



# Build a Model and Survey the Dynamics of Electric Vehicles according to the Testing Cycle

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**Abstract**—Electric vehicles are becoming part of the modern transportation system because of their reduced dependence on petroleum-based fuels and reduced local noise and emissions during vehicle operations. In line with the general trend of the world, to have in-depth research on electric vehicles, it is necessary to have a reliable electric vehicle model. The study built an electric vehicle model using Simscape and Matlab Simulink tools. It used the built model to study the changes in dynamic parameters of the vehicle under standard working conditions according to the New European Driving Cycle (NEDC), including four Urban Driving Cycle (ECE15) and one Extra Urban Driving Cycle (EUDC). The model allows for determining typical parameters for dynamic features such as velocity, acceleration, and tangential traction force at the active wheel. At the same time, the model also allows for determining the parameters of the electric motor, such as voltage, current intensity, and power. The accuracy of the results confirms that the electric vehicle model is highly reliable and can be used for further research on electric vehicles.

**Keywords**—electric vehicles, European test cycle, simulation model, environmental pollution

## I. INTRODUCTION

Today, automobiles are pivotal and pervasive in societal dynamics and economic advancement. The escalating vehicle count has fueled heightened global usage of fossil fuels, consequently elevating the discharge of air contaminants like particulate matter, nitrogen oxides, sulfur dioxide, and others. As per a report by the European Union, emissions of carbon dioxide from the transportation sector represent approximately 28% of the overall emissions, with road traffic comprising roughly 70% of that total [1, 2]. This has caused automakers to look for alternatives to fossil fuels, such as using alternative fuels or improving vehicle technology. One of the solutions to reduce environmental pollution is to use electric vehicles. According to experts, electric vehicles will be the main means of transport in the future and the main object of intelligent transportation systems. Electric vehicles currently on the market are divided into three types: hybrid electric vehicles, plug-in hybrid electric vehicles, and pure

Electric Vehicles (EVs) running on batteries [3, 4]. Among various developing technologies, electric vehicles (EVs) have attracted significant attention as an alternative technology and are becoming a part of modern transportation systems [5]. The average efficiency of an EVs is 80%, but it has limitations in terms of total range and charging time compared to vehicles using internal combustion engines [6, 7]. Electric vehicles combine various technologies, covering many fields such as mechanical, electrical, automotive, chemical engineering, and electronics [8]. By combining other technologies, the overall performance and fuel consumption of EVs are reduced, making them more efficient than traditional vehicles.

Electric vehicles have the main parts as the power source, the electric motor and the power converter. Electric vehicles operate thanks to energy from the battery that powers the electric motor. By combining electronic, chemical, and mechanical technologies, electric vehicles have reduced energy consumption and do not emit environmental pollutants [9, 10]. Unlike conventional vehicles that run on fuel, electric vehicles never emit pollution during operation, which makes them more environmentally friendly [11]. To get the highest efficiency from electric vehicles, the energy source that produces electricity must also be made from renewable sources such as solar, hydroelectric, wave, etc. [12–14].

Analysis of the above studies shows that electric vehicles are a reliable means of use that helps reduce environmental pollution. They are a means of road transport and new electrical equipment technology for our society. Therefore, providing clean and efficient road transport meets current practical requirements. In this study, the authors built an electric vehicle model and evaluated the model according to the European NEDC test cycle. Therefore, the test results will be highly reliable, and the electric vehicle model can be used for further research.

## II. LITERATURE REVIEW

### A. Electric Motor Model

Models of some elements of electric vehicles such as the electric motor, body, and tires are shown in Fig. 1.

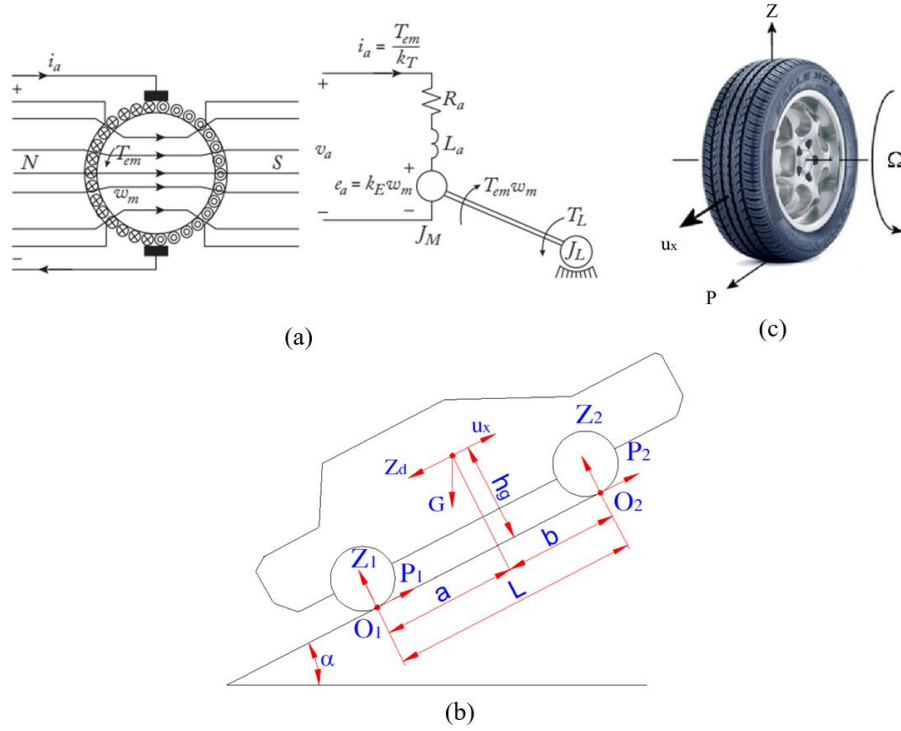


Fig. 1. Some models of electric vehicle components. (a) DC motor circuit diagram; (b) Vehicle body model on an inclined plane; (c) Tire model-road surface.

Fig. 1(a) depicts the formation of the magnetic field in a DC motor, achieved by bending the wires of the rotor section and utilizing a set of permanent magnets as the stator. These permanent magnets establish a consistent magnetic field or flux density. When analyzing an unstable state, it is crucial to account for the current rate of change attributed to the presence of the inductor. This leads to a system of equations, with one equation for each Electrical and Mechanical component. All motor equations are amalgamated [15].

$$\begin{aligned} \frac{dI}{dt} &= \frac{1}{L}(V - E - I.R) \\ \frac{d\omega}{dt} &= \frac{1}{J}(T - T_L - B.\omega) \\ E &= K_E.\omega \\ T &= K_T.I \end{aligned} \quad (1)$$

The system parameters are rotor inertia ( $J$ ), rotational damping ( $B$ ), torque or voltage constant ( $K_T = K_E$ ) and armature resistance ( $R$ ), load torque ( $T_L$ ), motor torque ( $T$ ), Induced electromotive force ( $E$ ), armature inductance ( $L$ ).

### B. Vehicle Body Model

The vehicle axle is in a plane parallel to the road surface. The  $x$  direction is along the vehicle axis and parallel to the road surface; the  $z$  direction is perpendicular to the road surface. Suppose the vehicle moves on an inclined slope  $\alpha$  with the diagram in Fig. 1(b).

The motion of a vehicle depends on all the forces acting on the body of the vehicle. Axial forces pull the vehicle forward or backwards. Gravity pulls the vehicle forward or backwards depending on the angle of inclination. Wind

resistance is always in the opposite direction of the vehicle movement. To simplify proceed to move the force vectors to the center of gravity of the vehicle [16, 17].

The dynamic equation describing the motion of the vehicle body:

$$M u_x = P + Z_d - G.\sin\alpha \quad (2)$$

In which the axial force at the road surface contact point and the wind resistance force are described by the equation:

$$\begin{cases} P = P_1 + P_2 \\ Z_d = -\frac{1}{2} C_d \cdot \rho \cdot F \cdot u_w^2 \cdot \text{sign}(u_w) \end{cases} \quad (3)$$

Force perpendicular to the road surface at the point of contact of the front and rear wheels with the road surface:

$$\begin{cases} Z_2 = \frac{h(Z_d - G.\sin\alpha - M.\dot{u}_x) + b.G.\cos\alpha}{a+b} \\ Z_1 = \frac{-h(Z_d - G.\sin\alpha - M.\dot{u}_x) + a.G.\cos\alpha}{a+b} \end{cases} \quad (4)$$

The force acting in the axial direction (direction of the vehicle movement) changes the force acting perpendicular to the road surface at the point of contact. This force is analyzed in the vehicle stability problem.

In there:

- $\alpha$ : slope angle of the road;
- $M$ : mass of the vehicle;
- $G$ : Gravity of the vehicle;
- $h$ : height of the centre of gravity;

$a, b$ : distance from the centre of gravity to the front and rear axle;  
 $u_x$ : speed of vehicle;  
 $u_w$ : wind speed;  
 $P_2, P_f$ : longitudinal force acting on the front and rear axle;  
 $Z_2, Z_f$ : normal force from the road surface acting on the front and rear wheels;  
 $F$ : Frontal bumper area of the vehicle;  
 $C_d$ : air resistance coefficient;  
 $\rho$ : air density;  
 $Z_d$ : air resistance.

### C. Model of Tyre Interaction with the Road Surface

Tires are an essential part that connects the vehicle body and the road surface. This critical factor determines the dynamics in three directions of the vehicle: vertical, longitudinal, and horizontal. In particular, in the vertical direction, the tire supports the entire mass of the vehicle and directly affects the vibration properties of the vehicle. In the longitudinal and transverse directions, the tire-road surface connection has a decisive influence on the traction properties, braking properties, and stability direction of motion of the vehicle. Fig. 1(c) shows a diagram of the force acting on the tire of a vehicle.

The driving force  $P$  is calculated according to the formula of the Pacejka model [18]:

$$P = f(N, Z) = Z \cdot U \cdot \sin(T \arctan[\{S \cdot N - O [S \cdot N - \arctan(S \cdot N)]\}]) \quad (5)$$

$S, T, U$  and  $O$  are coefficients depending on the hardness, type of road surface, roughness, and curvature of the road.  $N$ : vertical slip coefficient determined by the expression:

$$N = \frac{r_e \Omega - u_x}{|u_x|} \quad (6)$$

In which:

$\Omega$ : angular velocity of the wheel;  $u_x$ : linear velocity at the centre of the wheel;  $r_e$ : average working radius of the wheel.

### D. Battery Model

Because this is a lithium-ion battery, this model uses the following formulas:

If the model is in a discharge state ( $i^* > 0$ )

$$f_1(i_\tau, i^*, i) = Q_0 - R \frac{E}{E - i_\tau} i^* - R \frac{E}{E - i_\tau} i_\tau + A \cdot \text{Exp}(-B i_\tau) \quad (7)$$

If the model is in a loaded state ( $i^* < 0$ )

$$f_2(i_\tau, i^*, i) = Q_0 - R \frac{E}{i_\tau + 0.1 E} i^* - R \frac{E}{E - i_\tau} i_\tau + A \cdot \text{Exp}(-B i_\tau) \quad (8)$$

with:

Voltage  $Q_0$  (V); Exp is curve exponent; Polarization resistance  $R$  ( $\Omega$ ); current in  $i^*$  (A); External current  $i_\tau$  (A); Rated capacity  $E$  (Ah); Variable voltage  $A$  (V); Variable capacity  $B$  ( $\text{Ah}^{-1}$ ).

## III. MODEL AN ELECTRIC VEHICLE AND ENTER DATA FOR THE MODEL

Electric vehicle is composed of an electric motor, battery, gearbox, and wheels. When an electric vehicle operates, the wheels are pulled by an electric motor. The electric motor gets power from the battery. When the vehicle goes downhill or brakes suddenly, the engine will act as a generator to help recharge the battery.

### A. Build an Electric Vehicle Model

#### 1) Electric model

- **Battery block:** This block represents the general kinetic model for the most common self-charging batteries available today. It allows the evaluation of multiple output parameters, including state of charge, voltage, and current.
- **Motor block:** The motor block represents the power and torque characteristics of a DC electric motor. The DC motor block represents the electrical and torque characteristics of the DC motor. This block assumes that no electromagnetic energy is lost. DC motor parameters can be specified directly or derived from no-load speed and torque.

#### 2) Model of mechanical elements

- **Model of gearbox and body block:**

**Simple gear block:** This block represents a pair of gears with constant and variable ratios; an active gear is denoted  $B$ , and a passive gear is  $Q$ , which can be selected in the same or opposite direction as the motor. If you want the Model to be closer to reality, you can choose additional parameters such as moment of inertia, loss...

The kinematic constraints that the Simple Gear block imposes on the two connected axes are:

$$i_{FB} = \frac{\omega_Q}{\omega_B} = \frac{n_Q}{n_B} \quad (9)$$

In there:

$\omega_Q$ : Angular speed of the passive gear.

$\omega_B$ : Angular speed of the engaged gear.

$n_Q$ : Number of teeth of passive gear

$n_B$ : Number of teeth of active gear

$i_{QB}$ : Transmission ratio

**Vehicle body block:** This block represents the two axes of the vehicle body moving vertically. The number of wheels on the front and rear axles is adjustable. This block also has the center of gravity of the vehicle to fit the calculation. This block calculates vehicle conditions such as mass, aerodynamic coefficient, road conditions, load distribution, etc. Parameters from the actual vehicle can be entered for calculation. For simplicity, the problem ignores wind resistance and road conditions, and there will be no sway when changing the steering axis.

- **Wheel model and throttle control:**

**Tyre block:** This block will model a tyre running vertically, calculated by the magic formula. This

block can calculate kinematics in fixed or changing conditions. For simplicity, tire characteristics as well as inertia and rolling are ignored.

The steering condition control block represents the long-range speed adjustment controller. Based on the given speed and the actual speed of the vehicle response. This block can help create acceleration and deceleration signals like a real vehicle. It can be used in many different modes to suit each simulation purpose. This controller uses the PI algorithm, which tracks parametric longitudinal speed to generate normalized

acceleration and braking commands based on reference velocity and feedback. To help the driving process follow the test cycle.

3) Electric vehicle model

The constructed electric vehicle model is shown in Fig. 2, including the electric motor, battery, reducer, wheels, and test cycle. When the vehicle is in operation, the wheels are pulled by an electric motor; the electric motor draws energy from the battery. When the vehicle goes downhill or brakes, the engine will act as a generator to help recharge the battery.

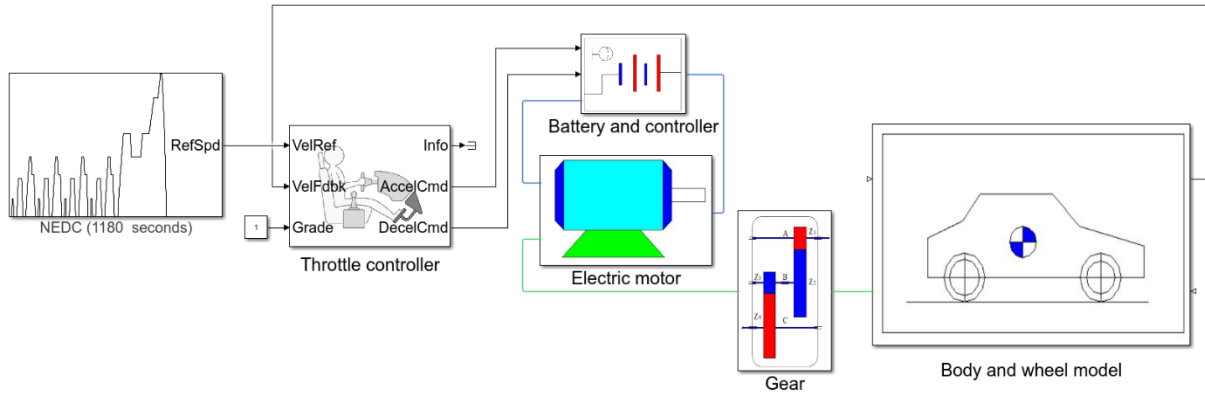


Fig. 2. Electric vehicle model on Matlab software.

B. Enter Data for the Model

1) NEDC test cycle

A standard driving cycle is used to evaluate model accuracy or vehicle performance. The New European Driving Cycle (NEDC) is commonly used because it includes city driving with some stops and motorway driving. This cycle will perform just as well as in real driving. The NEDC cycle consists of the Urban cycle. This cycle contains four primary cycles: ECE15 and the driving cycle on suburban roads. The NEDC cycle time is 1180 s [15, 19].

2) Specifications of electric vehicle

To survey the performance of electric vehicle, the authors used vehicle with basic technical parameters shown in Table I.

TABLE I. TECHNICAL SPECIFICATIONS OF ELECTRIC VEHICLES

No	Name	Value
1	Distance from centre of gravity to the front axle (m)	1.580
2	Distance from centre of gravity to rear axle (m)	1.580
3	Centre of gravity height (m)	0.45
4	Wheel rolling radius (m)	0.3
5	Rolling resistance coefficient	0.018
6	Vehicle weight (kg)	1609
7	Frontal Barrier area (m <sup>2</sup> )	2.6
8	Drag coefficient	0.4
9	Air density (kg/m <sup>3</sup> )	1.18

- Calculate and select the electric motor and select the gear ratio of the reducer:

The initial parameters of the electric vehicle used in the calculation are shown in Table I. Maximum speed of the vehicle:  $v = 120 \text{ km/h} = 33.33 \text{ m/s}$ . The traction balance equation of electric vehicles in the case of vehicles running on flat roads ( $\alpha = 0$ ) as in Eq. (2):

$$P_k = P + Z_d$$

Rolling resistance is calculated:

$$P = f \cdot Z_1 + f \cdot Z_2 = f \cdot G$$

$Z_1, Z_2$ : normal road reactions acting on the front and rear wheels;  $G$ : is the gravity of the vehicle;  $f$ : Total resistance coefficient of the road.

$$f = f_0 \left(1 + \frac{v^2}{1500}\right) = 0.018 \left(1 + \frac{33.33^2}{1500}\right) = 0.0313$$

Because of electric vehicle accommodate 5 people. On average, each person weighs 70 (kg), so the weight of the person then is:  $5 \times 70 = 350$  (kg). Then, the rolling resistance is :  $P = f \cdot G$

$$P = 0.0313 \times (1609 + 350) \times 9.8 = 0.0313 \times 1959 \times 9.8 = 600.9 \text{ (N)}$$

Air resistance:

$$Z_d = K \cdot F \cdot v^2$$

In which:  $K$  is the air resistance coefficient, choose  $K = 0.31 \text{ N s}^2/\text{m}^4$ ;  $F$  is the frontal barrier area  $F = 2.6 \text{ m}^2$ ;  $v$  is the maximum speed of the vehicle,  $v = 120 \text{ km/h} = 33.33 \text{ m/s}$ .

$$\Rightarrow Z_d = K \cdot F \cdot v^2 = 0.31 \times 2.6 \times 33.33^2 = 895.4 \text{ N}$$

The traction force of a vehicle when running at a speed of 120 Km/h is:

$$P_k = P + Z_d = 600.9 + 895.4 = 1496.3 \text{ N}$$

When running at maximum speed, obstruction capacity the of vehicle is now:

$$N_c = N_k = P_k \cdot v$$

The required power of the engine for the vehicle to operate well and satisfy the above forces is:

$$N_M = \frac{P_k \cdot v}{\eta} \text{ kW}$$

$\eta$ : is the performance of the powertrain system, choose  $\eta = 0.92$

$$\Rightarrow N_M = \frac{1496.3 \times 33.33}{0.92} = 54208 = 54.2 \text{ kW}$$

Therefore, an electric motor with a maximum power of more than 54.2 kW is selected. So select an electric motor with a capacity of 60 kW, voltage 360 V, speed with maximum torque of 5200 rpm, and no-load speed of 5525 rpm.

Gear reduction gear ratio:

The gear ratio of the reducer is determined according to Eq. (9):

$$i_{QB} = \frac{n_Q}{n_B}$$

In which  $n_Q$  maximum speed of electric motor ( $n_Q = 5200 \text{ rpm}$ ).

$n_B$  are the angular velocity and maximum required number of wheel revolutions.

$$n_B = \frac{30v}{\pi \cdot r_w} \text{ rpm}$$

With  $r_w = 0.30 \text{ m}$ ;  $v_{max} = 34.72 \text{ m/s}$

$$n_B = \frac{30v}{\pi \cdot 0.3} = \frac{30 \times 34.72}{3.14 \times 0.3} = 1105 \text{ rpm}$$

$$i_{QB} = \frac{n_Q}{n_B} = \frac{5200}{1105} = 4.7$$

Select the gear reduction gear ratio:  $i_{QB} = 4.7$

- **Battery specifications:**

The battery in an electric vehicle is a lithium-ion cell battery connected in series or parallel. Specifications of a cell with standard capacity: 4200 mah ( $\pm 5\%$ ); Voltage: 3.7 V; Maximum discharge current: 30 (A) continuous.

From there, the cells can be connected as follows:

- With an electric motor capacity of 60 kW and a motor voltage of 360 V, the battery requires 10 Blocks to be connected in series, and each Block has a voltage of about 37 V (When connecting blocks in series, the voltage will be equal to the total voltage of the Blocks, and the capacity of the blocks will be equal). On the other hand, for a vehicle to operate for about 1.5 h continuously at maximum capacity, the battery capacity needs about 250 A.h.
- To get the voltage at the output of a module of 3.7 V, the author will combine 6 Cells in parallel into one Module as shown in Fig 3(a). Then the voltage of a Module is 3.7 V with capacity  $C_M = 6 \times 4200 = 25.2 \text{ A.h}$ . Then, connect ten modules in series, and the voltage of one row will be  $3.7 \times 10 = 37 \text{ V}$ ;
- For the electric vehicle to operate for about 1.5 (hour) continuously at maximum capacity, the battery capacity needs about 250 A.h. At that time, it is necessary to connect ten rows of modules; each row has ten modules; consider this entire Block as one Block, and the block capacity is  $C_B = 10 \times 25.2 = 252 \text{ A.h}$ . The voltage of the Block is 37 V, as shown in Fig. 3(b).
- With a motor voltage of 360 V, when connecting 10 Blocks (Battery cells) in series, the output voltage of the battery is:  $10 \times 37 = 370 \text{ V}$ , connection results are as shown in Fig. 3(c).

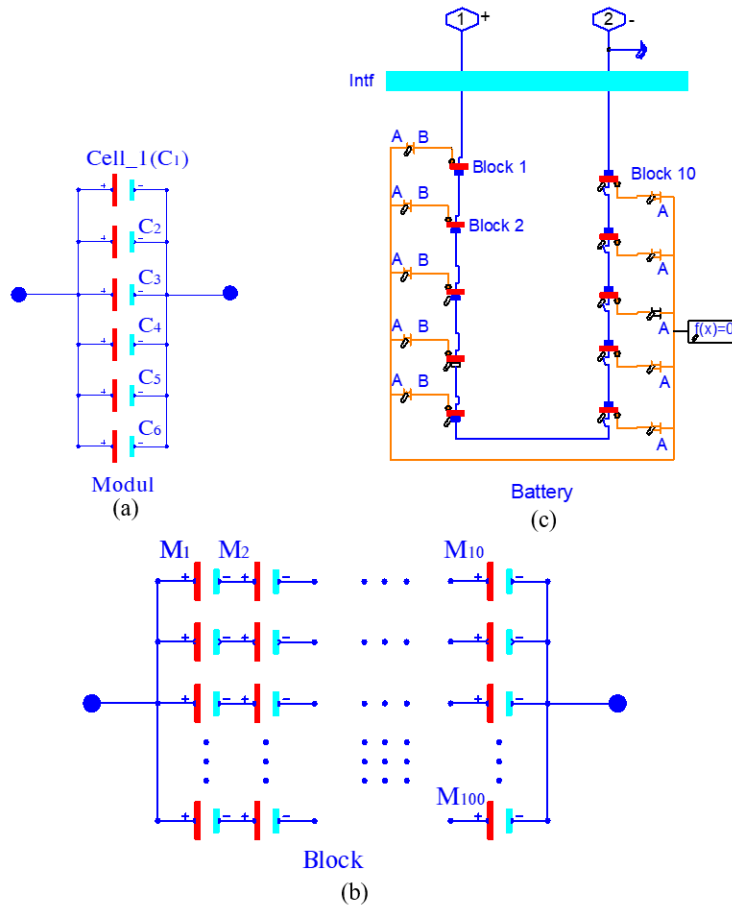


Fig. 3. Battery connection diagram. (a) Cell connection diagram to create Module; (b) Block creation module connection diagram; (c) Battery creation Block connection diagram.

#### IV. RESULT AND DISCUSSION

##### A. Evaluate the Accuracy of the Model

Fig. 4 shows the test cycle according to the European NEDC standard. This cycle consists of two phases: the urban vehicle cycle (the start time of this period is from the 0 to 780 s) and the suburban vehicle phase (the start time of this phase is from the 780 to 1180 s). After simulating according to the NEDC test cycle, as shown in Fig. 4, the simulated speed line always follows the actual speed line of the vehicle according to the test cycle. This indicates that the established electric vehicle model is highly accurate and reliable enough to conduct other surveys [15, 19].

##### B. Some Results when Surveying the Operation of Electric Vehicles

For an electric vehicle to run according to the NEDC cycle, the parameters of the electric motor must also change accordingly. Therefore, when analyzing the dynamics of the vehicle graph along with the voltage, current, and power graphs of the electric motor, it will be possible to evaluate the overall performance of the electric vehicle. The simulation results of calculating the dynamic parameters of the vehicle are shown in Fig. 5, and the results of the current intensity, voltage, and power of the electric motor are shown in Fig. 6.

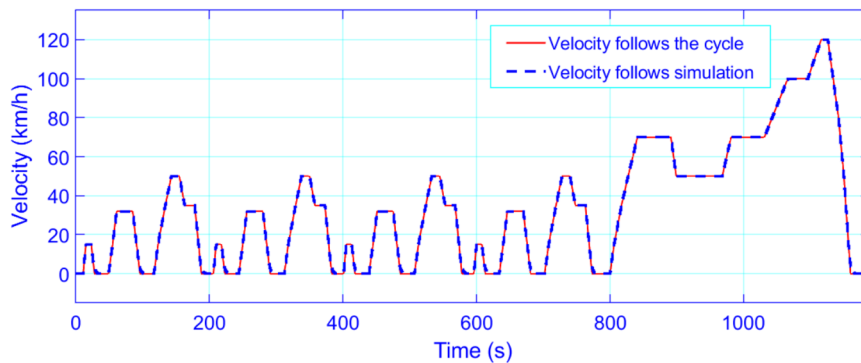


Fig. 4. Graph of simulated output velocity and driving cycle.

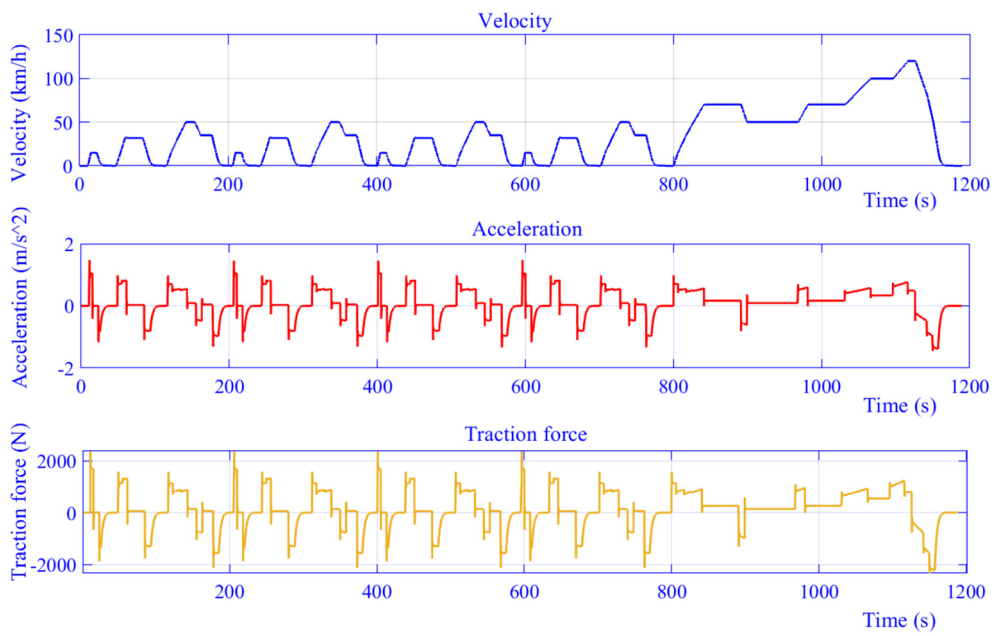


Fig. 5. Graph of vehicle velocity, acceleration, and traction.

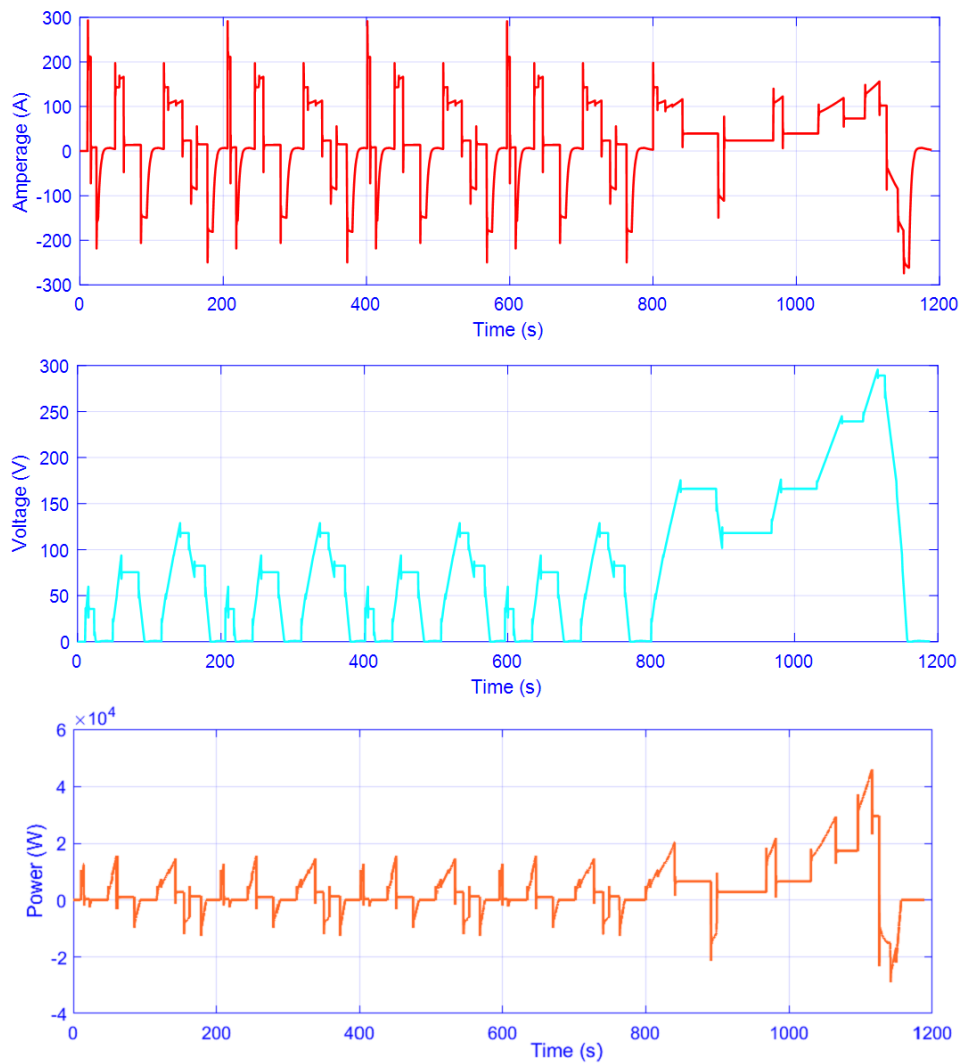


Fig. 6. Graph of voltage, current and power of an electric motor.

During the NEDC cycle, state of the vehicle will change depending on the different conditions of the cycle, but following the operating conditions are the acceleration phase, steady running phase, deceleration phase and engine stop phase [19, 20]. Below, the authors will analyze developments according to a part of the NEDC cycle at period  $117 \div 188$  s as follows:

**Acceleration phase:** During the acceleration phase, the speed of the vehicle increases, requiring large traction force, leading to a rise in motor current intensity to provide enough energy for rapid acceleration of the vehicle. From a speed of  $0 \div 50$  km/h (corresponding to  $117 \div 143$  s), as shown in Fig. 5, the most significant acceleration and most significant force are maximum acceleration of  $1.0 \text{ m/s}^2$ , maximum pulling force of 1650 N. As shown in Fig. 6, the voltage varies from  $0 \div 125$  V, the maximum current is 167 A, and the full power is 13 kW.

**Stable running phase with constant speed:** During the steady speed phase, the traction force will not change while the voltage and current of the motor are maintained stable. From 144 to 162 s, the traction force is held at 1650 N, resulting in the voltage and current being held at 125 V and 104 A, respectively.

**Deceleration phase:** During the deceleration phase, the traction force drops sharply, causing the voltage and current to decrease rapidly. When the traction force is opposing, the current intensity also has a negative value corresponding to the time of regenerative braking to charge the battery. Specifically, from a speed of  $50 \div 0$  km/h (corresponding to  $163 \div 188$  s, as shown in Fig. 5, the most significant negative acceleration and most significant force are Maximum negative acceleration  $-1.25 \text{ m/s}^2$ , leading opposing traction force  $-2150$  N. As shown in Fig. 6, the voltage changes from  $125 \div 0$  V, the full negative current intensity is  $-167$  A and the maximum negative power in this stage is  $-13$  kW.

**Engine stopping phase:** When the vehicle stops moving, the traction force will decrease to zero, causing the voltage and amperage of the Engine to fall to nearly zero because it does not require much energy to maintain operation.

Similar in the non-urban phase:

**Acceleration phase:** from a speed of  $0 \div 70$  km/h (corresponding to  $805 \div 841$  s), as shown in Fig. 5, the most significant acceleration and most significant force are maximum acceleration  $1.0 \text{ m/s}^2$ ; Maximum pulling force is 1500 N, as shown in Fig. 6 with voltage varying from  $0 \div 175$  V, maximum current 167 A and maximum power in this stage is 20 (kW). At the vehicle speed of 120 km/h, the engine capacity reaches 45 kW.

**The deceleration phase:** from a speed of  $120 \div 0$  km/h (corresponding to  $1145 \div 1160$  s), as shown in Fig. 5, the most significant acceleration and most significant force are Maximum negative acceleration  $-1.4 \text{ m/s}^2$ , leading to opposing traction force  $-2250$  N. As shown in Fig. 6, the voltage changes from  $290 \div 0$  V, the full negative current intensity is  $-167$  A and the total negative power in this stage is  $-30$  kW.

## V. CONCLUSION

The study built an electric vehicle model using Simscape and Matlab Simulink tools. The model allows determining typical parameters for dynamic features such as: velocity, acceleration, tangential traction force at the active wheel. At the same time, the model also allows determining parameters of the electric motor such as voltage, current intensity and power of the electric motor.

The study uses the built model to study the changes in dynamic parameters of vehicles under standard working conditions according to the NEDC cycle including four ECE15 test cycles and one EUDC cycle.

The change in the traction voltage and current intensity of the motor on an electric vehicle depends on the energy requirements of each stage and the moving speed of the vehicle. This helps optimize performance and save energy during the operation of electric vehicles.

With the model built in the next research, the authors will research the regenerative braking system, battery model, and controller for electric vehicles.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

NVT conducted the research; analyzed the data; wrote the paper; NPT supervised the paper; all authors had approved the final version.

## REFERENCES

- [1] J. A. Sanguesa, T. S. Vicente, G. Piedad, F. J. Martinez, and J. M. Marquez-Barja, "A review on electric vehicles: Technologies and challenges," *Smart Cities*, vol. 4, pp. 372–404, March 2021.
- [2] A. Favez, "Electric vehicles: Benefits, challenges, and potential solutions for widespread adaptation," *Applied Sciences*, vol. 13, 6016, May 2023.
- [3] M. U. Cuma and T. Koroglu, "A comprehensive review on estimation strategies used in hybrid and battery electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 517–531, February 2015.
- [4] T. T. An, D. Q. Minh, and N. V. Tuan, "Calculation and design of power split device on a hybrid vehicle," *Journal of Applied Science and Engineering*, vol. 27, pp. 2643–2651, 2024.
- [5] A. Poullikkas, "Sustainable options for electric vehicle technologies," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1277–1287, January 2015.
- [6] X. Cen, H. K. Lo, L. Li, and E. Lee, "Modeling electric vehicles adoption for urban commute trips," *Transportation Research Part B Methodological*, vol. 117, pp. 431–454, November 2018.
- [7] M. Coffman, P. Bernstein, and S. Wee, "Electric vehicles revisited: A review of factors that affect adoption," *Transport Reviews*, vol. 37, pp. 79–93, January 2017.
- [8] K. Madhav, K. P. Panda, T. N. Ramasamy, T. Ritula, and P. Gayadhar, "Comprehensive review of electric vehicle technology and its impacts: Detailed investigation of charging infrastructure, power management, and control techniques," *Applied Sciences*, vol. 13, 8919, August 2023.
- [9] C. William, X. Wu, M. Zhou, Y. Liang, and Y. Wang, "Review and development of electric motor systems and electric powertrains for new energy vehicles," *Automotive Innovation*, vol. 4, pp. 3–22, February 2021.
- [10] Z. Chen, N. Guo, X. Li, J. Shen, R. Xiao, and S. Li, "Battery pack grouping and capacity improvement for electric vehicles based on a genetic algorithm," *Energies*, vol. 10, 439, March 2017.

- [11] N. T. Jeong, S. M. Yang, K. S. Kim, M. S. Wang, H. S. Kim, and M. W. Suh, "Urban driving cycle for performance evaluation of electric vehicles," *International Journal of Automotive Technology*, vol. 17, pp. 145–151, February 2016.
- [12] Y. W. Wang, "An optimal location choice model for recreation-oriented scooter recharge stations," *Transportation Research Part D: Transport and Environment*, vol. 12, pp. 231–237, May 2007.
- [13] Q. Zhang, C. Li, and Y. Wu, "Analysis of research and development trend of the battery technology in electric vehicle with the perspective of patent," *Energy Procedia*, vol. 105, pp. 4274–4280, May 2017.
- [14] S. Snigdha, K. P. Amrishi, and M. M. Tripathi, "Storage technologies for electric vehicles," *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 7, pp. 1–49, June 2020.
- [15] A. O. Kiyakli and H. Solmaz, "Modeling of an electric vehicle with MATLAB/Simulink," *International Journal of Automotive Science and Technology*, vol. 2, pp. 9–15, December 2018.
- [16] R. A. Vimal, A. Fauzi, H. Khisbullah, and J. Hishamuddin, "Modelling and PID control of antilock braking system with wheel slip reduction to improve braking performance," *International Journal of Vehicle Safety*, vol. 6, pp. 265–296, July 2013.
- [17] Y. Yang, Q. Tang, L. Bolin, F. Chunyun, "Dynamic coordinated control for regenerative braking system and anti-lock braking system for electrified vehicles under emergency braking conditions," *IEEE Access*, vol. 8, pp. 172,664–172,677, September 2020
- [18] J. A. Cabrera, J. J. Castillo, J. Pérez, J. M. Velasco, A. J. Guerra, and P. Hernández, "A procedure for determining tire-road friction characteristics using a modification of the magic formula based on experimental results," *Sensors*, vol. 18, 896, March 2018.
- [19] T. A. T. Mohd, M. K. Hassan, A. Ishak, A. C. Soh, B. S. K. K. Ibrahim, and M. K. Hat, "Simulation based study of electric vehicle parameters," *ARPN Journal of Engineering and Applied Sciences*, vol. 10, pp. 8541–8546, October 2015.
- [20] K. L. Butler, M. Ehsani, and P. Kamath, "A Matlab-based modeling and simulation package for electric and hybrid electric vehicle design," *IEEE Transactions on Vehicular Technology*, vol. 48, pp. 1770–1778, November 1999.

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