when the brake pedal is applied.

For the 48V P2 hybrid configuration, first test results with a basic calibration of the control strategy are presented. These control functions are implemented through the simulation of a 48V battery. A charge-sustaining operation is achieved in the low phase of WLTC. However, the calibration should be further improved, and the CO_2 and NO_x emission reduction potential should be evaluated. The functioning of the 48V P0 configuration during a vehicle launch event is presented. The next part of this work includes the full calibration of the 48V P0 configuration and the evaluation of the control strategy in terms of the CO_2 and NO_x emission reduction potential. Finally, an optimized hybrid powertrain configuration for different customer requirements and operating characteristics in the LCV segment will be proposed by the "Build Your Hybrid" approach.

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Definitions/Abbreviations

BSG - Belt-driven Starter Generator

DPF - Diesel Particulate Filter

DSE - Design Space Exploration

EATS - Exhaust gas After Treatment System

ECU - Engine Control Unit

EGR - Exhaust Gas Recirculation

EU - European Union

HCU - Hybrid Control Unit

HEV - Hybrid Electric Vehicle

HV - High Voltage

LCV - Light Commercial Vehicle
OC - Open Circuit
SCR - Selective Catalytic Reduction
SOC - State Of Charge
UART - Universal Asynchronous Receiver Transmitter
WLTC - Worldwide harmonized Light vehicles Test Cycle

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