

Modeling and Road Condition Simulation Analysis of Electric Vehicle Integrated Model

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Abstract: To address the limitations of high costs and prolonged testing cycles associated with traditional real-vehicle evaluation methods for electric vehicle (EV) road condition analysis, a novel forward simulation approach was developed. Based on the longitudinal dynamics theory and the parameters of a specific pure EV, a high-fidelity simulation model was constructed using the MATLAB/Simulink platform. Actual driving cycles were incorporated as input conditions to allow for the systematic evaluation of key power performance indicators, including acceleration capability, maximum gradability, and speed tracking accuracy. It was demonstrated through experimental results that the maximum deviation between simulated values and design targets was merely 3.3%. Through these findings, the model's precision in replicating real-world driving scenarios and its effectiveness in performance assessment were validated. By comparison with conventional testing, development costs can be significantly reduced through the proposed methodology, and a versatile theoretical framework for EV power system optimization can be established. In addition, flexible adaptation to various vehicle configurations and driving environments is enabled by the model's modular architecture.

Keywords: Electric vehicles, Forward simulation, Longitudinal dynamics, Power performance.

1. Introduction

As a key industry for energy conservation, emission reduction, and sustainable development, new energy vehicles have developed rapidly in recent years, playing a vital role in mitigating energy shortages and advancing sustainability in the transportation sector^[1]. However, their core indicators such as range, battery performance, and energy management efficiency are closely related to the dynamic characteristics of road conditions, including vehicle speed changes, slope, ambient temperature, and driving behavior^[2]. The traditional R&D model relies on extensive real-vehicle road testing, which is costly, time-consuming, and often fails to account for extreme driving scenarios. In this context, road condition simulation technology, which recreates complex driving environments and predicts vehicle dynamics using high-fidelity digital models, has become a key means to shorten the R&D cycle, optimize control systems, and verify safety^[3].

Based on the basic dimensional parameters of a pure electric vehicle and the analysis of longitudinal dynamics during vehicle operation, a modular electric vehicle integrated simulation model was established using MATLAB/Simulink. Power output was dynamically adjusted through a driver model, which was better aligned with real-world feedback control mechanisms compared to traditional backward simulations. Simulation parameters and numerical algorithms were selected to initiate the simulation process. Through this process, the correctness of the model was verified, and vehicle performance under various working conditions was simulated. Dynamic performance indicators were calculated to enable a comprehensive evaluation of vehicle performance.

Additionally, flexible replacement of condition data and vehicle parameters was supported through the encapsulation design between modules, which solves the problem of limited adaptability in traditional single models and provided a more universal theoretical reference for the optimization of electric vehicle design.

2. Vehicle Longitudinal Dynamics and Dynamic Performance Analysis

2.1. Longitudinal Dynamics Analysis of Vehicle Road Driving

In electric vehicle operation, longitudinal dynamics forms the core of force analysis, which is deeply related to the essential functions, core performance, typical working conditions, and key system design of the vehicle. Serving as the foundation for forward vehicle motion, longitudinal dynamics directly determines core performance such as power, braking performance, and energy efficiency, and covers the main force states of most straight-line driving conditions. From the design perspective, its analysis conclusions provide core theoretical basis for parameter matching of key components such as the power system, braking system, and tires, and are essential for ensuring the fundamental driving capability of the vehicle^[4].

During normal driving, the vehicle is mainly subjected to rolling resistance F_f from the ground, aerodynamic resistance F_w , grade resistance F_i when climbing, and inertial force F_j that hinders acceleration due to the vehicle's own mass during acceleration. The forces acting on the vehicle during driving are shown in Figure 1.

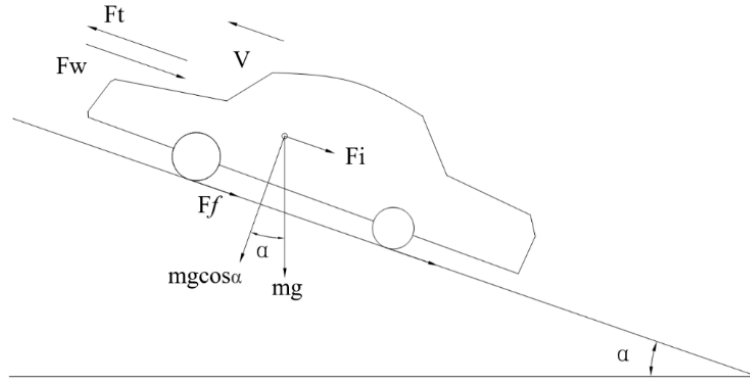


Figure 1. Force analysis of vehicle road driving

When an electric vehicle is running, the power battery outputs energy to overcome driving resistance. Electrical energy is converted into torque driving the wheels through the motor and mechanical transmission system; the torque output by the motor to the wheels interacts with driving resistance to generate traction force that propels the vehicle forward. The longitudinal dynamics of electric vehicles adhere to Newton's second law, and the dynamic equation considering resistance can be expressed as:

$$F_t = F_w + F_i + F_f + F_j \quad (1)$$

where F_t is the traction force, F_w is the aerodynamic resistance, F_i is the grade resistance, and F_f is the rolling resistance.

Furthermore, the traction force F_t is generated by the motor torque transmitted through the transmission system, and its mathematical expression is:

$$F_t = \frac{T_e \cdot i_g \cdot i_0 \cdot \eta_t}{r} \quad (2)$$

In the above equation, T_e denotes the motor output torque, i_g is the transmission ratio of the gearbox, i_0 represents the final drive ratio, η_t stands for the mechanical efficiency of the transmission system, r is the effective rolling radius of the driving wheel.

Substituting the traction force formula into Equation (1) and expanding the physical expressions of each resistance, the complete longitudinal dynamic equilibrium equation is finally derived:

$$\frac{T_e i_g i_0 \eta_t}{r} = \frac{1}{2} \rho C_d A V^2 + mg \sin \alpha + mg f \cos \alpha + \delta m \frac{dv}{dt} \quad (3)$$

where ρ is the air density, C_d is the aerodynamic drag coefficient, A is the vehicle's frontal area, V is the vehicle speed, m is the total mass of the vehicle, g is the gravitational acceleration, α is the road slope angle, f is the rolling resistance coefficient, and δ is the rotational mass conversion coefficient, which can usually be calculated using the following formula:

$$\delta = 1 + \frac{I_w \cdot n_w}{mr^2} + \frac{I_e \cdot i_g^2 \cdot i_0^2}{m \cdot r^2} \quad (4)$$

In the above equation, I_w is the moment of inertia of a single wheel, n_w is the number of wheels, and I_e is the equivalent moment of inertia of the engine and transmission system.

Due to the unknown information of some vehicle parameters, the following empirical relationship can be used to estimate the rotational mass conversion coefficient^[5]:

$$\delta = 1 + \delta_1 + \delta_2 i_0^2 i_g^2 \quad (5)$$

In the above equation, δ_1 denotes the equivalent coefficient of the wheel's rotational inertia, while δ_2 represents the equivalent coefficient of the rotational inertia of the engine and transmission system. Reasonable estimated values for δ_1 and δ_2 are 0.04 and 0.0025, respectively.

Therefore, Equation (5) can be simplified as:

$$\delta = 1 + 0.04 + 0.0025 i_0^2 i_g^2 \quad (6)$$

2.2. Analysis of Vehicle Dynamic Performance Evaluation Indicators

The acceleration time reflects the EV's responsiveness, requiring the coupling of translational and rotational inertia. The core formula for calculating acceleration time is the energy integral of the variable acceleration process. The acceleration time t can be calculated as:

$$t = \int_{V_1}^{V_2} \frac{\delta m}{F_t - (F_w + F_i + F_f)} dv \quad (7)$$

where δ is the rotational mass conversion coefficient, F_t is the vehicle traction force, F_w is the aerodynamic resistance, F_i is the grade resistance, F_f is the rolling resistance, V_1 and V_2 are the vehicle speeds before and after acceleration, respectively.

The maximum gradeability, which measures the vehicle's climbing capability, is one of the core evaluation indicators of vehicle dynamic performance, reflecting the vehicle's ability to continuously drive on longitudinal slopes. It is defined as the tangent of the slope angle α . According to the vehicle longitudinal dynamics equation, when the vehicle climbs at a constant speed, the gradeability i can be calculated as:

$$i = \tan \left[\arcsin \frac{F_t - (F_f + F_w)}{mg} \right] \quad (8)$$

where F_t is the vehicle traction force, F_w is the aerodynamic resistance, and F_f is the rolling resistance.

3. Construction of the Complete Vehicle Model

The simulation analysis methods for electric vehicles are generally classified into forward simulation and backward simulation. In forward simulation, power system parameters are dynamically adjusted based on a driver operation model and control strategies, making it suitable for the analysis of dynamic performance. In contrast, backward simulation is used to calculate required system parameters in reverse based on a preset speed curve and is more suited for evaluating energy efficiency and component matching. While forward simulation is associated with higher computational

complexity, it allows actual driving conditions to be more accurately replicated. Backward simulation, although computationally efficient, fails to account for transient responses^[6]. The forward simulation method was selected to analyze electric vehicle performance under complex driving conditions. To ensure accuracy in modeling and performance evaluation, a modular strategy was applied to construct a multi-module simulation model. The model was composed of driving condition input, driver, motor, battery, vehicle control unit, vehicle, and performance calculation modules. The structure of the integrated simulation model is shown in Figure 2.

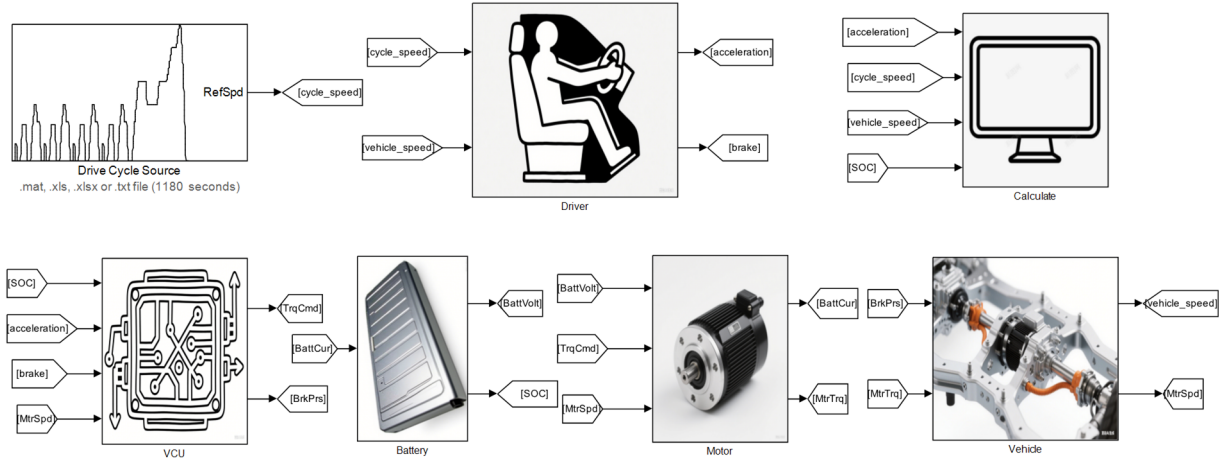


Figure 2. System architecture

4. Simulation Analysis

A pure electric vehicle was simulated using a MATLAB/Simulink-based forward simulation model, with core parameters detailed in Table 1. Simulation tests were conducted under UDDS and FTP-75 standard conditions, as

well as under performance-limiting scenarios such as acceleration, climbing, and maximum speed, in order to assess the simulation capability of the model for vehicle power performance and energy consumption.

Table 1. Partial vehicle parameters

Parameter	Value
Curb weight (kg)	1940
Frontal area (m ²)	2.86
Tire rolling radius (m)	0.325
Aerodynamic drag coefficient	0.233
Transmission system efficiency	0.92
Total transmission ratio	10.5
0-100 km/h acceleration time (s)	7.9
Maximum gradeability (%)	30
Maximum speed (km/h)	185

4.1. Dynamic Response Simulation Under Standard Conditions

Two standard driving cycles, UDDS and FTP-75, were selected as simulation inputs to represent varying road conditions. Simulation results are shown in Figures 3 and 4.

From the figures, it can be observed that the vehicle's dynamic responses under frequent acceleration, deceleration, and stop-start conditions were successfully reproduced, thereby verifying the longitudinal dynamics model and confirming the suitability of the selected transmission system parameters.

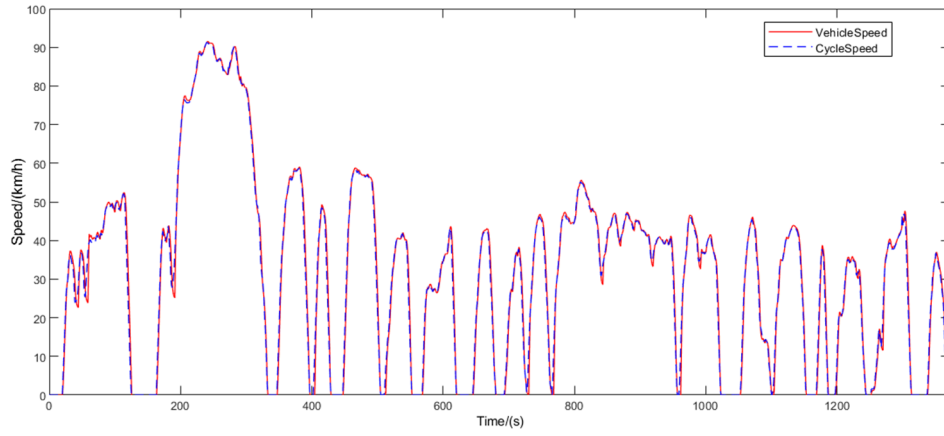


Figure 3. UDDS standard condition speed tracking curve

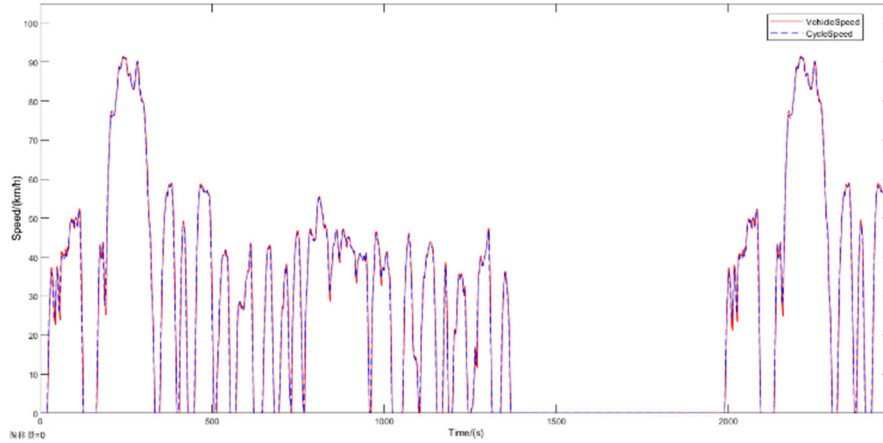


Figure 4. FTP-75 standard condition speed tracking curve

4.2. Simulation Verification of Dynamic Performance

As illustrated in Figures 5 and 6, a consistent trend was exhibited by the vehicle's dynamic performance curves: steady at low speeds, attenuated at medium speeds, and diminished at high speeds. In the low-speed region, constant torque was maintained by the motor, resulting in stable net driving force and consistently high acceleration and gradability. In the medium-speed region, a transition to

constant power operation was observed, accompanied by torque reduction and increased resistance, leading to performance attenuation. In the high-speed region, field-weakening control and increasing resistance led to the gradual exhaustion of net driving force. Around 180 km/h, equilibrium was reached between traction force and resistance, with minor fluctuations attributed to numerical precision. From the speed–acceleration data, a 0–100 km/h acceleration time of 7.8 s was calculated, confirming the performance characteristics of the vehicle's power system.

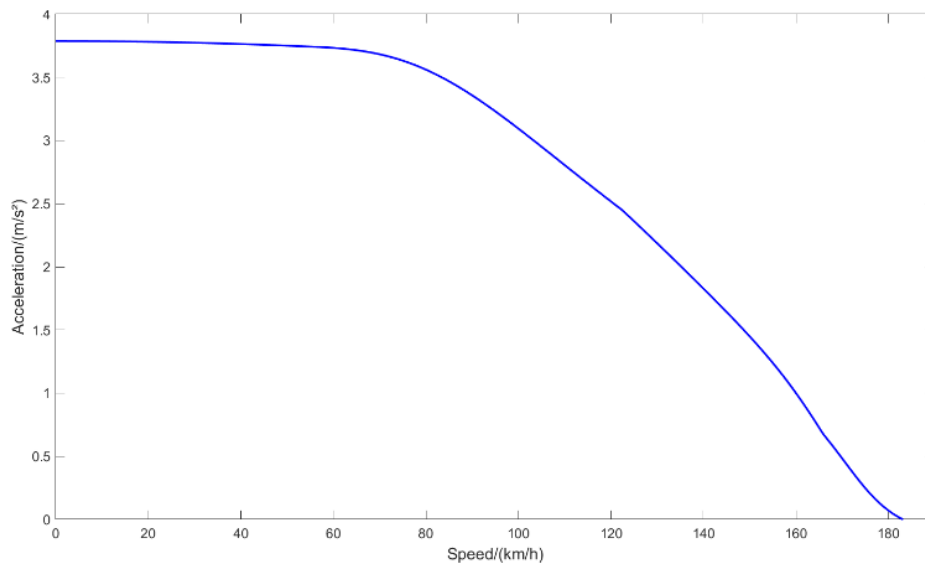


Figure 5. Acceleration curve

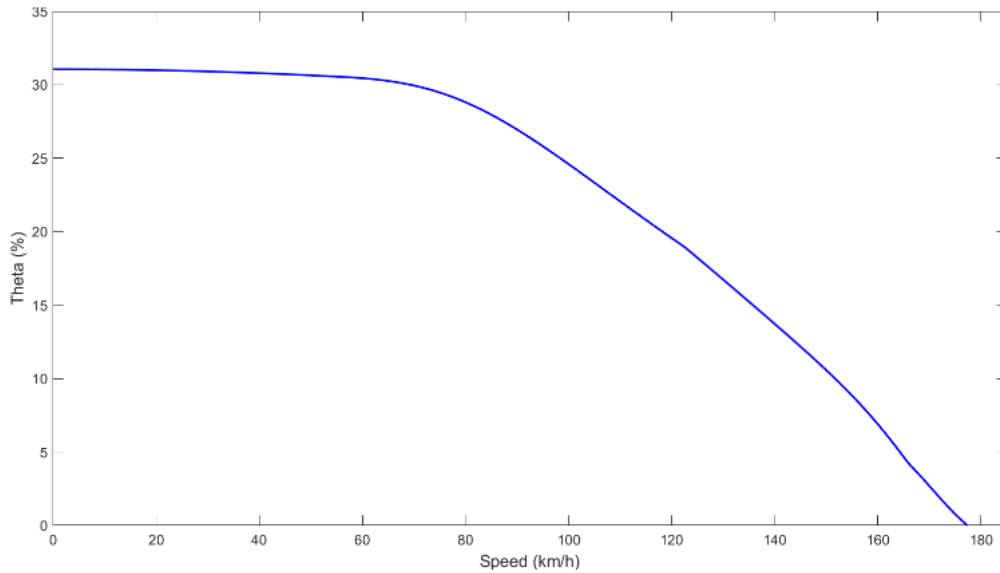


Figure 6. Gradeability curve

4.3. Comparison of Simulation Results

The simulation results of the core indicators are compared with the design targets in Table 2. The deviations between the simulated values and target values of the vehicle's key dynamic performance indicators are all within the engineering allowable error range of less than 5%. These deviations mainly stem from two aspects: first, the reasonable simplification of environmental factors (such as road smoothness and air density fluctuations) in the simulation model; second, the approximate assignment of component efficiency parameters (such as transmission system efficiency and motor output characteristics), which conforms to the conventional logic in simulation modeling of simplifying complex factors to balance accuracy and computational efficiency.

Table 2. Simulation comparison

Indicator	Target Value	Simulation Result	Deviation
Maximum gradeability	30%	31%	3.3%
0-100 km/h acceleration time	7.9 s	7.8 s	1.3%
Maximum speed	185 km/h	183 km/h	1.1%

5. Conclusion

A forward simulation model was constructed using MATLAB/Simulink to simulate electric vehicle behavior with high precision, based on longitudinal dynamics and modular design. A maximum deviation of only 3.3% was shown in simulation results, thereby confirming the model's

effectiveness in dynamic performance evaluation. The replacement of working conditions and vehicle parameters was supported by the model, making it a practical and reliable tool for the optimization of electric vehicle design. In future research, the model is expected to be extended to cover extreme driving conditions, such as low temperatures and full-load operation. Integration with energy recovery systems may also be considered to further enhance the engineering applicability of the model.

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