EVALUATING ELECTRICITY CONSUMPTION OF SPECIALISED BATTERY ELECTRIC VEHICLES USING SIMULATION MODEL

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Abstract

Battery Electric Vehicles (BEVs) are widely seen as one of the available options to combat increasing greenhouse gas emissions. However, these vehicles' use is less widespread than conventional combustion engine vehicles. One reason for this is their still relatively short range and long charging times. For this reason, it is becoming increasingly crucial in BEV development to use the most accurate simulation models that allow the impact on electricity consumption to be analyzed based on changes made to individual powertrain components. To this end, the author's dissertation deals with developing a simulation model for estimating the power consumption of a BEV powertrain, describing the definition of the efficiency parameters of the individual powertrain components. The results from the simulation model were then compared with measurements performed in a test facility. The maximum deviation of approximately 8% was measured depending on the driving cycle and parameters.

Keywords

Energy consumption; Simulation; Powertrain; BEV; Efficiency.

Introduction

Battery electric vehicles are now becoming an increasingly common alternative to vehicles with ICE. Their gradual expansion is mainly due to the desire to reduce greenhouse gas emissions and protect the environment. This effort is supported by the European Union's long-term strategy [1], which aims to transform the transport system in Europe by 2050, thereby contributing to reducing emissions and increasing the use of renewable energies. According to the results published in [2], unlike other sectors, greenhouse gas emissions in road transport have increased by 27.8% from 1990 to 2019, and despite the decline caused by the Covid-19 crisis, emissions are expected to increase again briefly in the coming years. However, this increase will be gradually eliminated by better energy efficiency, reduced energy consumption and the use of alternative fuels. In this respect, BEVs offer higher efficiency, i.e. higher energy savings and emission reductions (especially if the electricity is generated from renewable sources). According to the results published in [3], BEVs are more efficient than gasoline or diesel vehicles in terms of emissions in all scenarios considered. In the ideal case where an EV is charged only with electricity generated from renewable sources and is equipped with a battery produced in an environmentally friendly way, EVs are about five times more environmentally friendly than conventional vehicles with combustion engines.

As mentioned in [2], BEVs are expected to reduce their greenhouse gas emissions in the future, mainly due to the increasing efficiency of these vehicles. Simulation models are ones of how this problem can already be accelerated today. Despite advances in EVs, many factors are still to consider, and simulation models are still an essential tool to achieve the best results. These simulation models allow us to calculate how specific changes made to an individual component of a vehicle will affect its performance and electricity consumption based on the exact data of each component. These models can then incorporate many factors into the calculation, which may include, for example, the effect of ambient conditions or the driver's driving style, in addition to the physical parameters of the individual vehicle components. This allows researchers and vehicle manufacturers to create the highest possible efficiency of BEVs.

1 Research Subject

The present work describes the design of the BEV simulation model, a description of the input parameters definition and its validation. With the help of this model it will be possible to estimate the power consumption of the powertrain and thus determine with sufficient accuracy, among other things, the range of the vehicle. All this is to search for the potential to improve its energy efficiency. In contrast to other publications that assume constant efficiency of the individual powertrain components, the effort is to include in this model, as precisely defined as possible, the efficiency maps of the mentioned components as a dependence of torque on speed over the entire range in which the specific component will operate.

2 Methodology

The research in this article is based on a simulation model of the driving dynamics of a battery electric vehicle, which allowed us to define the powertrain consumption of the vehicle during specific driving cycles. The simulation model was created in software Ricardo Ignite [4]. The results from this simulation were then validated in a dedicated facility. The Ricardo Ignite software based on the Modelica programming language is commonly used in the automotive industry to simulate various dynamic phenomena. The software contains many libraries that make it possible to model various powertrain components of commercially available vehicles.

2.1 Simulation Model

Currently, according to [5], two types of simulation models are mainly used to simulate vehicle driving dynamics. These are the forward simulation model and the backward simulation model. The fundamental difference between these simulation models lies in the calculation procedure. In this work, we have used the forward simulation model to calculate the power consumption of the powertrain. In this case, it provides more accurate results than the backward simulation model, albeit at the cost of higher computational time. The architecture of the forward simulation model describing the general arrangement of the elements is shown in Figure 1.

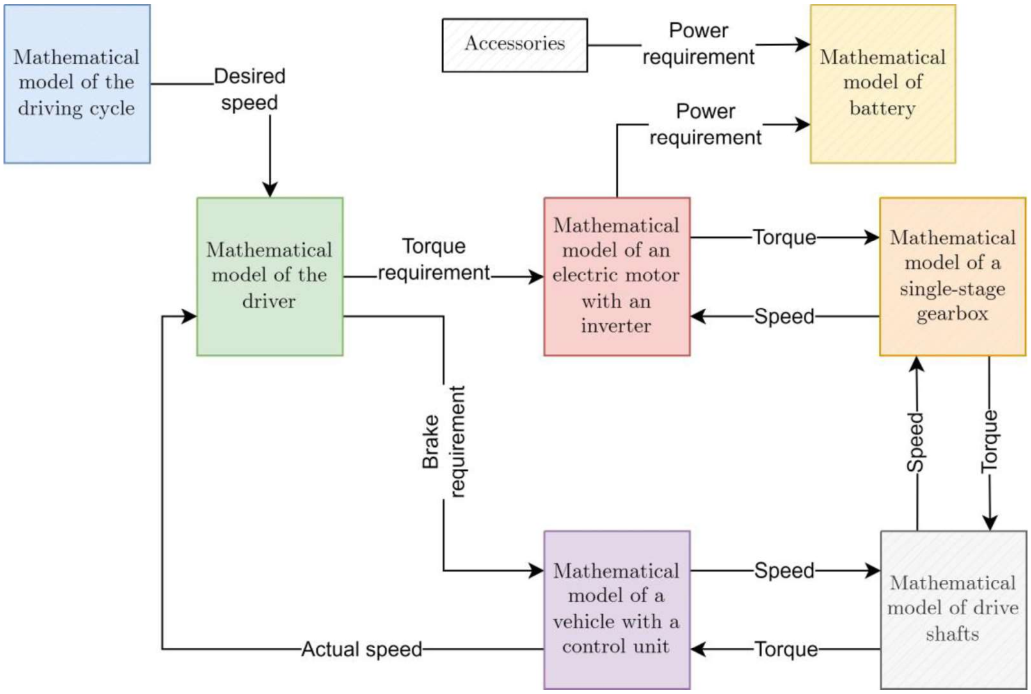

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Fig. 1: *Layout of the simulation model*

2.1.1 Description of Defined Input Parameters

To ensure the desired function of the simulation model, it was necessary to define the parameters of the individual mathematical blocks that make up the model. These elements of the model include various aspects of the vehicle, such as powertrain parameters, environmental parameters and driving cycle parameters, on which the simulation model results are evaluated. The parameters of a specific vehicle were defined through detailed analyses of the different parts of its powertrain, which included, for example, the characteristics of the engines, transmission, and batteries, including a detailed definition of their efficiency at different speeds and different loads. Table 1 lists the basic vehicle parameters considered in the simulation. In addition to these parameters, environmental parameters such as terrain topography, temperature and weather conditions that can affect the vehicle behaviour were also included in the individual models. Another important aspect in developing the simulation model was defining the driving cycle parameters to match the actual vehicle operation as closely as possible. In this case, two driving cycles were simulated, which are the CARB Heavy-Duty Diesel Truck (HHDDT) Creep Segment (CARB-HHDDT-CS) and the NREL Port Drayage Creep Queue Cycle (California) (NREL-PDCQC). Both drive cycles were taken from the Drive Cycle Analysis Tool (DriveCAT) [6], which provides drive cycle data based on real vehicle operations. The CARB-HHDDT-CS drive cycle was developed in California and is used for testing heavy-duty vehicles. The second driving cycle, NREL-PDCQC, is used for testing trucks that are used to transport goods in port areas. This driving cycle focuses on speeds up to 30 km/h and frequent stopping and starting of the vehicle, corresponding to the actual operation of vehicles in port areas.

Tab. 1: *Basic parameters of the vehicle*

Parameter	**Value**
Rated torque of one electric motor	42 Nm
Rated power of one electric motor	10 kW
Total vehicle weight	3000 kg
Dimensions (h x w x l)	1000 mm x 1925 mm x 3850 mm
Maximum speed	30 kmh^{-1}
Vehicle frontal area	1,82 m^2
Air drag coefficient	0,6
Tyre outer radius	0,362 m
Coefficient of rolling resistance	0,1

Source: Own

A unique feature of the modelled vehicle is that it comprises four identical electric motors and four converters with each electric motor driving one wheel. Related to this is the identical number of single-speed gearboxes and drive shafts. At the same time, the vehicle contains a single electric battery that is common to all the high-voltage electric elements. According to the definition of the powertrain of electric vehicles given in [7], the vehicle can contain four powertrains. For this reason, the results below will only be given for “one-quarter of the vehicle”, i.e. one powertrain. The system of one powertrain mounted on one vehicle axis is highlighted in blue in Figure 2.

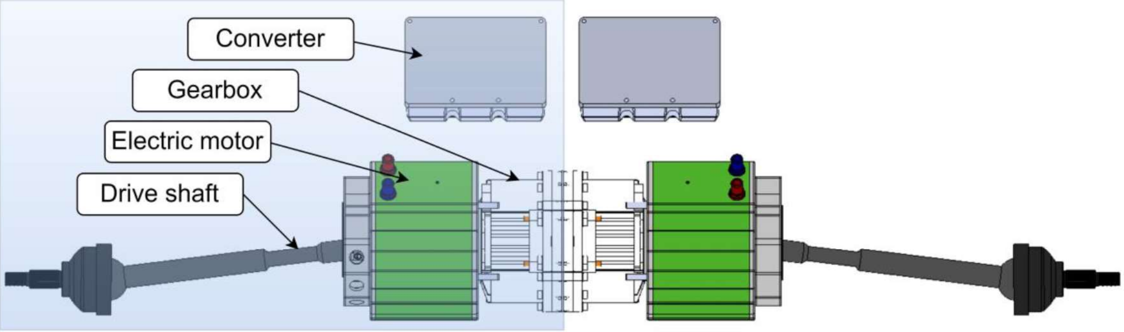

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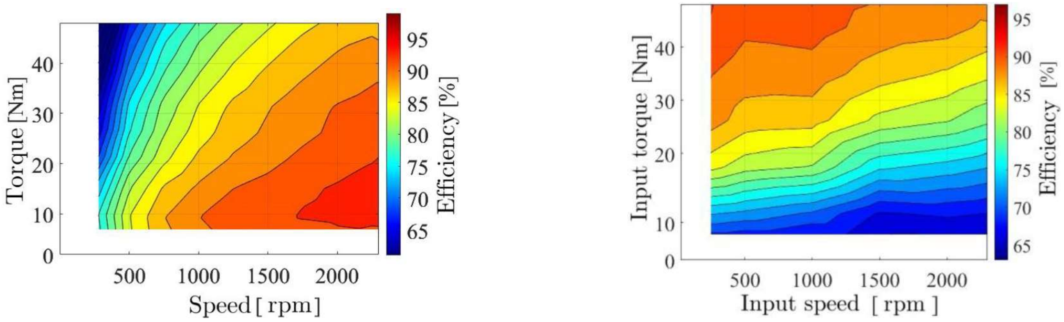
Fig. 2: *Two powertrains on one vehicle axis with the evaluated driveline highlighted*

2.2 Determining the Efficiency of Individual Powertrain Components

Along with defining the general vehicle parameters, it was necessary to determine the efficiencies of the individual powertrain components in the relevant mathematical models. Although individual powertrain components currently achieve relatively high efficiencies, the product of these efficiencies across the whole system can significantly impact the vehicle’s overall efficiency. It could adversely affect the results generated by the simulation model. The efficiency of electric vehicles (“Tank to Wheel”) can range from 50% to 80% for BEVs according to study [8]. In order to determine the efficiencies of the individual components in the respective mathematical models, the equipment and test facilities available at the powertrain laboratory of the Technical University of Liberec were used. Among the most crucial equipment we can mention the engine test bench with dynometer HORIBA DYNAS$_3$ LI 250 and the Powertrain test bench designed for long-term tests of the entire powertrain system of all types of vehicles.

In total, three measurements were performed in the experimental part which is shown in Figure 3. The individual sub-figures show the efficiency maps of the individual components of the powertrain of the vehicle under consideration, which are the electric motor system with converter in Figure 3 (a), and the gearbox in Figure 3 (b). These maps represent the efficiency as a dependence of speed on torque.



(a) Efficiency of the electric motor with converter **(b)** Efficiency of gearbox

Source: Own

Fig. 3: *Efficiency of the electric motor with converter and gearbox*

The efficiency of the electric motor and converter was measured on a motor station equipped with an asynchronous dynamometer HORIBA DYNAS$_3$ LI 250, to which a shaft coupling connected the electric motor. A battery emulator of a high voltage battery with a DC source ITECH IT6000C realized the power supply of the electric motor and the inverter. This power supply was set to deliver a maximum voltage of 100 V. The maximum current was limited to ± 290 A. The input power was calculated from the voltage supplied and the current drawn. The output power was then calculated from the speed and torque of the electric motor. The electric motor was operated at a certain speed level with a gradual increase in torque. The speed of the electric motor was increased in steps of 250 rpm and the torque of the motor in steps of 5 Nm. The electric motor was operated at each defined point for 40 s. The first 10 s were used for settling the values and the subsequent 30 s for the data recording. From the data thus recorded, an average value was then calculated for each variable, which was fitted into relationship (1), where P_{dyno} is mechanical power measured on dynamometer and P_e is the electrical input power of the assembly of electric motor and the converter.

$$\eta_m(n,M)=\frac{P_{dyno}}{P_e}=\frac{2\cdot\pi\cdot\frac{\overline{n_{dyno}}}{60}\cdot\overline{M_{dyno}}}{\overline{U_{DC}}\cdot\overline{I_{DC}}} \tag{1}$$

The second step was to define the mechanical efficiency of the gearbox. This efficiency was determined using a method referred to in the literature as "*Back to back electrical*" [9], where the gearbox is placed between two dynamometers, one connected to the input and the other to the output shaft of the gearbox. One of these dynamometers always serves to drive the gearbox and the other serves as a load. For this purpose, the Powertrain test bench, also available in the powertrain laboratories at the Technical University of Liberec, was used. Both dynamometers are equipped with speed and torque sensors used to calculate the power on input and output shafts. As in the previous case, the gearbox was loaded for 40 s, with the first 10 s being used for settling the values and the subsequent 30 s for the actual data recording. From the data recorded in this way the average value for each variable was calculated and then the mechanical efficiency at each measured point was calculated according to relationship (2), where P_{PP} is the mechanical power measured on the front right dynamometer and P_{LP} is the mechanical power measured on front left dynamometer. The measurements were again always carried out for a certain speed level with a gradual increase in torque. The speed was increased in the interval of 250 rpm and the torque in the interval of 8 Nm.

$$\eta_{pr}(n, M) = \frac{P_{PP}}{P_{LP}} = \frac{2 \cdot \pi \frac{\overline{n_{PP}}}{60} \cdot \overline{M_{PP}}}{2 \cdot \pi \frac{\overline{n_{LP}}}{60} \cdot \overline{M_{LP}}}, \quad (2)$$

The last component of the powertrain is the drive shaft. The mechanical efficiency of the drive shaft was not directly measured in this work. The drive shaft usually comprises two joints of the Rzeppa and Tripod type. The overall efficiency of the drive shaft depends precisely on the efficiency of these joints, which depends mainly on their angle. If I consider the zero angle of the joints in this work, i.e. the wheel axis is in alignment with the output shaft of the gearbox, I will take the efficiency of these joints from work [10] where the mechanical efficiency of the Tripod joint was defined as 99.8% and the mechanical efficiency of the Rzeppa joint as 99.5%. Multiplying these values according to the relation (3) gives an overall efficiency of one drive shaft 99.3%.

$$\eta_h(n, M) = \eta_{Tripod}(n, M) \cdot \eta_{Rzeppa}(n, M) \quad (3)$$

2.3 Calculating Energy Consumption Using a Simulation Model

The above-defined efficiencies of the individual powertrain components were then defined in the corresponding mathematical models. Subsequently, a calculation was performed in which the simulation model provided the results of the energy consumed by the powertrain. These results are presented in this chapter. The simulation model calculates the cumulative energy consumption shown in Figure 4.

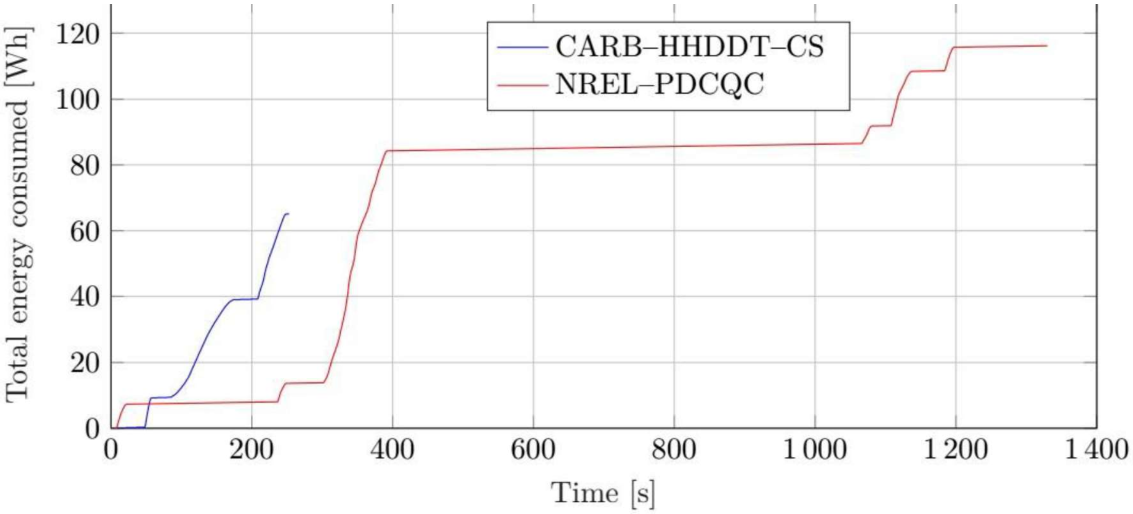


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Fig. 4: *Energy consumption during individual driving cycles obtained from the simulation model*

From the results, we can see that in the case of the CARB-HHDDT-CS driving cycle, which is marked here in blue, the total accumulated energy extracted from the battery was equal to 65.1 Wh, while the driving time of the vehicle on this driving cycle is 253.8 s. During the simulated driving during the second NREL-PDCQC driving cycle, the vehicle moved 1330 s with a total consumed accumulated energy 119.5 Wh.

2.4 Validation of the Simulation Model

The validation of the correct simulation model consisted in comparing its results of energy consumed by the powertrain with the consumption of the real powertrain. For this purpose, the aforementioned Powertrain test bench was used again. The powertrain of the vehicle consisting of the electric motor, the converter, the gearbox, and the drive shaft, including all necessary accessories, was placed on the test bench similarly as described in chapter 2.2. In this case, the gearbox's output shaft was also connected by a drive shaft to a dynamometer in the test room which replaced the car wheel. The electric motor and converter were again powered by a high-voltage battery emulator with a DC power supply ITECH IT6000C. The control system of the testbed controlled the electric motor and dynamometer to accurately simulate the vehicle driving at speeds defined by the speed profiles of the driving cycles under test. The energy drawn from the battery emulator was recorded during these driving cycles.

3 Results

This chapter presents the results of electricity consumption from measurements and simulation for both driving cycles. From the data shown in Figures 5 and 6 it can be seen that the results produced by the simulation model (red) show a relatively high agreement with the results obtained from the measurements (blue) carried out on the Powertrain test bench on both driving cycles. Despite this relatively good agreement, it is essential to note that the simulation model slightly overestimates the powertrain power consumption. This phenomenon was observed for both driving cycles. For the CARB-HHDDT driving cycle, the total measured energy drawn from the battery was 56.9 Wh. In this case, the calculated value from the simulation was 59.9 Wh. The results measured during the NREL-PDCQC run look similar. In this case, the measured total energy consumption was 114.3 Wh, and the calculated value was 123.7 Wh. Based on these data, it can be said that the percentage deviation is approximately 5% for the CARB-HHDDT run and 8% for the NREL-PDCQC run.

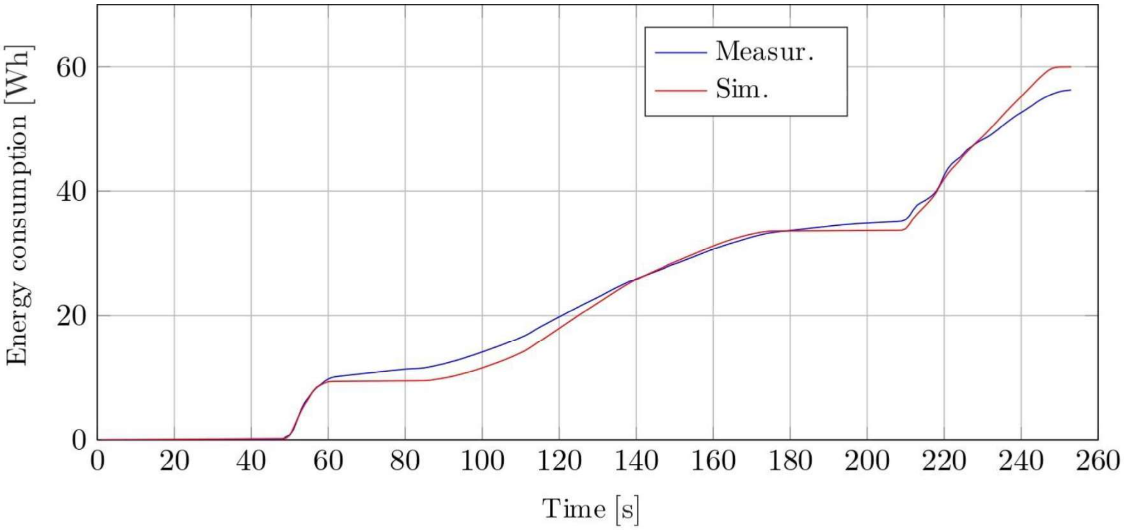

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Fig. 5: *Comparison of cumulative powertrain consumption values from simulation and measurements on drive cycle CARB–HHDDT–CS*

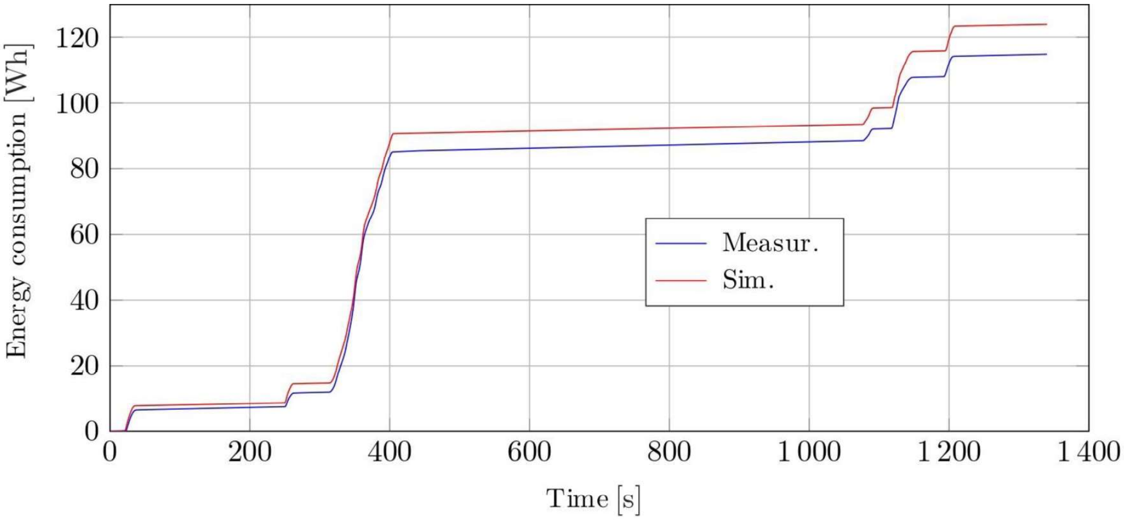

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Fig. 6: *Comparison of cumulative powertrain consumption values from simulation and measurements on drive cycle NREL–PDCQC*

Conclusion

The main objective of this research was to describe and implement a simulation model of a four-motor electric vehicle that would calculate the power consumption of the vehicle's powertrain with the required accuracy.

Evaluating powertrain power consumption using a simulation model and experimental measurements in the laboratory are two different approaches that differ in their advantages and limitations. Different scenarios and vehicle operating conditions can be easily investigated using a simulation model, allowing accurate determination of energy consumption in different situations. Simulations also provide the opportunity to investigate the effect of different components on the overall energy consumption of the vehicle, which can lead to the optimization of the powertrain design. The disadvantage of this solution is that the simulation model needs to be often and adequately tediously tuned so that the results provide sufficient accuracy. On the other hand, measurements made in the laboratory provide results for the specific type of driveline that will be installed in the vehicle, often without the need for further tuning, but the accuracy of the sensors used must be taken into account.

The results of this research have shown that the simulation model thus developed can predict the amount of energy consumed in the vehicle drivetrain with an accuracy of more than 8% (depending on the driving cycle). Although there is still room for increasing the accuracy of the calculation and the related further refinement of the simulation model, I believe that using the proposed simulation model and the described approach for defining the efficiency of the individual elements of the powertrain can be used to evaluate with sufficient accuracy the consumption of the aforementioned four-engine vehicle.

Acknowledgment

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HODNOCENÍ SPOTŘEBY ELEKTRICKÉ ENERGIE SPECIALIZOVANÝCH BATERIOVÝCH ELEKTRICKÝCH VOZIDEL POMOCÍ SIMULAČNÍHO MODELU

Bateriová elektrická vozidla (BEV) jsou v současné době všeobecně považována za jednu z dostupných možností boje proti rostoucím emisím skleníkových plynů. Jejich rozšíření je však stále výrazně menší než v případě vozidel s konvenčním spalovacím motorem. Z důležitých faktorů, které brání jejich širšímu rozšíření, je jejich stále relativně krátký dojezd a dlouhá doba nabíjení. Z tohoto důvodu je při vývoji BEV stále důležitější používat co nejpřesnější simulační modely, které umožňují analyzovat dopad změn provedených na jednotlivých komponentech hnacího ústrojí na spotřebu elektrické energie vozidla. Za tímto účelem se autorova disertační práce zabývá vývojem simulačního modelu pro odhad spotřeby elektrické energie hnacího ústrojí BEV a popisuje způsob definování činnostních parametrů jednotlivých komponent hnacího ústrojí. Výsledky ze simulačního modelu pak byly porovnány s měřeními provedenými ve specializované zkušebně. V závislosti na jízdních cyklech byla naměřena maximální odchylka přibližně 8 %.

BEWERTUNG DES VERBRAUCHS ELEKTRISCHER ENERGIE SPEZIALISIERTER BATTERIEBETRIEBENER FAHRZEUGE MIT HILFE EINES SIMULATIONSMODELLS

Batteriebetriebene Fahrzeuge (Battery Electric Vehicles / BEV) werden weitgehend als eine der machbaren Mittel zur Bekämpfung der Treibhausgase betrachtet. Allerdings sind diese Fahrzeuge bislang weit weniger verbreitet als Fahrzeuge mit Verbrennungsmotoren. Ein Grund dafür besteht in ihrer noch immer relativ kurzen Reichweite und der langen Ladezeit. Aus diesem Grunde wird es bei der Entwicklung von BEV immer wichtiger, möglichst genaue Simulationsmodelle zu verwenden, welche eine Analyse der Auswirkung der an den einzelnen Komponenten des Antriebssystems ausgeführten Änderungen der auf den Energieverbrauch eines batteriebetriebenen Fahrzeugs ermöglichen. Zu diesem Zweck beschäftigt sich die Dissertation des Autors mit der Entwicklung eines Simulationsmodells zur Schätzung des Verbrauchs elektrischer Energie des Antriebssystems eines BEV und beschreibt die Art und Weise der Definierung der Tätigkeitsparameter der einzelnen Komponenten des Antriebssystems. Die Ergebnisse aus dem Simulationsmodell wurden dann mit den in einem spezialisierten Versuchslabor durchgeführten Messungen verglichen. In Abhängigkeit von den Fahrzyklen wurde eine maximale Abweichung von etwa 8 % gemessen.

OCENA ZUŻYCIA ENERGII ELEKTRYCZNEJ PRZEZ SPECJALISTYCZNE AKUMULATOROWE POJAZDY ELEKTRYCZNE PRZY UŻYCIU MODELU SYMULACYJNEGO

Akumulatorowe pojazdy elektryczne (APE) są obecnie powszechnie uważane za jedną z dostępnych opcji walki z rosnącą emisją gazów cieplarnianych. Jednak ich wykorzystanie jest nadal znacznie niższe niż w przypadku pojazdów z konwencjonalnym silnikiem spalinowym. Wśród ważnych czynników, które uniemożliwiają ich szersze rozpowszechnienie, jest ich wciąż stosunkowo niewielki zasięg i długi czas ładowania. Z tego powodu w rozwoju APE coraz ważniejsze staje się wykorzystanie najdokładniejszych modeli symulacyjnych, które umożliwiają analizę wpływu zmian wprowadzonych w poszczególnych komponentach układu napędowego na zużycie energii przez pojazd. W tym celu rozprawa doktorska autora dotyczy opracowania modelu symulacyjnego do szacowania zużycia energii elektrycznej przez układ napędowy APE oraz opisuje metodę definiowania parametrów pracy poszczególnych elementów układu napędowego. Wyniki modelu symulacyjnego zostały następnie porównane z pomiarami wykonanymi w specjalistycznym centrum testowania. W zależności od cykli jazdy zmierzono maksymalne odchylenie wynoszące około 8 %.