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Comparative Analysis of Single, Double and Quad Electric Vehicle Powertrain Systems

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Abstract

Electric vehicles offer a promising solution to solving environmental problems related to air pollution. The typical powertrain design of an electric vehicle includes a relatively high-speed-low-torque electric motor integrated with some mechanical system to transmit the output mechanical energy to the wheels, such as the gearbox, transmission and differential. Different drivetrain configurations with single, double and quad electric motors can be used in electric vehicles. In this study, it is aimed to compare the effects of different powertrain configurations on the acceleration performance, range and energy consumption of the electric vehicle. Single, dual and quad motor electric vehicle powertrain systems were simulated with MATLAB Simulink according to the New European Driving Cycle (NEDC). The Volvo XC40 Recharge electric car was used as the reference vehicle with the same vehicle characteristics, battery type/capacity and the same total power output by changing only the electric motor powertrain configurations. It has been determined that quadruple electric motor powertrain configuration has lower energy consumption, longer range and better acceleration performance than the single and double electric motor powertrain configurations.

Keywords: Acceleration performance; Electric vehicles; Energy consumption; Powertrain; Range

Research Article

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1. Introduction

Fossil fuel combustion produces a lot of carbon dioxide (CO_2) emissions; hence the European Union has been issuing more strict regulations in recent years [1]. The automotive sector is clearly interested in these new laws. In fact, the transport sector generates around 20% of global CO_2 emissions before the Covid-19 pandemic, while it decreased by 7.8% in 2021 [1]. As electric vehicles (EVs) become more popular, CO_2 emissions might be minimized. Electric vehicles do not produce any harmful emissions; they indicate a three-times more efficiency over traditional vehicles with internal combustion engines (ICEs) when it comes to converting chemical energy into mechanical energy. The internal combustion engines ICEs have compression and combustion strokes, which are absent in EVs. This resulting in reduction of vibrations and sounds also improvement in driving comfort.

EVs are considered the future alternative to traditional vehicles in order to reduce greenhouse gas emissions from transportation. Despite the great development in electric vehicle technology, the limited driving range poses a major challenge to its spread. There are many research and studies that work on increasing the energy density of used batteries. However, improving the efficiency of the transmission can be an effective and economical solution to increase the driving range of electric vehicles. Improving the efficiency of the powertrain reduces the loss in power transmission from the electric motor to the wheels, which leads to a reduction in electrical energy consumed.

Conventional vehicles using internal combustion engines rely on multi-speed transmissions. Multi-speed transmissions are necessary in order to maintain good dynamic performance of the vehicle such as speed, acceleration and starting, and it also allows the internal combustion engine to work at the highest possible efficiency by shifting gears, which leads to reduced fuel consumption. However, there are some electric vehicles that rely on a multi-speed transmission such as that used in internal combustion engine vehicles. The high rotational speed in addition to the maximum and constant torque from zero speed to rated speed is the most important features of the electric motor. A satisfying dynamic performance is therefore provided by the single-speed transmission [2–4]. On the other hand, a central motor drive with a single-speed transmission can also effectively minimize the weight, volume, losses, and cost of the drivetrain [5].

With the possibility of dispensing with the multi-speed transmission while maintaining the same dynamic performance of the electric vehicle, its use can raise the overall efficiency of the transmission circuit, which contributes to an increase in the driving range of the electric vehicle. At lower speeds and lower torque, the efficiency of electric motors decreases, so a multi-speed transmission helps the electric motor operate in the higher efficiency range. Studies show that the use of a multi-speed transmission in an electric vehicle reduces the vehicle's energy consumption. As with conventional vehicles, there are several types of transmissions that can be used in electric vehicles, such as: manual transmission (MT), automatic transmission (AT), dual clutch transmission (DCT), and continuously variable transmission (CVT) [6-8].

To maximize the power-to-weight ratio and, thus, the motor power density, electric vehicle manufacturers often install the driveline with a single high-speed, low-torque electric motor. This configuration requires a transmission, clutch, and gearbox in order to transmit the rotational speed and torque to each wheel. Moreover, a mechanical differential that can distribute torque to all of the driving wheels is required. Meanwhile, the efficiency of the driveline is reduced by 20% as a result of all of these mechanical components [9].

There are several methods in which to improve acceleration and top speed with high and low gear ratio gearing, depending on the vehicle's speed restrictions. Since torque interruption occurs during gear shifting in a multi-speed gearbox, it has a disadvantage in terms of driving performance. Multi-motor and multi-speed transmissions for electric cars have been shown to be more efficient than single motor and multi-speed transmission systems [10, 11].

The electric vehicle powertrain affects the total efficiency of the vehicle. Amount of energy saved are classified as all-wheel drive, front-wheel drive, and rear-wheel drive configurations, from best to worst. Also, the average energy savings for all-wheel drive are 19.11%, 9.38%, and 7.93% for front-wheel drive, rear-wheel drive, and all-wheel drive, respectively. Different power systems also use different amounts of power [12].

To improve the energy efficiency and acceleration performance of pure electric vehicle, three configurations of powertrain will be proposed by this study, based on the manufacturer specifications of Volvo XC40 Recharge pure electric vehicle. Firstly, using single 300 kW permanent magnet DC electric motor with gear and differential to transmit the power to the front axle. Secondly, two identical 150 kW permanent magnet DC electric motors were used to transmit the power to the front wheels, each motor is connected to one wheel in the front axle, while there will be no need for using differential gears. Thirdly, four identical 75 kW permanent magnet DC electric motors were used to drive the four wheels, where each motor is connected to one wheel. The three configurations will be modeled and simulated using MATLAB Simulink with same battery capacity, motor power and vehicle specifications. Since the power efficiency and performance of a propulsion system are highly dependent on the driving track, it is essential to rely on a standard for which to evaluate and compare the data obtained. Since there is not any driving test cycle standard in Türkiye, therefore the New European Driving Cycle (NEDC) is used as a reference driving cycle during the analysis.

2. Model Development

The model was created using MATLAB Simulink and divided into four parts or subsystems. Electric vehicle model block diagram is shown in Figure 1. The first part or subsystem is vehicle body; vehicle body subsystem includes tires, chassis, differential and gearbox. Second part or subsystem is the motor and controller part; different types of motors and controllers could be used in the model. However simple DC motor and H-bridge controller were used in this model. The third part or subsystem is drive input; in the single motor configuration this subsystem input or reference signals are generated from inbuilt drive cycle block and the last subsystem is the battery; electric motor provides mechanical power to the gearbox for the operation, while the motor takes power from the battery. In order to control the speed of the motor, controller is connected between the battery and the motor.

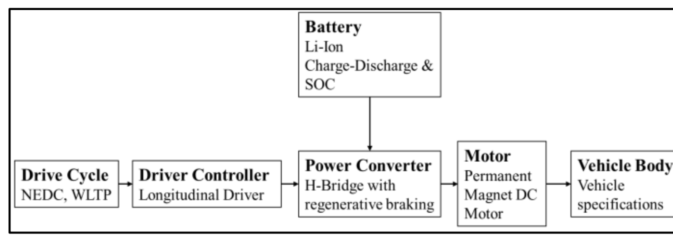

Fig. 1. Electric vehicle model block diagram

2.1 Vehicle body subsystem

The vehicle body subsystem shown in Figure 2 consists of vehicle body block and four tires' blocks (magic formula), the four wheels are connected to the front and rear axles, in the single motor model the power transmitted and distributed to the front wheels by a gearbox and a differential.

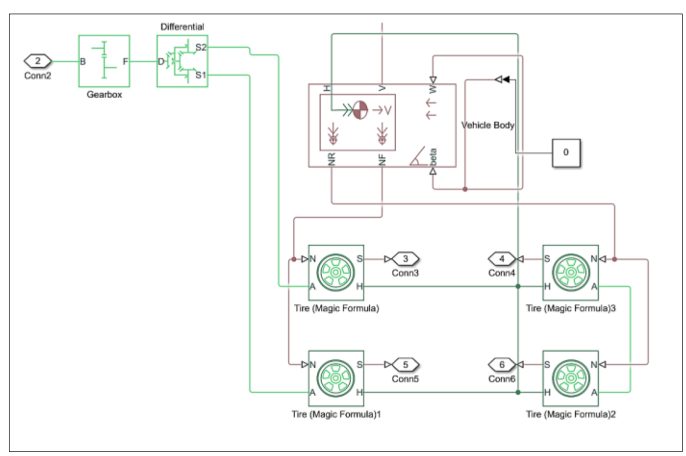

Fig. 2. Vehicle body subsystem

2.2 Electric motor subsystem

The motor subsystem shown in Figure 3 represents the motor or motors that converts the electrical energy into mechanical energy, the number of motors in each configuration is different but the total power of each model is 300 kW. This model uses the electric DC Motor to simulate the electric motor of the electric vehicle. The electric motor consists of electrical part and mechanical part. The electrical part is connected to the electric power converter, while the mechanical part is connected to the vehicle body.

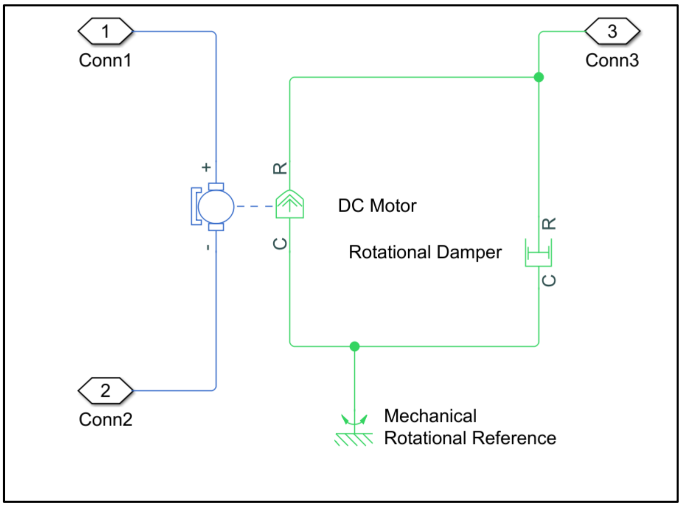

Fig. 3. Electric motor subsystem

2.3 Power converter subsystem

The power converter subsystem consists of H-bridge motor drive. As shown in Figure 4 the H-bridge is driven by Controlled PWM Voltage in average mode. In Averaged mode, the PWM port voltage divided by the PWM signal amplitude parameter defines the ratio of the on-time to the PWM period. Using this ratio and assumptions about the load, the block applies an average voltage to the load that achieves the correct average load current. The regenerative breaking is assumed always enabled in this model. This subsystem converts the acceleration or deceleration performance of the driver into electrical signal drives the electric DC motor.

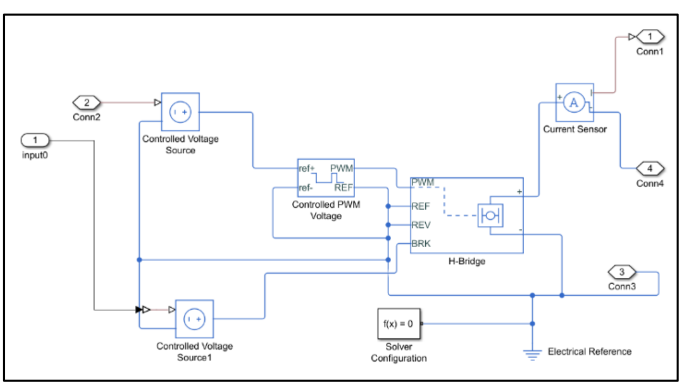

Fig. 4. Power converter subsystem

2.4 Battery subsystem

The battery block in Simulink shown in Figure 5 provides a generic battery model for many battery types. In this model the Lithium-Ion type is used since its commonly used in electric and hybrid vehicles. Similar to the real VOLVO XC40 a 78kWh battery used with 600 V as nominal voltage. The full specifications of the battery model are summarized in Table 1.

Table 1. Battery specifications

Nominal voltage	600 V
Rated capacity	130 Ah
Initial state-of-charge	100%
Nominal discharge current	56.5 A
Internal resistance	0.046 Ω

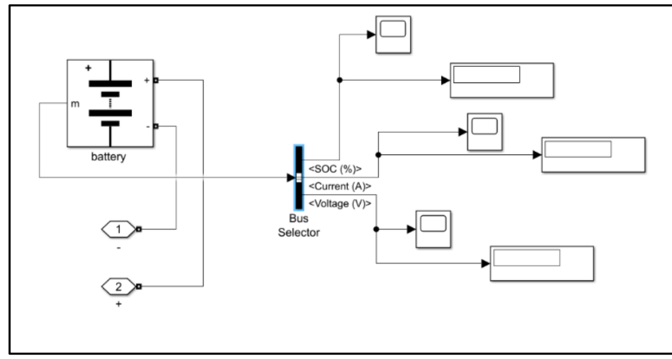

Fig. 5. Battery subsystem

2.5 Driver controller subsystem

In this model the driver controller subsystem uses longitudinal driver block. The Longitudinal Driver block shown in Figure 6 implements a longitudinal speed-tracking controller. Based on reference velocity from the drive cycle and feedback velocities from the vehicle body, the block generates normalized acceleration and braking commands that can vary from 0 through 1, the commands are converted into electrical signals as an input to the power converter subsystem.

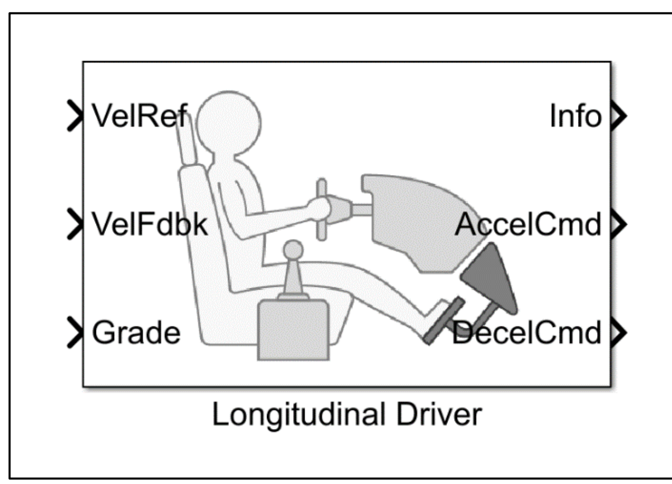

Fig. 6. Longitudinal driver block

2.6 Drive cycle subsystem

The drive cycle subsystem generates a standard or user-specified longitudinal drive cycle. In this simulation the NEDC is used as a standard cycle, the drive cycle will be repeated cyclically in order to compare the range of the different configurations.

3. Configurations of Electric Vehicle's Powertrain

In this study, three configurations of electric vehicle powertrain are provided, including single, double and quad electric powertrain configurations. All configurations were simulated using MATLAB Simulink refereeing to Volvo XC40 Recharge electric vehicle with the same vehicle specifications, drive cycle, battery capacity and total electric motor power as shown in Table 2.

Table 2. Volvo XC40 Recharge electric vehicle specifications [13]

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
Rolling Resistance	0.018
Air Density	1.18 kg/m^3
Inclination angle	0°
Mass moment of the wheel	1 kgm^2
Distance between rear tires and center of gravity	1.6 m
Distance between front tires and center of gravity	1.4 m
Height of the center of gravity	0.5 m
The efficiency of the final drive	0.95

3.1 Single electric motor powertrain system

In this configuration; a single 300 kW permanent magnet DC electric motor was used to drive the vehicle. The electric motor was controlled by H-Bridge, while the H-Bridge was supplied by electric energy using a 78 kWh Li-ion battery. The mechanical power was transmitted from the electric motor to the front axle through a single gear and differential gears to distribute the rotational power to the front wheels as shown in Figure 7.

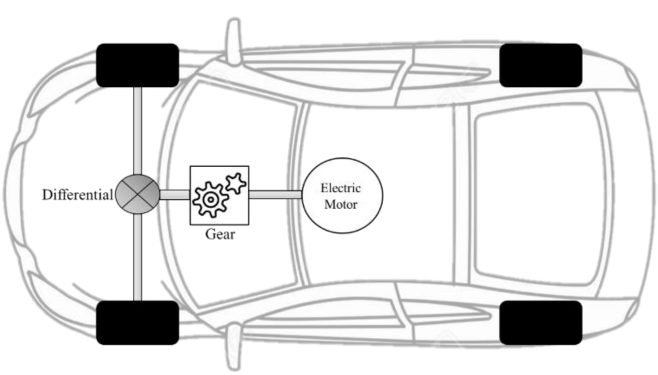

Fig. 7. Single electric motor configuration

3.2 Double electric motor powertrain system

In the twin motor configuration; two 150 kW permanent magnet DC motors were used to drive the vehicle. Similarly the electric motors were controlled by H-Bridge, while the H-Bridge was supplied by electric energy using a 78 kWh Li-ion battery. The mechanical power was transmitted from each electric motor to the front wheels independently without using differential as shown in Figure 8.

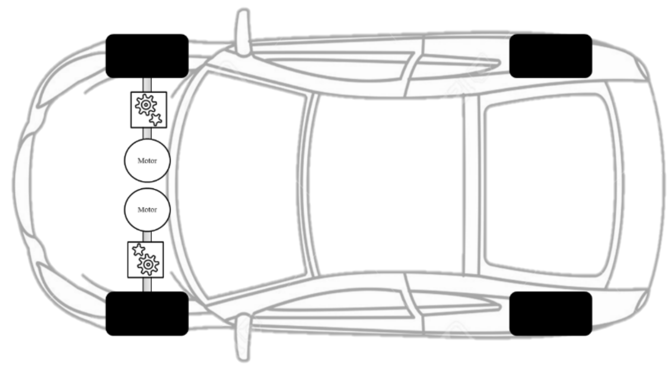

Fig. 8. Double electric motor configuration

3.3 Quad electric motor powertrain system

In the quad motor configuration; four 75 kW permanent magnet DC motors were used to drive the vehicle. Similarly the electric motors were controlled by H-Bridge, while the H-Bridge was supplied by electric energy using a 78 kWh Li-ion battery. The mechanical power was transmitted from each electric motor to the four wheels independently without using differential as shown in Figure 9.

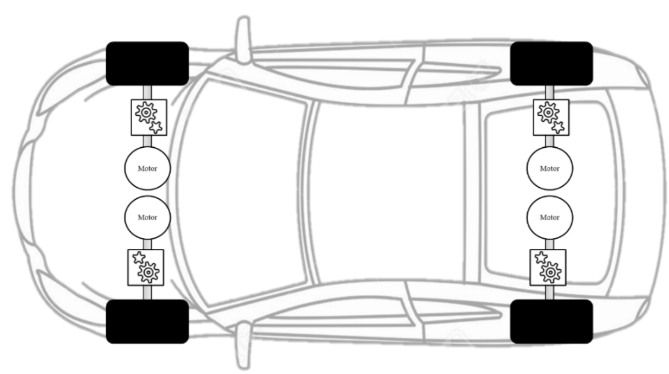

Fig. 9. Quad electric motor configuration

3.4 Drive cycle

There are many examples of transient driving cycles that may be used to evaluate the performance of a vehicle model. The New European Driving Cycle (NEDC) is the test cycle (speed-time profile) required for European type approval emissions and fuel consumption testing. The entire testing procedure is regulated by rule UNECE R83. As shown in Figure 10, it's a highly stylized cycle that flits among periods of rapid acceleration and deceleration as well as periods of constant speed. The NEDC consists of four repeated urban cycles and one highway cycle, with a maximum speed of 120 km/h and a total duration of 1180 seconds. All models provided by this study were simulated referring to the NEDC [14].

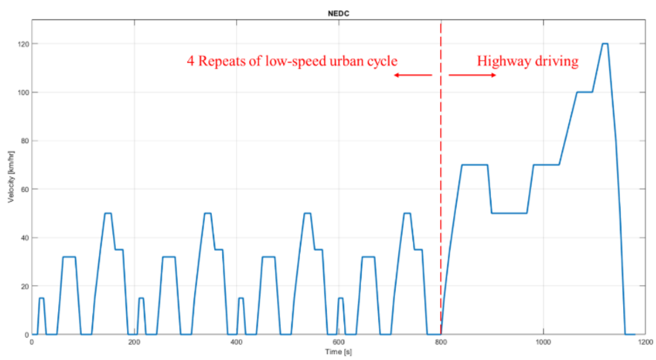

Fig. 10. New European Driving Cycle (NEDC)

4. Simulation and Analysis of Electric Vehicle

The primary focus of this study is the estimation of EV energy consumption and vehicle travel range based on vehicle simulation using MATLAB/Simulink software. To check the validity and reliability of the simulation results, the data of the Volvo XC40 Recharge all-electric car was chosen as a case study. The same methodology may be used to different types of EVs and that the results of this study are independent of the vehicle type used in this research. The proposed vehicle model is evaluated against manufacturer technical data as a crucial component of this study.

The vehicle model contains vehicle body, battery, motors, H-Bridge, longitudinal driver, and drive cycle subsystems, while the differences between three configurations were taken in considerations. The electric vehicle model was built with MATLAB Simulink, as shown in Figure 11.

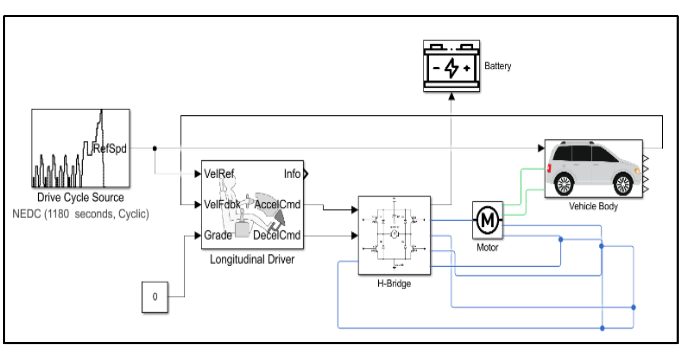

Fig. 11. Electric vehicle model

4.1 Acceleration performance

The acceleration time of a vehicle is an important indicator for evaluating its performance; the shorter the acceleration time, the better the vehicle's performance. Figure 12 presents the simulation results of acceleration time, in which the vehicle will accelerate from 0 to 100 km/h while the acceleration time were compared for the three configurations. Acceleration times were found to be 9.1 s, 8.2 s and 4.9 s, respectively, with single, double and quadruple permanent magnet DC electric motor configurations providing a total power output of 300 kW.

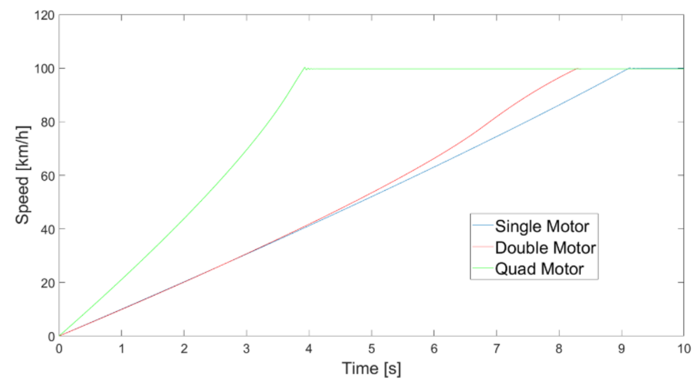

Fig. 12. Electric motor configurations on acceleration performance

4.2 Battery state of charge (SOC)

Energy consumption is one of the main factors used in vehicle evaluation. In this study, the time required for electric motor combinations to consume the usable charge of the battery (65 kWh according to manufacturer's data) was compared. The simulation results illustrated in Figure 13 show that the single permanent magnet DC motor combination with 300 kW power output consumes the battery after 10 hours and 25 minutes, the double permanent magnet DC motor combination with the total of 300 kW power output consumes the battery after 11 hours and 44 minutes, and the quadruple permanent magnet DC electric motor combination with the total of 300 kW power output consumes the battery consumes the battery after 13 hours and 18 minutes.

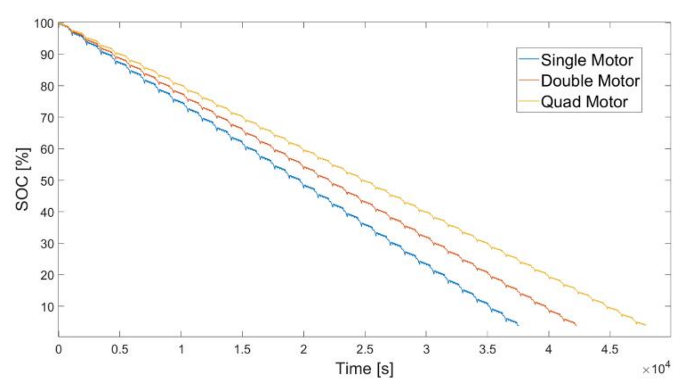

Fig. 13. Electric motor configurations on battery SOC time

4.3 Vehicle travel distance

One of the most important factors used in evaluating a vehicle is the range a vehicle travels on a full charge. In this study, the vehicle range was compared according to the NEDC based on the three configurations using 65 kWh, which is the usable charge of the battery according to the manufacturer's data. Figure 14 shows the distance traveled by the vehicle after the full charge is consumed based on the NEDC according to the simulation results. The single permanent magnet DC motor combination with 300 kW power output travels 348.1 km, the double permanent magnet DC motor combination with the total of 300 kW power output travels 391.7 km, and the quad permanent magnet DC motor combination with the total of 300 kW power output travels 442.5 km.

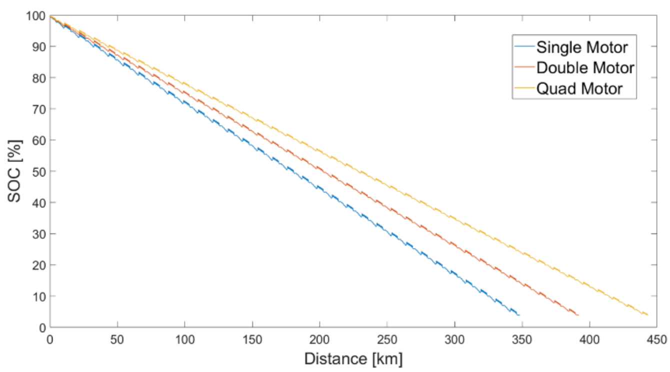

Fig. 14. Electric motor configurations on travel distance

4.4 Energy consumption

The energy consumption values obtained from the simulations are compared and presented in Table 3. The results shows that the energy consumption in kWh/100 km is 19.5, 17.4 and 15.4 respectively, with single, double and quadruple permanent magnet DC electric motor configurations providing a total power output of 300 kW.

Table 3. Electric motor configurations effect on energy consumption

Configuration	Energy Consumption
Single DC electric motor	19.5 kWh/100 km
Double DC electric motors	17.4 kWh/100 km
Quad DC electric motors	15.4 kWh/100 km

5. Conclusion

This paper has presented a comparative analysis between different powertrain configurations of a pure electric vehicle. In particular, powertrains systems with single, double and quadruple permanent magnet DC motor combinations with the total power output of 300 kW have been analyzed using the MATLAB Simulink according to the NEDC. For each configuration, the same battery capacity, vehicle specifications and electric motors power have been used. The results have been compared, in terms of acceleration, battery state of charge, vehicle range and energy consumption. It has been shown that powertrain with four independent electric motors has the best acceleration performance, discharging time, range and energy consumption. It has been determined that the simulation results are compatible with the test results of XC60 Recharge pure electric vehicles with single and double permanent magnet DC motor combinations with the total power output of 300 kW. The research shows that the energy consumption of an electric vehicle can be improved using independent quad motor power train. Thus, quadruple permanent magnet DC motor combination present the best performances compared with the single, double permanent magnet DC motor configurations and, in addition, their features can provide four-wheel drive without using mechanical connections between the front and the rear axis. The single motor configuration relies on a gearbox and differential such as that used in internal combustion engine vehicles, the double and quad motor models have a constant gear reduction only. The Elimination of gearbox reduces mechanical losses and reduces the weight of the power train. While the direct drive feature in the quad motor model enables the allows to use lighter, slower and more efficient electric motors. The reduction in mechanical losses and the use of highly efficient motors increases the overall efficiency of the power train which lead to longer vehicle range.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Zeedan Taha: Conceptualization, Writing-original draft,
Kadir Aydın: Conceptualization, Validation, Supervision.

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