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Article

Comparative Simulation Analysis of Electric Vehicle Powertrains with Different Configurations Using AVL Cruise and MATLAB Simulink

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Abstract: Electric vehicles are now recognized as a crucial answer in the worldwide effort to achieve sustainable and environment-friendly transportation. As the automotive industry moves towards using electric power, it is crucial to assess and improve the powertrain configurations in electric vehicles. This study aims to meet this need by conducting an in-depth comparative analysis of single, double, and quad electric vehicle powertrain systems. The performance of these configurations is rigorously simulated by using two widely used platforms: AVL Cruise and MATLAB Simulink. This study mainly covers the analysis of energy efficiency, which is a critical factor in determining the environmental impacts and feasibility of electric vehicles. In order to conduct a thorough comparison, the energy consumption per kilometer is evaluated as a crucial performance measure. Our research primarily focuses on model validation, namely by comparing it with manufacturer data to determine the accuracy and reliability of the simulation results. The findings reveal a compelling narrative in the pursuit of sustainable transportation. The use of a dual motor setup stands out as a prominent example of energy efficiency, demonstrating remarkable outcomes in both simulation platforms. Significantly, these findings closely correspond with the manufacturer's data for the Volvo XC40, confirming the appropriateness and dependability of our simulation models. Furthermore, the quad motor configuration shows significant energy efficiency, providing helpful insight regarding its applicability and performance. The broader implications of this research go beyond powertrain configurations, including the trustworthiness of simulation models in the automotive industry. These findings improve the continuous advancement of electric vehicle design and development, indicating a more environment-friendly and energy-efficient future for the automotive industry. This study offers invaluable insights and benchmarks for the transition to environment-friendly transportation solutions, as the world advances towards sustainable mobility.

Keywords: electric vehicles; simulation analysis; driving cycle; efficient transportation; energy efficiency; powertrain configurations

1. Introduction

The automobile industry at a worldwide level is now experiencing a significant shift, characterized by an increasing focus on sustainable transportation alternatives. This shift is driven by the need to address environmental issues and decrease our dependency on fossil fuels. Therefore, to attain various objectives related to environmental sustainability, it is essential to advocate for the generation of power from renewable sources and the use of electrification in the transportation industry [1]. Electric vehicles have evolved as a viable and environmentally sustainable alternative to conventional internal combustion engine automobiles [2]. The powertrain system of an electric vehicle is crucial to its performance, since it significantly influences factors like efficiency, range, and overall performance [3].

With the increasing demand for electric vehicles, scholars and professionals are actively investigating diverse powertrain designs to enhance their efficiency, power output, and cost [4]. In order to achieve this objective, simulation tools have become essential in the assessment and comparison of various powertrain designs, offering vital insights into their practical performance attributes without the need of expensive and time -consuming physical prototypes [5].

Modeling and simulation are used as a valuable tool in the process of determining the design and operational characteristics of electric cars, with the ultimate goal of optimizing their performance capabilities. There is a need for dynamic simulation studies to assess different situations and to facilitate the comparison of diverse technologies, such as converters, batteries, powertrains, and electric motors [6]. The AVL CRUISE software was used to conduct simulations and to examine the performance of the vehicle, specifically focusing on the New European Driving Cycle and Japan Mode 1 Urban Cycle. The simulation findings indicate that the vehicle design has favorable dynamic performance and economic performance [7]. A model of an electric car was developed by using the AVL Cruise software. The vehicle under consideration is derived from the pre-existing Dacia Sandero model. In contrast to the actual automobile, the shown model has distinct attributes due to its status as a fully electric vehicle. The data obtained indicates a comparatively narrow range in comparison with comparable electric cars. However, it is important to note that the testing circumstances were challenging, including a fully loaded vehicle, and demanding transitional regimes [8]. The selection of a driving cycle for vehicle simulation has a significant impact on the performance indicators. According to the NEDC driving cycle, the fuel consumption of A-ECMS falls by 3.8% over a distance of 100 km, while the battery state of charge (SOC) increases by 1.1%. The utilization of the A-ECMS in the CHTC-LT driving cycle results in a notable enhancement of fuel economy, with an observed increase of 3.6%. This finding serves as evidence supporting the superiority of the A-ECMS in terms of its performance in this specific driving cycle [9]. When comparing the experimental results with the simulation, the simulation yielded a fuel consumption rate of 36.9 L/100 km, whereas the testing produced a rate of 38.1 L/100 km for the fuel consumption index of the typical public bus during the actual Wuhan urban driving cycle. The discrepancies seen among them amount to approximately 3% and primarily stem from fluctuations in velocity, often ranging from ±1 km/h [10]. The AVL CRUISE software is utilized to establish a power system model of electric vehicles, and subsequently is employed to evaluate the dynamic performance of those vehicles. The results obtained from the simulation indicate that the most attainable speed is 178 km/h. Additionally, the time required to accelerate to a distance of 100 km is measured to be 11.59 s. Furthermore, the vehicle's maximum capability to ascend slopes is determined to be 30%. The simulation findings indicate that the electric car successfully fulfills the necessary design criteria. The aggregate energy consumption amounts to 4608 kJ [11].

The efficiency of an electric vehicle is influenced by its powertrain. The classification of energy savings is categorized into three configurations: all-wheel drive, front-wheel drive, and rear-wheel drive, ranked from the most efficient to the least efficient. Furthermore, it is worth noting that the mean energy conservation percentages for front-wheel drive, rear-wheel drive, and all-wheel drive are 19.11%, 9.38%, and 7.93%, respectively. Various power systems exhibit variations in power consumption [12]. In order to optimize the power-to-weight ratio and enhance the motor power density, electric vehicle manufacturers frequently employ a driveline configuration consisting of a solitary electric motor characterized by high rotational speed and moderate torque. The transmission, clutch, and gearbox are essential components of this system as they provide the transmission of rotational speed and torque to each individual wheel. In addition, it is necessary to have a mechanical differential that has the capability to evenly transfer torque among all the wheels responsible for propulsion. Consequently, the mechanical components collectively contribute to a 20% decrease in the efficiency of the driveline. The user did not provide any text to rewrite [13]. The electric motor's most significant attributes are its high rotating speed and its ability to maintain maximum torque from zero speed to rated speed. The single -speed transmission offers a gratifying and energetic performance [14]. Alternatively, it is worth noting that a central motor drive equipped with a single-speed transmission can be a viable approach to reduce the overall weight, volume, losses, and cost associated with the drivetrain [15]. The elimination of the gearbox results in a reduction of mechanical losses and a decrease in the weight of the powertrain. The inclusion of the direct drive capability in the quad-motor model facilitates the utilization of electric motors that are lighter, slower, and more efficient. The decrease of mechanical losses and the utilization of highly efficient motors enhance the overall efficiency of the powertrain, resulting in an extended range for the vehicle [16].

This research article aims to conduct a complete study that explores the comparative analysis of single, double, and quad electric vehicle powertrain systems within the given environment. The main aim of this study is to investigate the impact of various powertrain configurations on important performance indicators, including range, state of charge, and energy usage. In order to accomplish this objective, we use two commonly utilized simulation platforms, namely MATLAB Simulink and AVL Cruise, to thoroughly model and simulate these powertrain systems.

2. Materials and Methods

Currently, computer modeling is extensively employed in the design of motor transport to provide insights into potential outcomes of the developed mechanisms and machines. When considering the design of contemporary automobiles, the most appropriate software applications for managing its components and measurements are: The utilization of MATLAB Simulink and AVL Cruise in engineering applications has been widely recognized. These software tools offer valuable capabilities for modeling, simulation, and analysis in several domains, including automotive and power-train systems [17].

In this study, identical parameters were employed in both MATLAB Simulink and AVL Cruise to ensure consistency in comparative analysis. Specifically, the motor model represents a generic Permanent Magnet Synchronous Motor (PMSM) and drive operating in torque-control mode, equivalent to current-control mode. This model supports both motoring and generating regimes, suitable for servomotor and traction applications at a system level. The motor's performance is defined by a torque-speed envelope, and the output torque tracks the torque reference demand with a time constant. It is connected to a direct current (DC) supply network, with electrical losses proportional to the square of the torque. The motor produces a positive torque acting from the mechanical ports. The configurations include a single motor of 300 kW, a double motor setup with two 150 kW motors, and a quad motor setup with four 75 kW motors.

Additionally, the battery model implements a generic dynamic representation of widely used rechargeable batteries. The model's parameters can be adjusted to reflect the discharge characteristics of a specific battery type. During discharge, the battery follows its discharge characteristics, and during charging, it adheres to the same characteristics but in reverse. The state of charge (SOC) indicates the battery's charge level as a percentage of its full charge, with the depth of discharge (DOD) being the complement of SOC. For example, a fully charged battery has an SOC of 100% and a DOD of 0%, whereas a half-charged battery has an SOC of 50% and a DOD of 50%. In this simulation, a lithium-ion battery with a capacity of 78 kWh was used.

The models in both MATLAB Simulink and AVL CRUISE utilized predefined blocks to represent various components essential for a comprehensive simulation. These include the vehicle body, wheels, power converter (with the H-bridge driven by controlled pulse width modulation (PWM) voltage), driver performance (modeled using a longitudinal driver), and the driving cycle (WLTP stage 3). The predefined blocks for the battery and motor, as previously described, were also integrated into the simulations. This approach ensured that both software tools provided a detailed and accurate representation of the vehicle's performance under various operating conditions.

2.1. MATLAB Simulink Simulation

The development of detailed MATLAB Simulink models has been undertaken for each powertrain arrangement, encompassing the components shown in Figure 1. The construction of these models is facilitated through the utilization of standard blocks that are readily accessible within the MATLAB Simulink to create each subsystem. The simulations utilize a fixed-step solver with a time step of 1 ms. The input parameters encompass drive cycle data, vehicle mass, rolling resistance, and aerodynamic features [16].

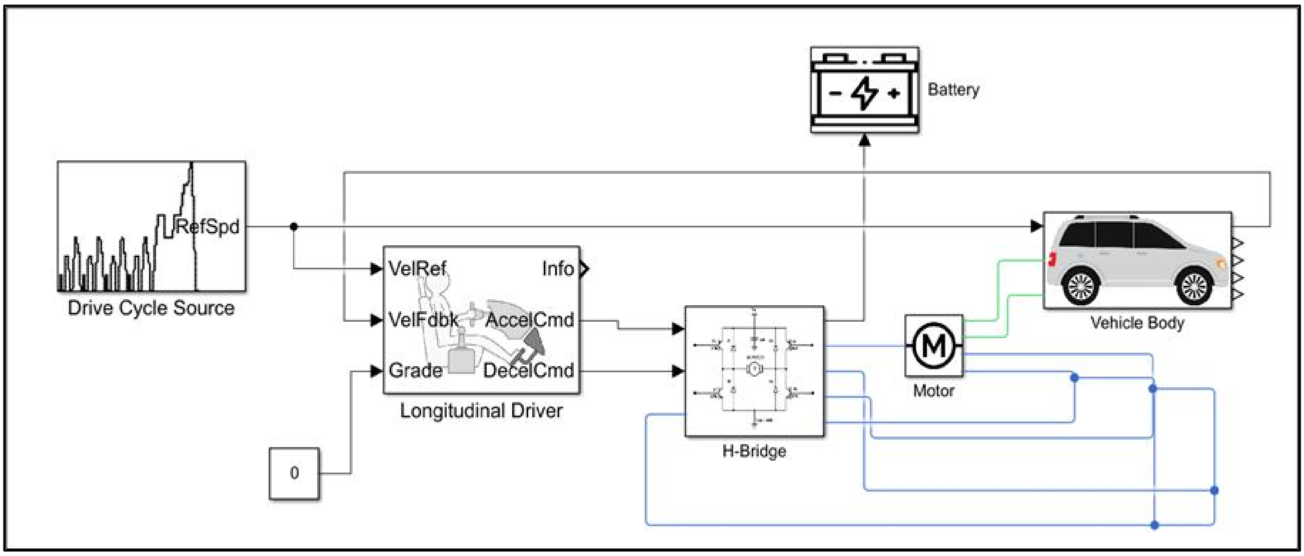

Figure 1. Electric vehicle model in MATLAB Simulink.

2.2. AVL Cruise Simulation

The powertrain combinations of electric vehicles in AVL Cruise were replicated by employing the software's graphical user interface for model assembly. The program offers a collection of powertrain components and enables customization. The AVL Cruise simulations utilize a meticulous technique, using road load models obtained from authentic driving cycles. The model shown in Figure 2 accurately represents the mass of the vehicle, the characteristics of the tires, and the environmental conditions.

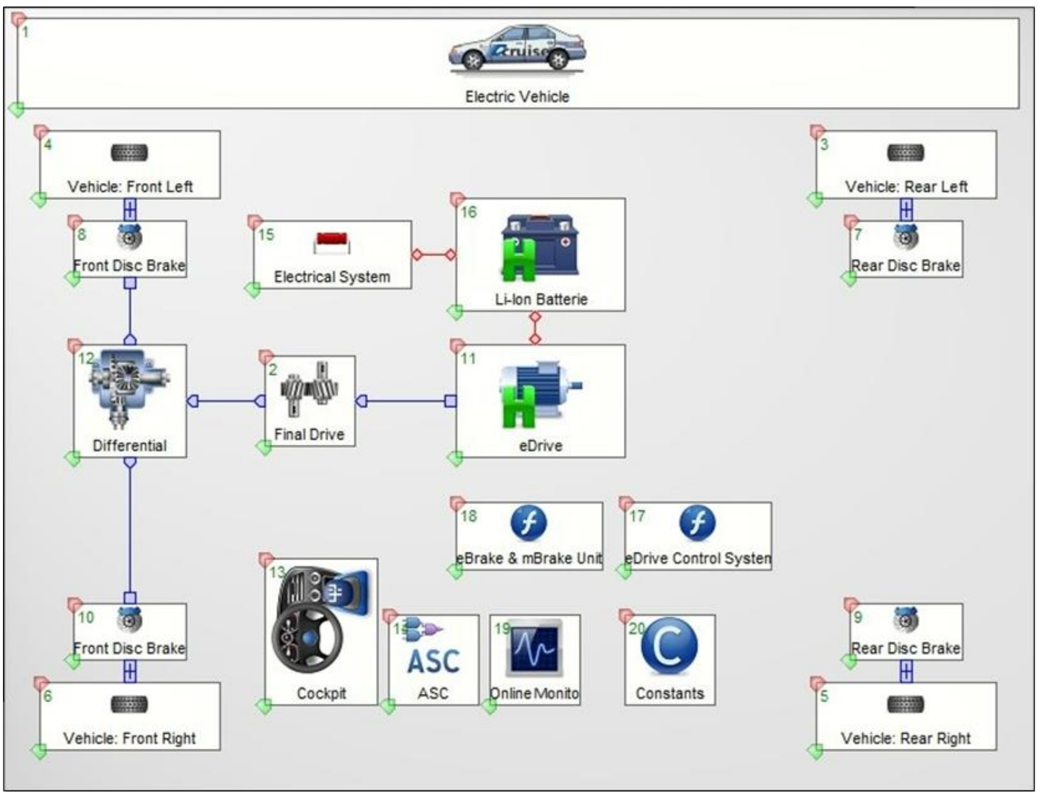

Figure 2. Electric vehicle model in AVL Cruise.

This study will present three variations of electric vehicle powertrain, including single, double, and quad electric powertrain designs. The MATLAB Simulink and AVL Cruise software were used to model all configurations, specifically referring to the Volvo XC40 Recharge electric vehicle. The simulations were conducted with identical vehicle parameters, drive cycle, battery capacity, and total electric motor power as indicated in Table 1.

Table 1. Vehicle specifications used in models' settings.

Parameter	Value
Vehicle Mass	2480 kg
Rolling Radius	0.36 m
Battery Capacity	78 kWh
Usable Battery Capacity	75 kWh
Frontal Area	2.56 m^2
Drag Coefficient	0.329
Total Electric Motor Power	300 kW

2.3. Data Collection and Analysis

Data is collected from both MATLAB Simulink and AVL Cruise simulations, encompassing a range of performance metrics, including energy consumption, torque output, acceleration times, and system efficiency. These data points are extracted at regular intervals throughout the simulation period.

2.4. Comparative Analysis

Data is gathered through MATLAB Simulink and AVL Cruise simulations, including several performance measures such as energy consumption, range, and power output. The data points are collected periodically throughout the simulation time.

2.5. Model Validation

Model verification is an essential and crucial stage in guaranteeing the precision and dependability of our simulations. This study involved a comparison of simulation results for single, double, and quad electric vehicle powertrain systems utilizing AVL Cruise and MATLAB Simulink. The comparison was made against the widely recognized Worldwide Harmonized Light Vehicle Test Procedure (WLTP) driving cycle data. The WLTP is a standardized test cycle that aims to replicate real-world driving situations. It has a fixed cycle length of 23,250 m.

To evaluate the accuracy of our simulation models, we performed 10 consecutive WLTP driving cycles using both AVL Cruise and MATLAB Simulink simulations. The cumulative distance covered throughout these cycles was compared with the anticipated distance of 23,250 m per cycle, yielding an anticipated total distance of 232,500 m for 10 cycles. The WLTP driving cycle is structured into four distinct segments, each characterized by a specific maximum speed: Low (up to 56.5 km/h), Medium (up to 76.6 km/h), High (up to 97.4 km/h), and Extra -High (up to 131.3 km/h). These segments represent different driving conditions, simulating urban, suburban, rural, and highway scenarios respectively. The driving cycle ensures a balanced representation of real-world driving, with urban and non-urban paths comprising 52% and 48% of the cycle, respectively. The WLTP class 3 driving cycle was chosen for this study because it effectively captures a wide range of driving conditions, providing a comprehensive evaluation of vehicle performance across various speeds and environments. This balanced approach between urban and non-urban scenarios allows for a more accurate and realistic assessment of energy consumption and vehicle behavior in different driving contexts. Figure 3 shows the speed profile and the distance supposed to be travelled by vehicle during single cycle of WLTP.

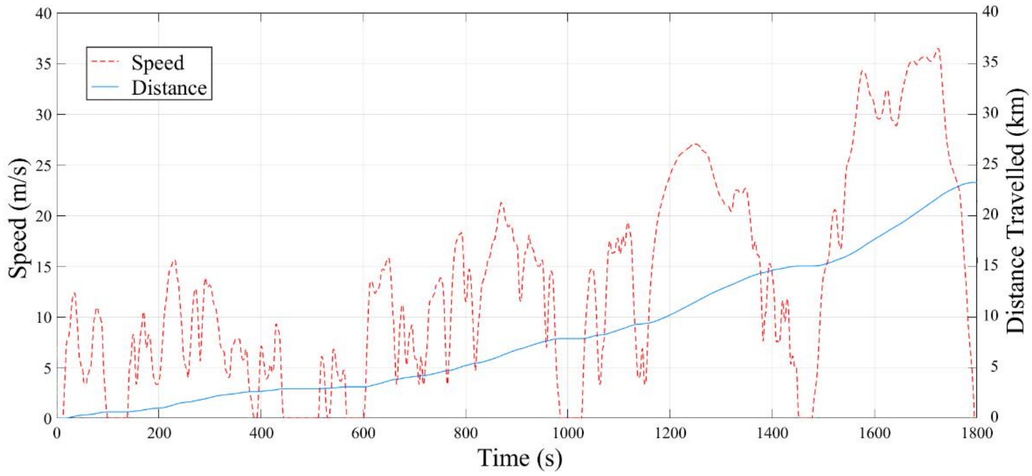

Figure 3. Distance travelled and speed profile during one WLTP cycle.

The AVL Cruise simulations yielded a total distance of 231,920 m traversed over 10 WLTP cycles. The measured distance deviates by only 0.24% from the expected value of 232,500 m. The simulations conducted using MATLAB Simulink resulted in a total distance of 232,032.9 m for 10 WLTP cycles, which is roughly 0.22% more than the anticipated number.

The close approximation of our simulation results to the optimal value of 232,500 m for 10 WLTP cycles showcases the precision of our models and the strong correlation between our simulation platforms and actual driving circumstances. These findings confirm the dependability of our simulations in evaluating the efficiency of electric car powertrain systems.

The slight differences observed between the simulated and ideal distances can be attributable to factors such as environmental conditions, vehicle attributes, and minor deviations in road load models, which are inherent to real-world driving scenarios. Moreover, the minor disparities between the two simulation platforms, AVL Cruise and MATLAB Simulink, emphasize the uniformity and excellence of our models in both tools. Given the successful verification of this model, we can now proceed with the comparative examination of single, double, and quad electric vehicle powertrain systems utilizing these validated simulation models.

The methodology of this research involves creating and simulating models of electric vehicle powertrains using MATLAB Simulink and AVL Cruise. The models include single, double, and quad powertrain configurations. Elaborate models are built for every power-train arrangement, and simulations are carried out under precise conditions. Data collection primarily concentrates on performance measures, facilitating a comparative examination across different powertrain systems. Furthermore, our models have been validated by comparing them with WLTP driving cycle data, which confirms their precision and dependability. Using this approach, the central aspect of this study is advanced by examining and comparing simulation outcomes to gain useful insights into the performance of electric car powertrains.

3. Results

3.1. Powertrain Configurations

Prior to examining the analysis of our simulation findings, it is crucial to present a graphical summary of the single, double, and quad motor setups, which were simulated in both AVL Cruise and MATLAB Simulink. Figures 4 and 5 depict the single motor setup, emphasizing the structure of components in the powertrain systems of AVL Cruise and MATLAB Simulink. Significantly, the single motor configuration has a front axle that is equipped with a gear and differential. Figures 6 and 7 depict the twin motor layout, in which two motors are directly linked to the front wheels individually. The lack of a gear and differential connecting the motors and wheels in the double motor configuration is evident. Figures 8 and 9 provide a peek of the quad motor configuration, which is distinguished by the presence of four motors that individually power each of the four wheels. The quad motor design, like the twin motor configuration, does not include a differential as each wheel is directly driven by an individual motor. These graphic representations familiarize readers with the complexities of the configurations and lay the framework for a thorough examination of energy usage and performance comparisons, which will be investigated in the subsequent sections.

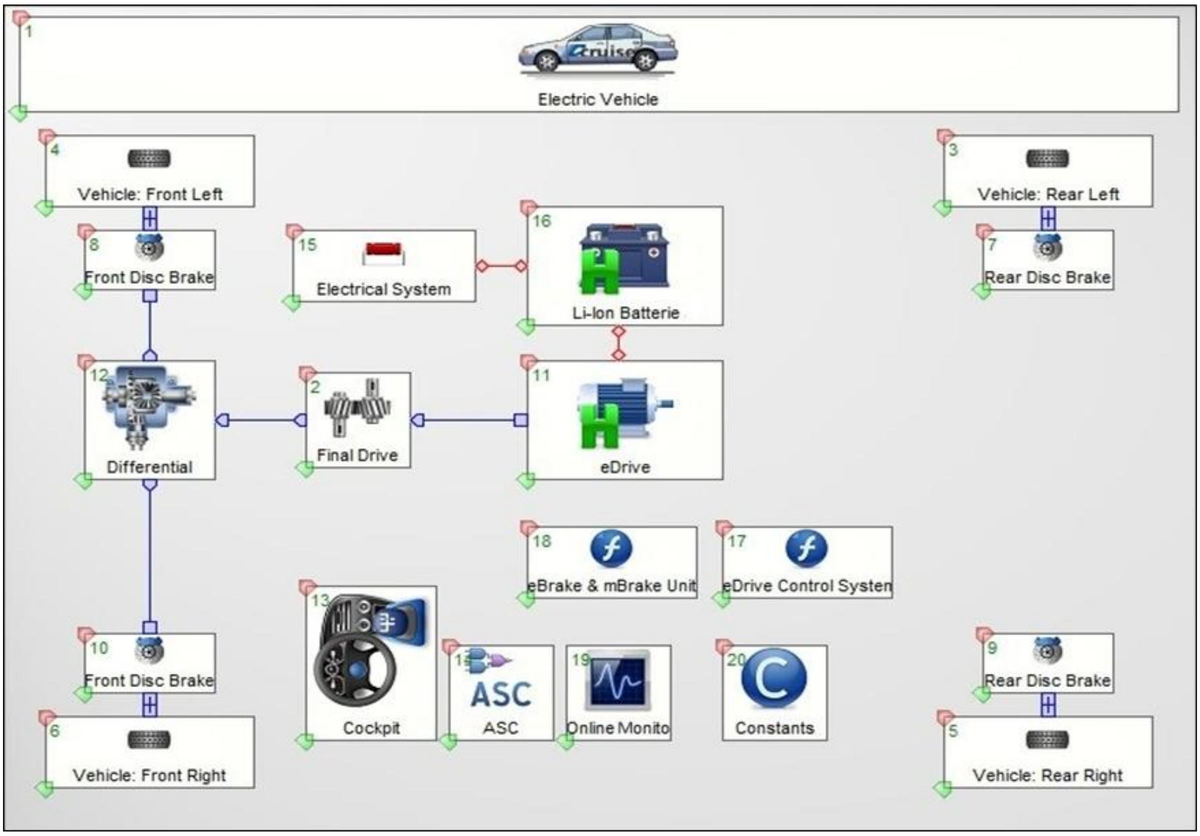

Figure 4. Single motor powertrain configuration in AVL Cruise.

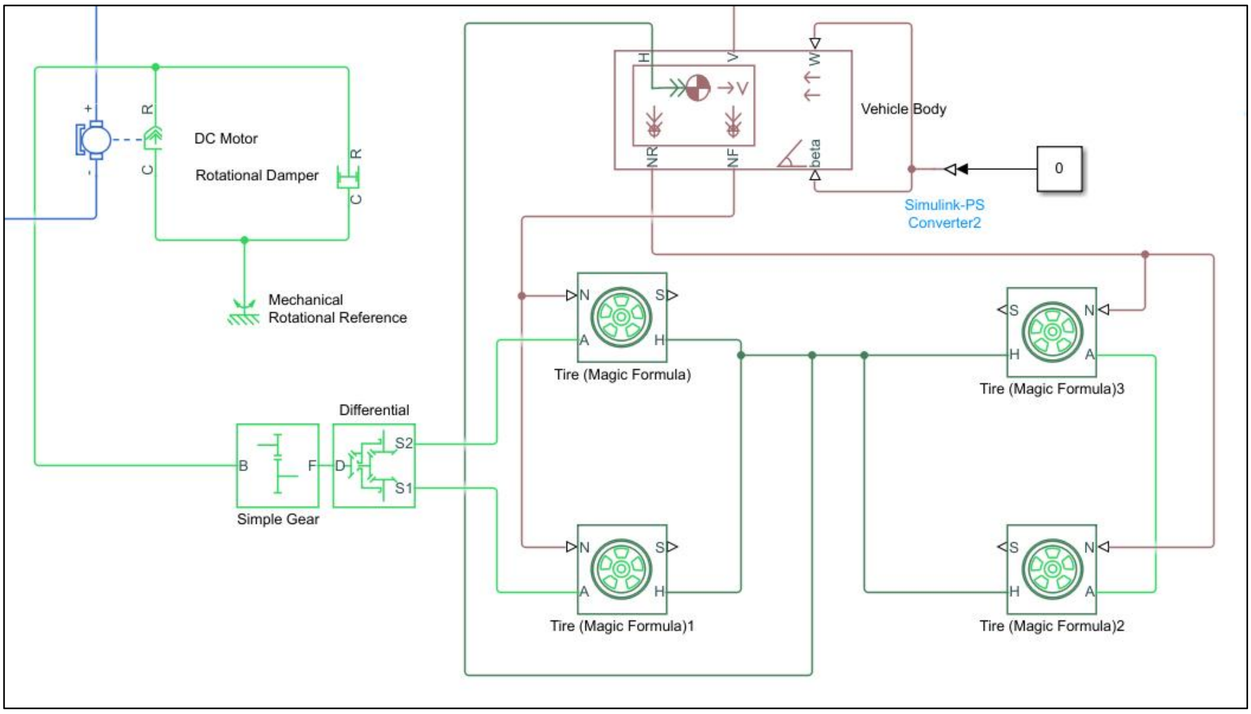

Figure 5. Single motor powertrain configuration in MATLAB Simulink.

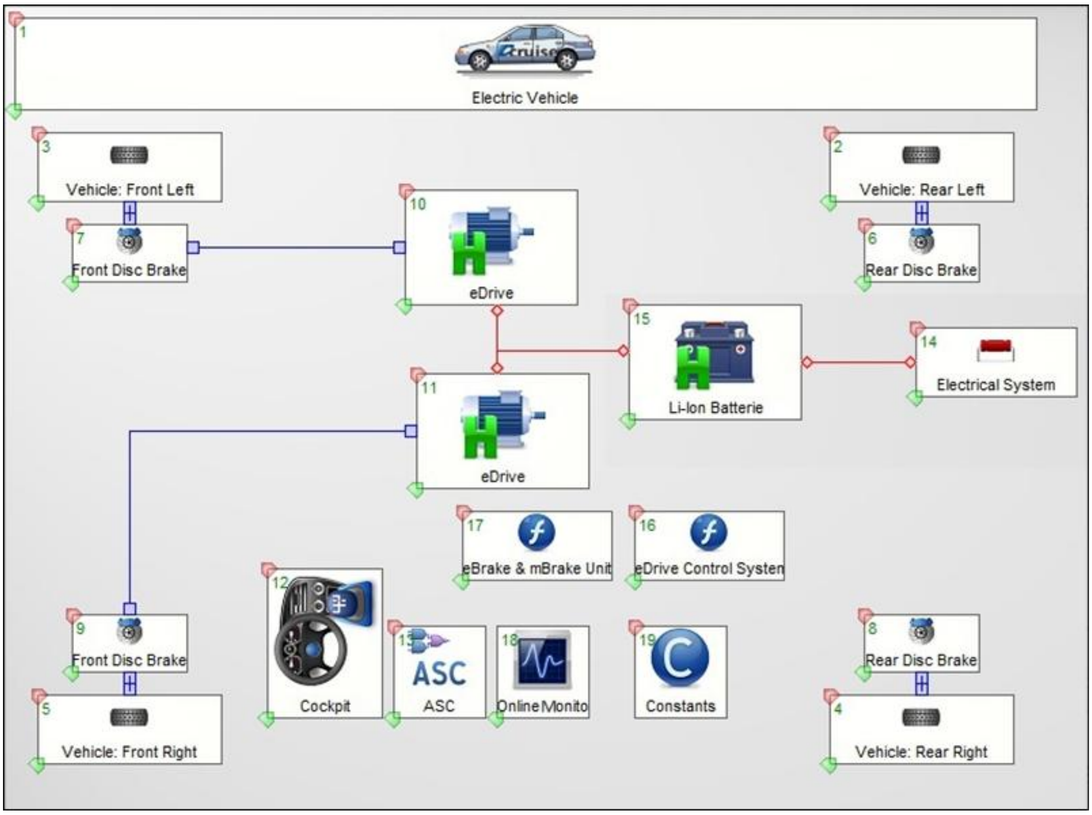

Figure 6. Double motor powertrain configuration in AVL Cruise.

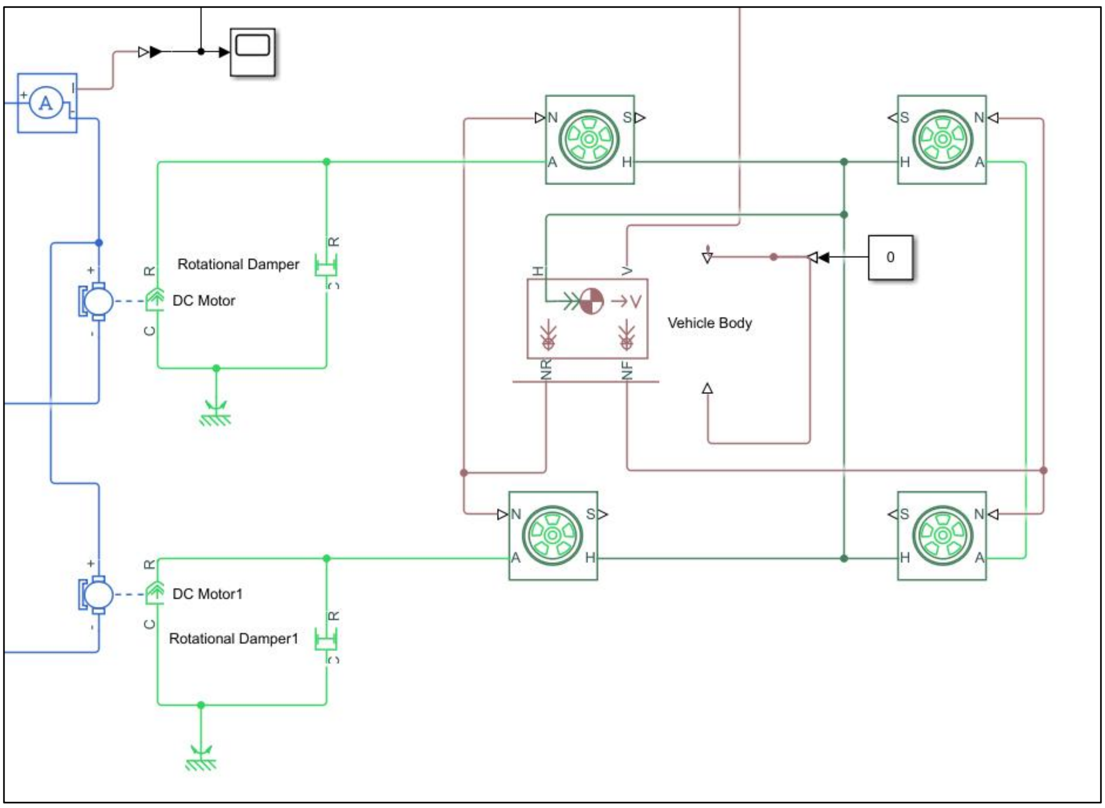

Figure 7. Double motor powertrain configuration in MATLAB Simulink.

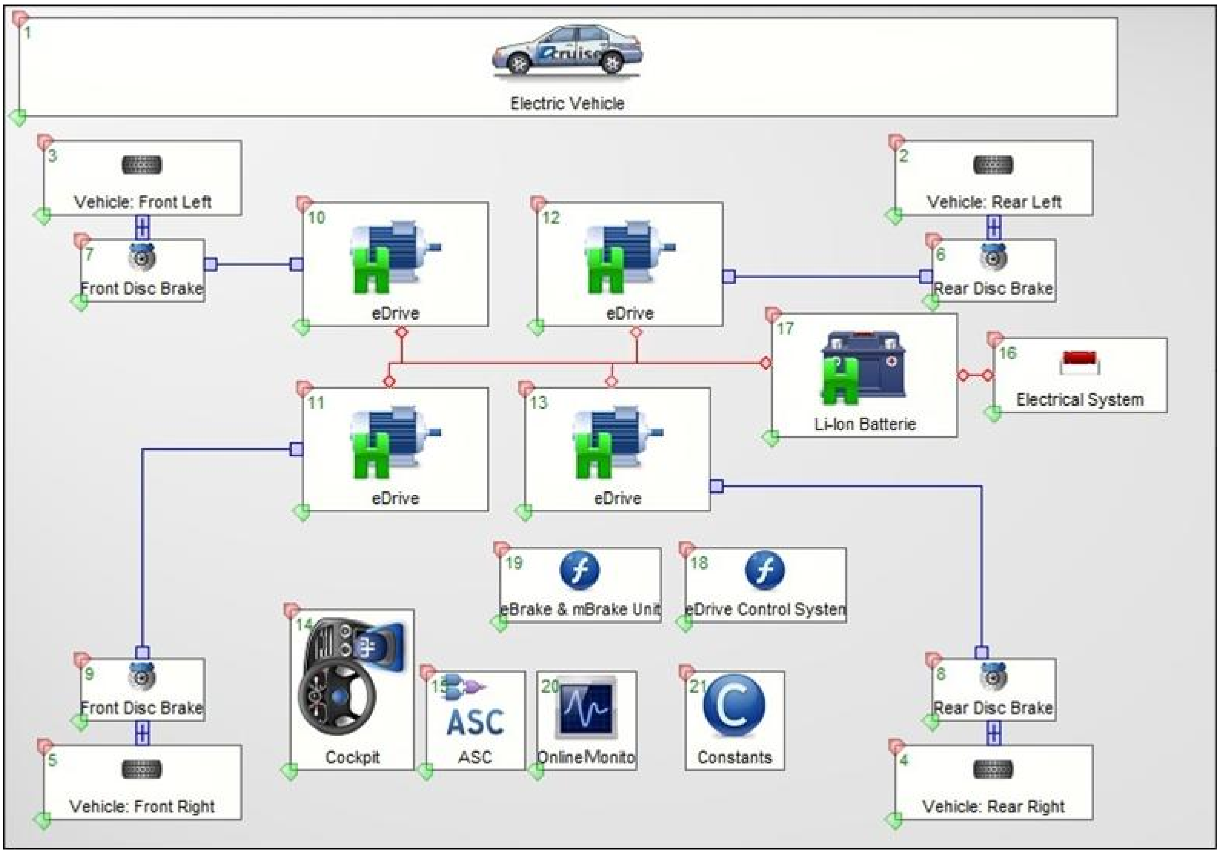

Figure 8. Quad motor powertrain configuration in AVL Cruise.

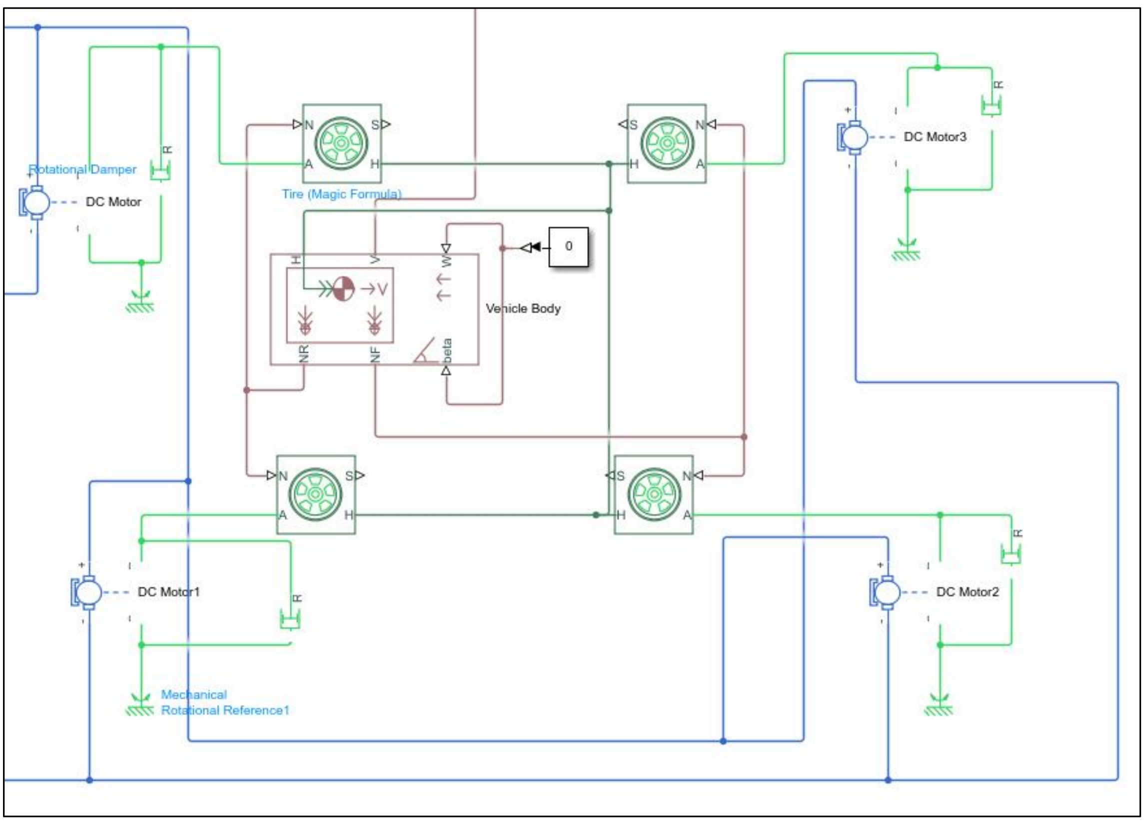

Figure 9. Quad motor powertrain configuration in MATLAB Simulink.

Section 3 showcases the findings of the comprehensive examination of the single, double, and quad electric vehicle powertrain systems, carried out with both MATLAB Simulink and AVL Cruise. This section primarily investigates energy efficiency, namely by comparing energy usage after 10 WLTP driving cycles. In addition, the computation of energy usage per kilometer, a crucial measure for evaluating the sustainability and feasibility of electric vehicle power systems will be explored. These results provide important insights into the performance characteristics of each configuration and the capabilities of the simulation tools used.

Within this section, the outcomes of energy efficiency, encompassing the amount of energy consumed in every cycle for each powertrain system, will be investigated. Subsequently, the energy consumption per kilometer by standardizing the energy consumption across the entire distance covered will be computed, enabling a direct assessment of the sustainability of these arrangements. The comparison analysis will not only demonstrate the performance of each configuration, but also provide insights into the capabilities and constraints of MATLAB Simulink and AVL Cruise as simulation tools for assessing electric car powertrains. These findings play a crucial role in promoting the comprehension and progress of sustainable transportation solutions.

3.2. Analysis of Energy Consumption

The AVL Cruise software, when operating with a single motor configuration, showed an energy usage of 42,380 Wh. This energy was used to travel a total distance of 231.92 km, achieved throughout 10 WLTP cycles. In contrast, the MATLAB Simulink software measured an energy consumption of 43,270 Wh and a distance traveled of 232.03 km using the identical motor setup. The utilization of the twin motor configuration led to an energy consumption of 41,060 Wh during the AVL Cruise test, covering a total distance of 231.17 km. When MATLAB Simulink was employed with identical specifications, the energy consumption amounted to 39,810 Wh, while the distance covered reached 231.64 km. When operating with a quad motor configuration through AVL Cruise, 39,410 Wh of energy was consumed and a total distance of 231.81 km was traveled. Using MATLAB Simulink with identical settings, the energy consumption amounted to 37,930 Wh, allowing for a coverage of 231.88 km. It is important to mention that the energy usage per kilometer was measured in watt-hours per kilometer (Wh/km) to ensure accurate comparability with manufacturer data. Table 2 summarizes the energy consumption and distance traveled after 10 WLTP driving cycles for different configurations using AVL Cruise and MATLAB Simulink.

Table 2. Energy consumption and distance travelled after simulating 10 WLTP driving cycles for different powertrain configurations using AVL Cruise and MATLAB Simulink.

Configuration	AVL Cruise		MATLAB Simulink	
	Energy Consumption (Wh)	Distance (km)	Energy Consumption (Wh)	Distance (km)
Single Motor	42,380	231.92	43,270	232.03
Double Motor	41,060	231.17	39,810	231.64
Quad Motor	39,410	231.81	37,930	231.88

To ensure a standardized and easily compared metric for energy efficiency, it is necessary to compute the energy consumption per kilometer (E_{km}) for each configuration using Equation (1):

$$E_{km} = (\text{Total Energy Consumption (Wh)})/(\text{Distance Travelled (km)}) \tag{1}$$

AVL CRUISE indicated an energy consumption of 183.03 Wh/km in its single motor powertrain, while MATLAB Simulink computed 186.39 Wh/km. In the dual motor configuration, AVL CRUISE recorded 177.58 Wh/km, and MATLAB Simulink showed 171.83 Wh/km. For the quad motor setup, AVL CRUISE demonstrated 170.12 Wh/km, and MATLAB Simulink computed 163.56 Wh/km. Figure 10 summarizes the energy consumption across different motor configurations and simulation platforms.

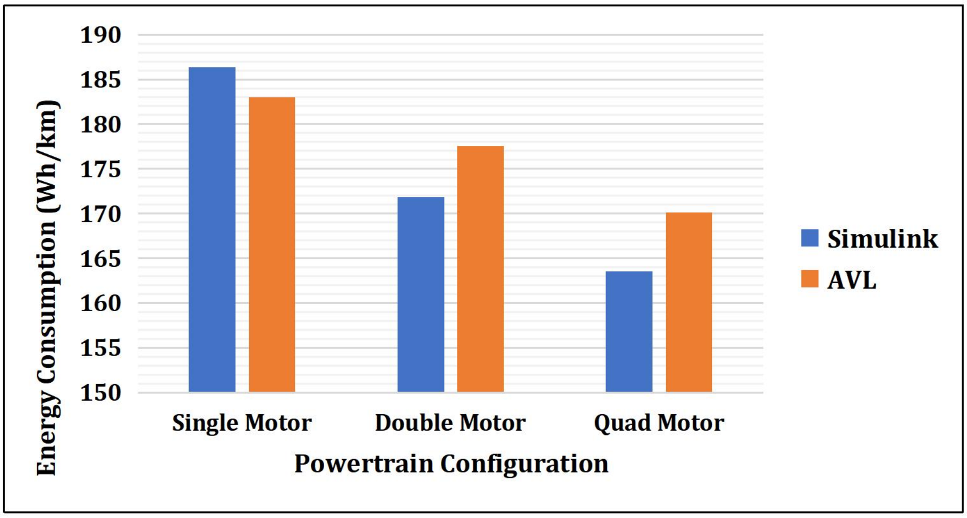

Figure 10. Energy consumption in Wh per km for different powertrain configurations.

3.3. Comparative Analysis

When comparing the simulation results with the manufacturer's data, it is crucial to note that the original vehicle, the Volvo XC40 with a 300 kW twin motor, corresponds to a dual motor configuration. The manufacturer offers two separate WLTP ratings: TEH and TEL, which indicate high energy and low energy configurations, respectively. TEH commonly denotes the model variant that has the greatest energy requirement, whereas TEL indicates the variant with the least energy requirement, taking into account differences in vehicle configurations. Based on the manufacturer's data, the XC40 has a TEH rating of 181 Wh/km and a TEL rating of 177 Wh/km [18].

Upon comparing the manufacturer ratings with our simulation results, a close alignment between our double motor configurations in both AVL Cruise and MATLAB Simulink, and the manufacturer's TEL rating was observed. This alignment indicates that our configurations are very energy-efficient and reflect the most efficient trim level. The simulation results for the double motor arrangement showed energy consumption values of around 177.58 Wh/km for AVL Cruise and 171.83 Wh/km for MATLAB Simulink. Figure 11 presents a complete comparison between the simulation results and the manufacturer's data for the XC40's double motor configuration. This comparison allows for a thorough assessment of the alignment between our modeling results and the manufacturer's ratings.

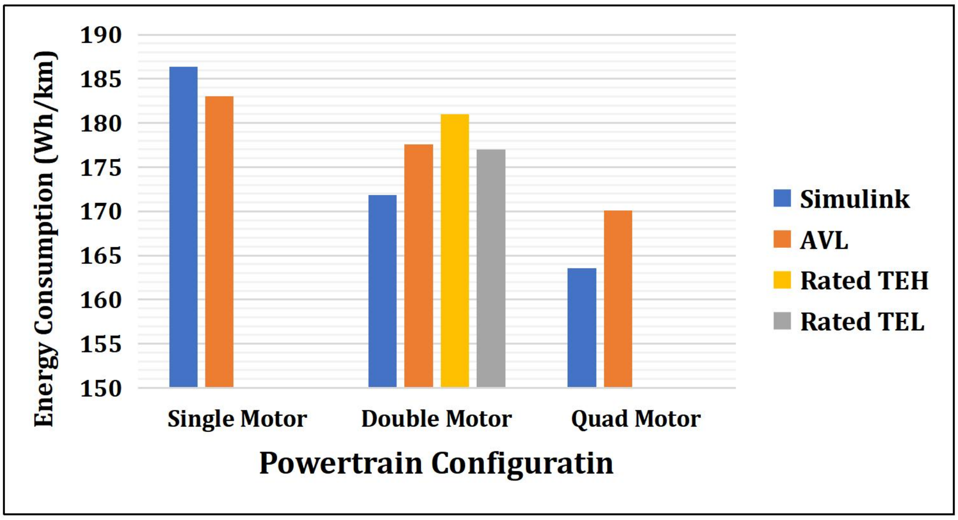

Figure 11. Comparison between simulation results and the manufacturer's data for the XC40's different powertrain configuration.

Our analysis reveals a remarkable alignment between the simulated results and the energy consumption data provided by the manufacturer for the XC40. This reaffirms the accuracy and dependability of our models in replicating real-world performance measurements for electric vehicle powertrain systems. Notably, the result obtained in the AVL double motor configuration, with an energy consumption of 177.58 Wh/km, closely mirrors both the manufacturer's TEH and TEL data, further underlining its accuracy and suitability for a range of XC40 trim levels.

4. Conclusions

This study conducted a comprehensive investigation into powertrain systems for electric vehicles, specifically examining single, double, and quad motor configurations. The simulations were performed using AVL Cruise and MATLAB Simulink, with a specific focus on energy efficiency, measured as energy consumption per kilometer (Wh/km). The investigation has given significant insights and discoveries that provide valuable information about the performance and suitability of certain electric vehicle configurations. The comparative analysis of our simulations indicated that the double motor design, with an energy consumption of around 177.58 Wh/km in AVL Cruise, is particularly noteworthy for its energy efficiency. The obtained result closely corresponds to the energy consumption data provided by the manufacturer for the XC40, indicating a high level of accuracy and dependability in our simulation models. In addition, the implementation of a dual motor configuration in MATLAB Simulink yielded a commendable energy consumption value of 171.83 Wh/km, further affirming its appropriateness for energy-efficient electric vehicle powertrains.

However, the single motor and quad motor configurations, albeit showing decent performance, had somewhat elevated energy usage, ranging from 163.56 Wh/km to 186.39 Wh/km, depending on the simulation platform employed. These findings offer crucial insights into the energy efficiency of various electric car powertrain structures. They emphasize the significance of meticulously choosing and optimizing powertrain configurations to achieve certain energy efficiency objectives, considering variables such as vehicle trims and energy requirements.

Furthermore, our research has also emphasized the durability and dependability of our simulation models. The strong correlation between our findings and the manufacturer's data for the XC40 confirms the reliability of our simulations and their potential utility in the practical design and advancement of electric vehicles. Ultimately, this work enhances our comprehension of electric car powertrain systems by a comprehensive comparative analysis of different configurations. This emphasizes the importance of energy efficiency and the relevance of simulation tools in attaining precise and dependable outcomes. These results have a dual impact: they contribute to the continuous advancement of electric vehicles and offer potential for a more sustainable and energy-efficient future in the automotive sector.

5. Future Work

Future research should explore additional performance metrics beyond energy efficiency, such as range and acceleration, to provide a comprehensive understanding of electric vehicle powertrain configurations. Broadening the comparative analysis to include a wider range of vehicle models and powertrain setups would enhance the applicability of the findings. Integrating real-world data and field testing could further validate simulation models, while investigating advanced features like regenerative braking and intelligent power management systems could optimize energy efficiency. Additionally, exploring the broader sustainability implications of powertrain configurations could inform policy decisions and industry practices. In summary, future work should aim to deepen our understanding of electric vehicle technology and its impact on sustainability through comprehensive research and analysis.

Author Contributions

Conceptualization, K.A., Z.T., D.A and M.S.; methodology, K.A. and Z.T.; software, Z.T., K.A. and D.A.; validation, Z.T., K.A., D.A. and M.S.; formal analysis, Z.T. and K.A,; investigation, Z.T. and K.A.; resources, Z.T.; data curation, Z.T. and D.A.; writing—original draft preparation, Z.T. and K.A.; writing—review and editing, K.A., D.A. and M.S.; visualization, Z.T.; supervision, K.A. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

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Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study are not publicly available.

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Conflicts of Interest

The authors declare no conflict of interest.

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