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Smart Hybrid Energy Management System in a Passenger Car

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The technological advancements of internal combustion engines, batteries, and electric propulsion technology have reached such a level that they bring a new dimension to the potential of hybrid propulsion systems. Partially or fully electric vehicle propulsion drivetrains receive significant attention when considering the future of mobility, as they have the potential to reduce the sector's greenhouse gas emissions and dependence on fossil fuels and hopefully mitigate climate change. This paper aims to design a hybrid powertrain for a conventional passenger vehicle that can cover the performance requirements of everyday average urban usage with electric propulsion to reduce consumption and emissions and improve sustainability. It aims to present the performance requirements of the vehicle based on road measurements conducted under various traffic conditions and usage environments. The energy savings achieved through the auxiliary powertrain will also be evaluated based on real-life, everyday usage conditions. Finally, the paper introduces a Life Cycle Assessment (LCA), which compares the original conventional propulsion system with the new hybrid powertrain.

1. Introduction

During the design phase of vehicles, most companies focus on the possible increase of fuel economy, reduction of carbon dioxide (CO_2), greenhouse gas (GHG), and pollutant emission, and provide higher driving experience and comfort with the increased torque and power of the drivetrain (Fritz et al., 2019). Besides mass production, each company tried to develop its powertrain and sought to exploit all potentials of the Internal Combustion Engines (ICE). The Brake Thermal Efficiency (BTE) of the ICE reached 40 %, but only at its best operation points. The most significant disadvantage of ICE is the urban driving cycle, it does not exploit the engine’s capabilities and the engine operates in its low-efficiency segment (Ehsani et al., 2018). Moreover, these operating points are associated with the engine map's worst Brake Specific Fuel Consumption (BSFC) values. Due to the emission, vehicles have a complex and expensive exhaust gas aftertreatment system, which manufacture requires several noble metals with high energy requirements (Lott and Deutschmann, 2021). In order to reach the requirements of sustainable transportation, an electric propulsion element is needed. The Battery Electric Vehicle (BEV) technology provides zero local (tank-to-wheel) emission, contributing to the urban air quality and supporting the citizen’s health. Otherwise, the pure electric drive has a low operation range due to the lower energy density of batteries than conventional fuels (Andwari et al., 2017). However, the hybrid propulsion technology provides a complex solution in urban and rural environments, combining each driving technology's advantages (Matharu et al., 2022). The e-drive-assisted hybrid drivetrain can cover the low efficiency ICE operating points with the traction force of the e-motor. At low RPMs, the e-motor can take over partially/totally the propulsion demand (Momoh and Omoigui, 2009). Moreover, this supplement propulsion can also be helpful in the unfavourable operating points of ICE, particularly in transient behaviours, where emission is significant. With the assistance of an e-motor, the ICE can work at a quasi-steady working point which means the highest possible efficiency and the lowest pollutant emission and fuel consumption. Besides the increased performance of the conventional drivetrain, the cooperation of these two drivetrains also reduces the size of the ICE, and the e-drive compensates for the loss of power, this strategy is called power-neutral downsizing (Klingebiel, 2008). The hybrid system also helps in the case of deceleration with regenerative braking. The produced electricity is stored in the onboard battery and is utilized for traction (Onori et al., 2016). This paper

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introduces real driving measurements with a Skoda Octavia Scout 2.0 CRTDI 4x4 car in urban and rural environments. Based on the system demands, the design and scale of a hybrid system are elaborated to save fuel in urban driving environments. A simplified Life Cycle Assessment of the new drivetrain will also be introduced.

2. Methodology

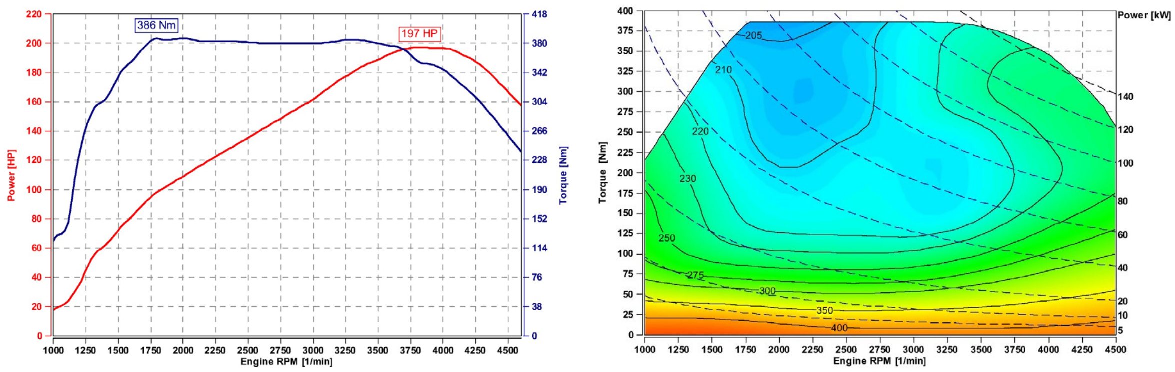
In order to achieve the possible advantages of hybrid drivetrains, it is essential to scale the propulsion system regarding the usage patterns. The scaling of the electric drive system requires the investigated vehicle's exact power and torque demands.

2.1 OBD measurement system

The car's On-Board Diagnostic (OBD2) socket collected the driving data. This standardized diagnostic system (ISO 9141) has been built in every new car since 2001. It monitors all the data in the car during the operation; its initial role is to alert the driver about engine problems, which can influence the efficiency of the exhaust gas after treatment. The extended role of this system includes storing the fault codes, monitoring live driving data of the car, inspection of the control units, and identification of the vehicle. The live driving data of the diagnostic system was used to monitor and record detailed values of the investigated car during different traffic and road environments. During the onboard diagnostic test, all the readable Packet Identifier (PID) channels (693 pcs.) were tracked by the DiagRA D software from RA Consulting GmbH. The Unified Diagnostic Service Volkswagen AG (UDS VAG) diagnostic protocol was used to communicate with the Engine Control Unit (ECU).

2.2 On-road measurements

Based on the recorded driving data, there were some dimensions which were necessary to be calculated. The car's power was defined at each recorded working point based on the measured torque and engine speed (RPM) value. Besides the torque, power, and RPM values, the BSFC is also a key figure of each operation point of the engine, which was calculated from the recorded liter/hour fuel consumption data.
The power, torque curves, and BSFC map were plotted based on these equations and on-road measurements.



(a) (b)

Figure 1: (a) Power and torque curves of the investigated car regarding OBD measurements, (b) BSFC [g/kWh] according to torque

Figure 1a represents the curve of the maximum power and torque values at each engine speed and their absolute maximum values. The behavior of the torque is very similar to the catalog data prognosis (torque maximum 1750-3250 RPM). It reaches its top value at 1750 RPM until 3500 RPM holds it. Similarly, to other state-of-the-art diesel engines, the torque is electrically controlled because of the mechanical boundaries of the powertrain. The power curve is also similar to factory data (power maximum 3500-4000 RPM). In this case, the maximum range is between 3750 RPM and 4000 RPM. The magnitude of the maximum data is near the catalog value (184 HP, 380 Nm), but in both cases, the measured values are higher (197 HP, 386 Nm). The BSFC map represents the engine speed, torque, BSFC and power in Figure 1b. This diagram clearly shows that the most efficient working range (205 g/kWh) of the car is at near full load between 1750-2250 RPM. The other end of the efficiency is the minimal load line, where BSFC is above 400 g/kWh. These are the worst operating points, and these should be avoided as much as possible during the driving sessions. Because the working points with the best efficiency are located in lower RPMs, the operation of the engine has to be forced to this region, this is one of the initial ideas of downspeeding.

2.3 Test drives in different environments

In order to determine the power and torque demand, it is necessary to investigate the vehicle in different traffic situations. From the measured records, only the positive power output (not engine brake operation) and positive vehicle speed operating points were only considered. The engine characteristics were analyzed in traffic jam, urban, highway, and urban combined and motorway environments. Evaluating all working points, it is evident that only a small part of the available power and torque is utilized during average driving conditions. The majority of power is spared for aggressive acceleration and overtaking. Based on these figures, the research question arises: *Do we need to operate the internal combustion engine all the time during our everyday life if we only utilize a fraction of the nominal power and torque?*
The abovementioned data provide the base for a real hybrid concept. In order to achieve the maximum efficiency of the drivetrain and less fuel consumption, it is essential to operate the internal combustion engine at the working points. Otherwise, a dedicated e-drive can cover the remaining propulsion demands of the car.

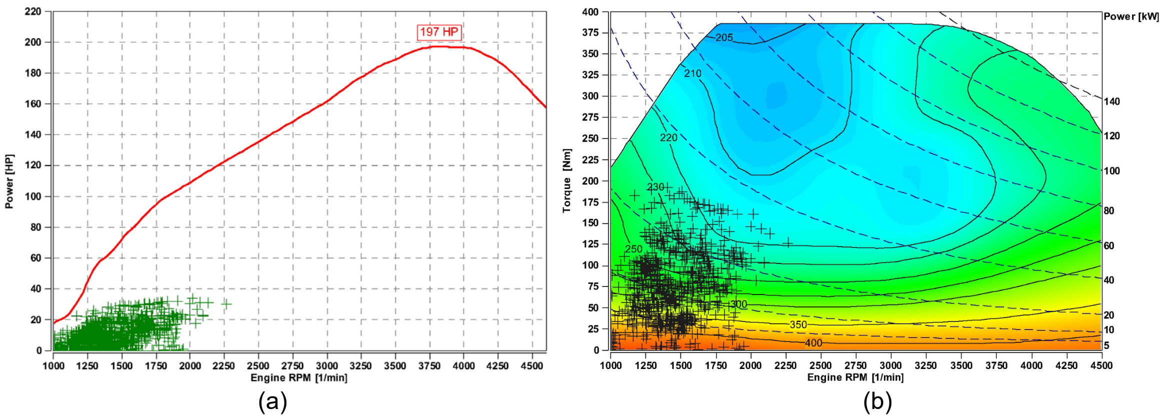


Figure 2 (a) BSFC [g/kWh] according to torque with urban working points, (b) Power curve of the car with urban working points

Figures 2a and 2b represent the urban working points with black crosses. Only a small part of the engine map is utilized for propulsion, and a more significant portion of the working points is located in low BSFC areas.

2.4 Scaling boundaries

According to the measurement objectives were set up, which have to be key factors during the design of the hybrid drivetrain of the investigated car:

- All urban working points have to be covered with e-propulsion. Based on the recorded power and torque demand in the city, the necessary continuous e-power has to be 50 kW with 200 Nm torque for dynamic urban accelerations.
- The battery must have an average day driving capacity with some spares for longer drives in bigger cities and engine-banned areas, so its range should be around 50 km.
- In urban and restricted areas, with the help of the properly scaled hybrid system, zero tank-to-wheel emission can be achieved, which can influence the city's air quality positively.
- The ICE has to be switched on when the power or the capacity of the e-drivetrain cannot cover the propulsion demands. Based on the BSFC map, the ECU has to try to keep the engine in its best efficiency range. If the energy demand for propulsion is higher than the energy produced by the ICE in its best working range, the ECU has to increase the load and/or the RPM to provide more energy output from the engine. Otherwise, if the operation of the ICE is necessary to cover driving demands, but the produced energy – operating at its best efficiency – is more than the required, with the help of the e-motor, the surplus energy can be recovered to the battery. As the following equations represent, it worth to operate the ICE in its best BSFC (205 g/kWh) environment and convert the surplus energy to electricity, store it in a battery and convert back to rotation, its efficiency is 32.23 %. Meanwhile forcing the ICE to work in a low BSFC (400 g/kWh) point is less efficient (BTE_1 = 21.13 %).

$$BTE_1 = \frac{1}{BSFC * Diesel\ LHV} = \frac{1}{400\ g/kWh * 0.01183\ kWh/g} = 21{,}13\ \% \quad (1)$$

$$BTE_2 = \frac{1}{BSFC * Diesel\ LHV} = \frac{1}{205\ g/kWh * 0.01183\ kWh/g} = 41{,}23\ \% \quad (2)$$

$$BTE_2 * \text{Generator } \eta * \text{Battery pack round-trip } \eta * \text{Motor } \eta = 0.4123 * 0.97 * 0.876 * 0.92 = 32.23\ \% \quad (3)$$

The efficiency of generator, battery and electrical motor are based on average literature percentages, the Eq.3. applied these efficiency values(Cuddy and Wipke, 1997). The diesel's lower heating value (LHV) is 11.83 kWh/kg (The Engineering ToolBox, 2003).

3. Results

3.1 Battery scaling

According to the measured data, in an urban test cycle, the average time for propulsion is 57.5% of the total driving time. Calculating with a 50 km range and the measured 28.8 km/h average speed, it results in 1 hour for propulsion.

$$\text{Time for propulsion [h]} = \frac{\text{Range [km]}}{\text{Average speed}\left[\frac{\text{km}}{\text{h}}\right]} \times \frac{\text{Positive power output [\%]}}{100} = \frac{50\text{ km}}{28.8\ \frac{\text{km}}{\text{h}}} \times \frac{57.5\ \%}{100} \cong 1\text{ h} \quad (4)$$

The 1-hour propulsion demand means 1.74 hours (50km / 28.8 km/h) total trip time. The following equation represents the scaling of the battery capacity.

$$C_b\ [\text{kWh}] = \left(\frac{1}{1 - \frac{SOC_{min}\ [\%]}{100}}\right) \times (T_p\ [h] \times P_a\ [kW] + T_t\ [h] \times (P_{aux}\ [kW] + P_h\ [kW])) - E_b\ [kWh] \cong \mathbf{17\ kWh} \quad (5)$$

The battery's optimal minimum (SOC_{min}) is around 20 % to maintain its maximum lifetime. So, it is necessary to scale the battery higher than the net energy demand to fulfill this objective. The calculated propulsion time (T_p) multiplied by the average traction power (P_a) gives the capacity demand for propelling the wheels. The power demand of auxiliaries (P_{aux}) and cooling or heating (P_h) are also added to the driving time. There is no significant difference in the magnitude of the surplus power demand for heating and air conditioning in the case of an electric car (Evtimov et al., 2017). It was assumed that -20 °C is the minimum in winter and +40 °C is the maximum in summer as two extremeness of the operating area of a car. In both cases, the heating or air conditioning system increases the basic consumption by ~80 Wh/km. There is one feature that could reduce the demanded capacity, and it is regenerative braking (E_b). There are several using patterns, but in an average urban environment, about 17 % of the traction energy can be regenerative braking, considering the efficiencies of all steps (Björnsson and Karlsson, 2016). In this case study, it means 1.4 kWh energy (1 h * 8.24 kW * 0.17).

3.2 Drivetrain scaling

The e-drivetrain's biggest drawback is the additional weight. As previously mentioned, a 50 kW power e-motor is needed, which assumed weight is ~60 kg based on industrial reference, including power electronics and transmission. The weight of the scaled battery is ~182 kg, moreover, the packaging and the electronics of the battery also mean ~40 kg (Toshiba, 2023). On the other side, assuming an axle-split hybrid design, some parts of the conventional drivetrain (cardan shaft, Haldex coupling, differential) can be removed for a total weight of approx. 50 kg. So, 232 kg remains as additional weight (60 kg + 182 kg + 40 kg – 50 kg). This value was considered in the Life Cycle Assessment. The fuel and power consumption data were measured with this extra weight in the car's trunk and considering the driver's weight of 100 kg.

3.3 Life Cycle Assessment

The Life Cycle Assessment compared the environmental impacts of the conventional drivetrain with the hybrid one. 200,000 km mileage was considered, distributed to 50,000 km of urban usage and 150,000 km extra-urban distance. Table 1 represents the input data that were considered during the LCA calculation.
The following simplifications were assumed during the Life Cycle Assessment:

- Only the electric drivetrain is used in urban environments with zero tank-to-wheel emission.
- Extra-urban usage pattern using only internal combustion engine driven section.
- The emission of production of the original car was neglected because this paper aims to represent the comparison of conventional and hybrid drivetrains. In both cases, the stock vehicle is the same with the same amount of production emission.
- The magnitude of recycling and disposal emissions is negligible in the case of conventional drivetrain because it is only a small amount of pollution which does not appear as an additional emission in the whole life cycle. This study does not include the determination of the amount of the carbon footprint regarding battery recycling.

Table 1: Input data to the LCA of the conventional and hybrid drivetrain

Parameter	Value	Source of data
Urban fuel consumption	8.5 l/100km	Measurement
Extra-urban fuel consumption	6 l/100km	Measurement
GHG emissions from diesel burned	2.67 kg CO_2 eq./l	(Valsecchi et al., 2009)
Production GHG footprint of the battery	0.185 kg CO_2 eq./Wh	(Peters et al., 2017)
Battery capacity	17 kWh	Based on Chapter 3.1
CO_2 emission of the electricity – world average	0,56 kg CO_2 eq./kWh	Sphera Solutions
Urban energy consumption	28.61 kWh/100km	Measurement
Extra-urban energy consumption	21.18 kWh/100km	Measurement
Diesel fuel Well-to-Tank emission	0.64 kg CO_2 eq./l	(Hoekstra, 2020)

Figure 3 shows the results of LCA, representing the break-even point and differences regarding GHG emissions during the whole lifecycle.

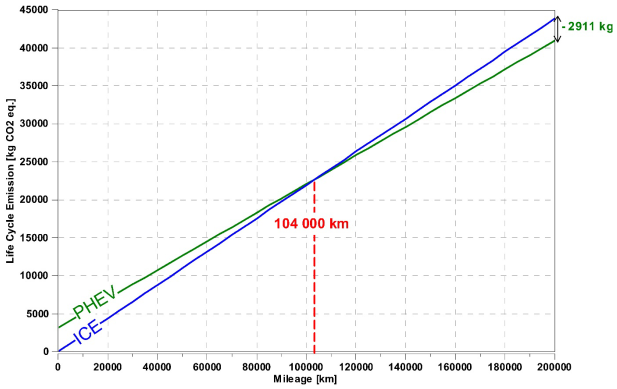


Figure 3: Life Cycle Assessment of the conventional and plug-in hybrid drivetrain

According to the calculation, at 0 km mileage, the PHEV has a disadvantage because of the additional CO_2 emission during battery production. However, this drawback disappears at 104,000 km, the break-even point. Above this mileage, the plug-in version is more environmentally friendly than the conventional one. After the break-even point, the difference between the two drivetrains becomes bigger and bigger, and at the end of the 200,000 km mileage, the hybrid's advantage will be 2911 kg CO_2 eq. It means less GHG emission with nearly 3 tons of CO_2 eq. then the conventional one.

4. Conclusion

The key target of this paper was to elaborate on a hybrid system, which is designed and scaled based on real driving situations, traffic, and usage patterns. The philosophy of multi-dimensional analysis and optimization, including the Life Cycle Assessment methodology, was integrated into evaluating the investigated systems. The outcome is a hybrid system with a 50 kW e-motor and 17 kWh battery capacity, allowing a minimum 50 km EV range under all realistic ambient conditions. A new algorithm was developed to define the battery capacity based on the average power demand but considers multiple variables of different use cases and climatic conditions (auxiliaries, heating/AC, regenerative braking). The Life Cycle Assessment based comparison of the conventional and hybrid drivetrain showed that the proposed system has the potential of nearly 3 tons of true GHG abatement during 200,000 km mileage.

Nomenclature

C_b – Battery capacity, kWh
E_b – Reusable energy of regenerative braking, kWh
P_a – Average power demand, kW
P_{aux} – Power demand for auxiliaries, kW
P_h – Power demand for heating/air conditioning, kW
SOC_{min} – Minimum battery state-of-charge, %
T_p – Time for propulsion, h
T_t – Total driving time, h

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