Journal of Electrotechnology, Electrical Engineering and Management (2023)
Clausius Scientific Press, Canada

DOI: 10.23977/jeeem.2023.060512
ISSN 2560-6697 Vol. 6 Num. 5

Electric Vehicle Performance Simulation under Parameter Variations

Tianshuo Jin[1,*]

[1]College of Information and Communication Engineering, Sungkyunkwan University, Suwon, South Korea
jts123@g.skku.edu
[*]Corresponding author

Keywords: Electric vehicle; parameter variations; environmental factors

Abstract: This study aims to investigate the acceleration performance of electric vehicles under varying parameters. To achieve this objective, a velocity iteration model will be developed based on the electric vehicle's power output while considering various environmental factors. Parameters such as mass, rolling resistance, and air resistance will be systematically adjusted, and a series of tests will be conducted to simulate the acceleration performance of electric vehicles under different road and environmental conditions. This research aims to provide a comprehensive understanding of electric vehicle performance characteristics, offering valuable insights for the design and optimization of electric vehicle performance. Ultimately, this research contributes to the advancement and application of electric vehicle technology.

1. Introduction

In recent years, global concerns over climate change and the increasing strain on fossil fuel supplies have heightened significantly. In this context, electric vehicles (EVs) have emerged as a pivotal solution to address these challenges. Worldwide, various sectors are actively promoting electrification to reduce reliance on finite fossil fuel resources, minimize greenhouse gas emissions, and enhance overall energy efficiency. EVs, as a sustainable mode of transportation for the future, are gradually becoming integrated into people's lives. While not yet universally prevalent, they have already become an indispensable component in many regions. The rapid development and widespread adoption of EVs not only contribute to environmental sustainability but also bring about substantial transformations in the global energy landscape.

However, ensuring that EVs meet users' needs and provide an enhanced driving experience in real-world scenarios necessitates a thorough investigation into their performance characteristics. Against this backdrop, the study of EV performance assumes paramount importance. Such research not only facilitates the optimization of EV design and manufacturing but also enhances their adaptability to diverse usage environments. To gain a comprehensive understanding of EV performance, a multitude of critical factors must be considered, including battery technology, electric motor efficiency, vehicle weight, rolling resistance, aerodynamic drag, and more. The intricate interplay among these factors demands systematic research and analysis.

In this study, we delve into the analysis of EV acceleration performance under varying parameters. This investigation encompasses a comprehensive examination of factors such as the electric powertrain system, drive efficiency, vehicle mass, road surface conditions, and climatic influences. We will construct intricate mathematical models and employ both simulation and experimental methodologies to gain an in-depth understanding of EVs performance across diverse driving.

2. Background and basic knowledge

2.1 Force at the wheel

To study the acceleration performance of electric vehicles, it is essential to understand the various forces acting on the vehicle during motion. In general, the primary forces to consider are the traction force generated by the electric motor, the rolling resistance between the tires and the road surface, the air drag encountered during motion, and hill climbing force.

2.1.1 Rolling resistance (Fr)

Rolling resistance, as one of the most prominent components in vehicle force analysis, is influenced by numerous factors. These factors encompass the rubber composition of the tires, temperature, tire dimensions, vehicle weight, road surface characteristics, speed, and tire slippage.[1] Figure 1 illustrates the variations in the coefficient of rolling resistance across a range of conditions.

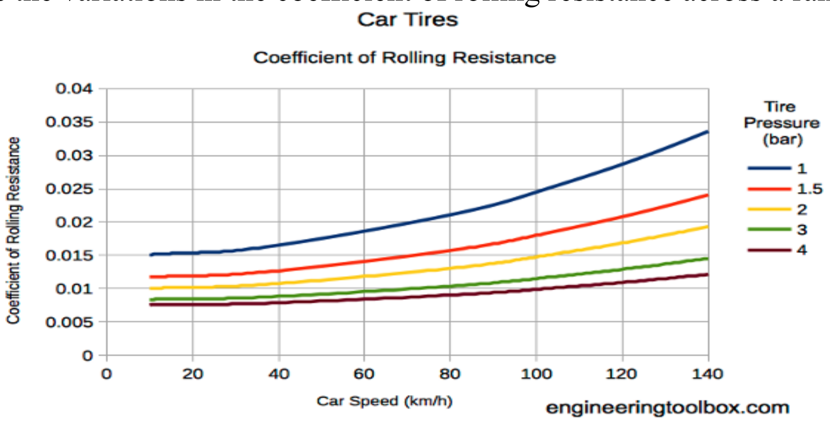


Figure 1: The rolling resistance of various coefficients of friction, speeds, and tire pressures.

Rolling Resistance Coefficient		
c	c_l *(mm)*	
0.001 - 0.002	0.5	railroad steel wheels on steel rails
0.001		bicycle tire on wooden track
0.002 - 0.005		low resistance tubeless tires
0.002		bicycle tire on concrete
0.004		bicycle tire on asphalt road
0.005		dirty tram rails
0.006 - 0.01		truck tire on asphalt
0.008		bicycle tire on rough paved road
0.01 - 0.015		ordinary car tires on concrete, new asphalt, cobbles small new
0.02		car tires on tar or asphalt
0.02		car tires on gravel - rolled new
0.03		car tires on cobbles - large worn
0.04 - 0.08		car tire on solid sand, gravel loose worn, soil medium hard
0.2 - 0.4		car tire on loose sand

Figure 2: The coefficient of rolling resistance for common road surfaces.

The specific values can be calculated using the formula:

$$Fr = m \times g \times fr \tag{1}$$

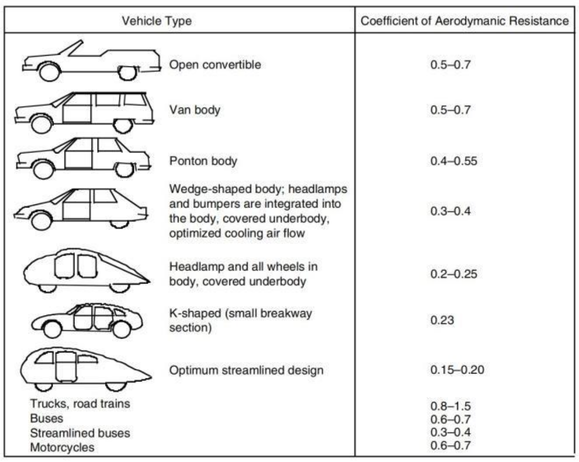
Where m is the total mass of the vehicle, g represent gravitational acceleration, which is close to $10m/s^2$, and fr is the coefficient of rolling resistance. In practice, fr represents the coefficient of rolling resistance of the road surface, which varies significantly across different road surfaces such as concrete, asphalt, and snow. (Figure 2)

2.1.2 Aerodynamic drag (Fair)

Aerodynamic drag, in the context of a moving vehicle through the air medium, refers to the force exerted by the air in the direction of motion. This force is proportional to the square of the vehicle's speed, meaning that at higher speeds, the drag force increases. Aerodynamic drag primarily consists of two components: "shape drag" and "skin friction." Firstly, Shape drag refers to that the forward progression of the vehicle compels the air ahead of it to be displaced. Nonetheless, the air cannot relocate immediately, thereby elevating its pressure and resulting in a region of high pressure at the front. Concurrently, the space vacated by the vehicle's advancement cannot be filled by the surrounding air instantaneously, leading to the formation of a low-pressure zone at the rear. Consequently, this dynamic establishes two opposing pressure gradients: the high pressure at the front endeavors to push the vehicle backward, while the low pressure at the rear exerts a pulling effect, both of which counteract the vehicle's forward movement. Secondly, skin friction, air close to the skin of the vehicle moves almost at the speed of the vehicle while air far from the vehicle remains still. In between, air molecules move at a wide range of speeds. The difference in speed between two air molecules produces a friction that results in the second component of aerodynamic drag.The drag coefficient is a measure of the vehicle's aerodynamic efficiency. For electric vehicles, the coefficient of drag typically falls within the range of 0.2 to 0.8. It can be calculated using the formula 2:

$$FAIR = \frac{1}{2} \times Cd \times A \times \rho \times V2 \tag{2}$$

Where, the P is air density, A is the projected frontal area of the body, and V is velocity. The reason aerodynamic losses are so important relative to motor power is that the power required to overcome these losses is a function of the cube of the velocity. That means a high drag coefficient will use up a lot of battery power, which usually range from 45-60 percent. Generally the vehicle size, and hence frontal area, is determined by the design requirements, and efforts to reduce drag are concentrated on reducing the drag coefficient.[2]



Vehicle Type	Coefficient of Aerodynamic Resistance
Open convertible	0.5–0.7
Van body	0.5–0.7
Ponton body	0.4–0.55
Wedge-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3–0.4
Headlamp and all wheels in body, covered underbody	0.2–0.25
K-shaped (small breakway section)	0.23
Optimum streamlined design	0.15–0.20
Trucks, road trains	0.8–1.5
Buses	0.6–0.7
Streamlined buses	0.3–0.4
Motorcycles	0.6–0.7

Figure 3: Indicative drag coefficients for different body shapes[3].

Different design geometries result in varying coefficients of aerodynamic drag; Figure 3 presents the aerodynamic drag coefficients associated with various vehicle shapes commonly encountered in daily life.

2.1.3 Grading resistance

When a vehicle is traveling on a non-flat road surface, the force of gravity acting on it is divided into two components: one vertically downward and the other along the slope of the road,as shown in the figure4. The component along the direction of the slope is referred to as "grade resistance." Its magnitude is closely related to the vehicle's own mass and the slope angle. Figure 4 presents the force analysis of a vehicle when traveling on a slope and the relationships between the magnitudes of its components in different directions.[4]

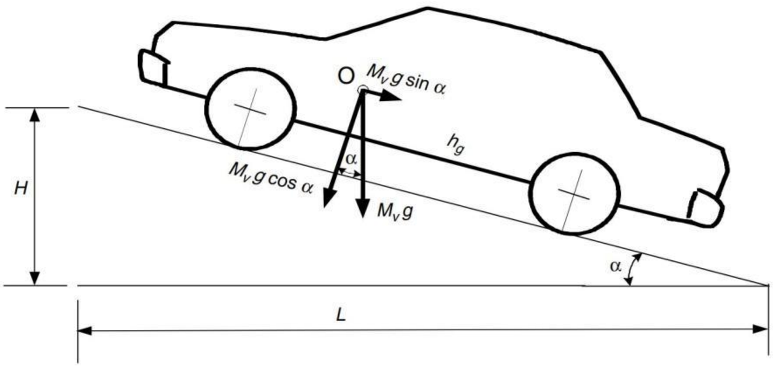


Figure 4: Grade resistance[3].

From the figure 4, the grading resistance can be expressed as

$$F_g = mgsin\alpha \tag{3}$$

2.1.4 Tractive effort

According to Newton's second law, the external force acting on an object is equal to the product of its mass and acceleration, and the acceleration is in the same direction as the external force. It can be calculated by the equation 4.

$$F = m \times a \tag{4}$$

It is worth noting that acceleration of inertia will add a small mass dm on the original mass of the car. This additional mass depends on gear ratio and moment of inertia of rotating equipment before and after the transmission. Therefore, the above equation will become F = (m+dm)*a. Where, generally, dm is between one and two orders of magnitude smaller than m.[5]

2.2 Power Analysis

Power is a critical parameter in vehicle dynamics, playing an essential role in the assessment of vehicle performance. To analyze the power output of a car, it is practical to consider it as a function of velocity, especially under various force conditions. Initially, let us contemplate the scenario where the vehicle reaches its maximum speed on a level surface, which implies that acceleration is nonexistent. In this context, it becomes imperative to focus exclusively on the forces of aerodynamic drag and rolling resistance. The power equation can be expressed as:

$$Pe \times \eta = \frac{1}{2}CdA\rho v^3 + mgfrv \tag{5}$$

In the equation under consideration, P_e represents the maximum power output of the engine, while η denotes the vehicle's transmission efficiency. Under non-ideal conditions, the power generated by a vehicle's engine or electric motor cannot be entirely transferred to the wheels without some losses. These losses typically manifest as frictional losses, thermal losses, and aerodynamic drag within components such as the differential. Therefore, the left side of the equation corresponds to the actual power transmitted to the wheels. Also, this equation indicates that the vehicle reaches its top speed when the tractive effort equals the resistance, expressed by the right-side terms. If the vehicle is operating on an inclined road, we need to incorporate an additional term into the power equation to account for the grading resistance. The modified equation can be expressed as:

$$Pe \times \eta = \frac{1}{2}CdA\rho v^3 + mgfrv + mgsin\theta v \tag{6}$$

Considering the scenario in which the vehicle has not reach the maximum velocity and is still undergoing acceleration, we need to consider the acceleration term in the power model and the force required to accelerate the vehicle is already represented on above. Therefore, in this situation, the power model will be presented as:

$$Pe \times \eta = \frac{1}{2}CdA\rho v^3 + mgfrv + mgsin\theta v + mav \tag{7}$$

3. Experiment

In this experiment, we aim to analyze the acceleration capability of a nominal vehicle under parameter variations. Assume the nominal vehicle has a mass of m=1500kg, a rolling resistance of fr=0.01, and an air drag coefficient-area product of $cdA = 1.0m^2$. Further assume the lumped power train efficiency to be at 0.9. Assume air density is equal to $1.2kg/m^3$ and all tests are done on a flat surface. Assume the e-motor output torque to be constant between 0 and 6000rpm at a value of 300Nm. Assume the overall gear ratio from motor to wheels to be 6.0 and the wheel radius to be 0.3m. All acceleration tests are supposed to be performed from 0 to 100km/h. (The vehicle is assumed as a Four-Wheel Drive(4WD) without wheel slip.) To analyze the acceleration performance of a vehicle from 0 to 100 km/h, one must construct an acceleration model in MATLAB for simulation purposes. By referring to the previously mentioned power equation, a function describing acceleration can be derived as follows:

$$a = \frac{1}{mv}(Pe \times \eta - \frac{1}{2}CdA\rho V^3 - mgfrv) \tag{8}$$

In computational simulations, the approximation of continuous processes is achieved through iterative calculations at discrete time points. Discretization aids in ensuring the stability of numerical computations and facilitates the visualization of simulation results. Therefore, in this experiment, we discretize velocity with a time step of 0.25 seconds. During the vehicle's acceleration phase, we record the data for velocity and acceleration at each point, storing this information in arrays for subsequent analysis. The discrete version of acceleration equation is expressed as:

$$d(vnT) = a(nT) = \frac{1}{mv(nT)}(Pe \times \eta - \frac{1}{2}CdA\rho v(nT)^3 - mgfrv(nT)) \tag{9}$$

Within the context of a discrete simulation framework, when the velocity and acceleration at a time step nT are known, we can estimate the velocity (v) and acceleration (a) at the next time step ($nT + T$). This estimation is performed using the formula $v(nT+T) = v(nT)+T \cdot a(nT)$. Here, it is assumed that the acceleration remains constant during the time interval T. This assumption simplifies the calculation and is a common approximation in discrete time simulations where the time step T is sufficiently small. Therefore, considering the discrete version of acceleration equation, the update equation of velocity can be represented as:

$$v(nT+T) = v(nT) + \frac{T}{mv(nT)}(Pe \times \eta - \frac{1}{2}CdA\rho v(nT)^3 - mgfrv(nT)) \tag{10}$$

To calculate the power output of a four-wheel-drive (4WD) vehicle, we utilize the formula $P = \eta \cdot \tau \cdot \omega$, where P is the power, τ is the torque, *eta* is the efficiency, and ω is the angular velocity. The angular velocity (ω) can be related to the linear velocity (v) of the car by the equation $\omega = {}^{v}\!/_{r}$ where r is the radius of the wheel. Given that the car is a 4WD, each of wheels contributes to the output power. Therefore, the total power of the vehicle would be:

$$P = 4 \cdot \left(\tau \cdot \frac{v}{r}\right) \tag{11}$$

The final update equation should be as follows:

$$v(nT+T) = v(nT) + \frac{T}{mv(nT)}[4 \cdot \left(\tau \cdot \frac{v}{r}\right) \cdot \eta - \frac{1}{2}CdA\rho v(nT)^3 - mgfrv(nT)] \tag{12}$$

Utilizing the equation 12, we proceed with the simulation and then repeat for reductions of mass, cdA and rolling resistance by 20% and 40% each. The outcomes of these adjusted simulations are meticulously recorded in arrays. After gathering the results, we plot the data to visualize the impact of these reductions. The graphical representation allows for an immediate and clear understanding of how changes in mass, rolling resistance, and aerodynamic drag influence the vehicle's performance, specifically its acceleration and velocity profiles over time.

4. Result

Figure 5 collectively displays the simulated results, encompassing the velocity, acceleration, and travel distance of the vehicle during rapid transit under all considered scenarios.

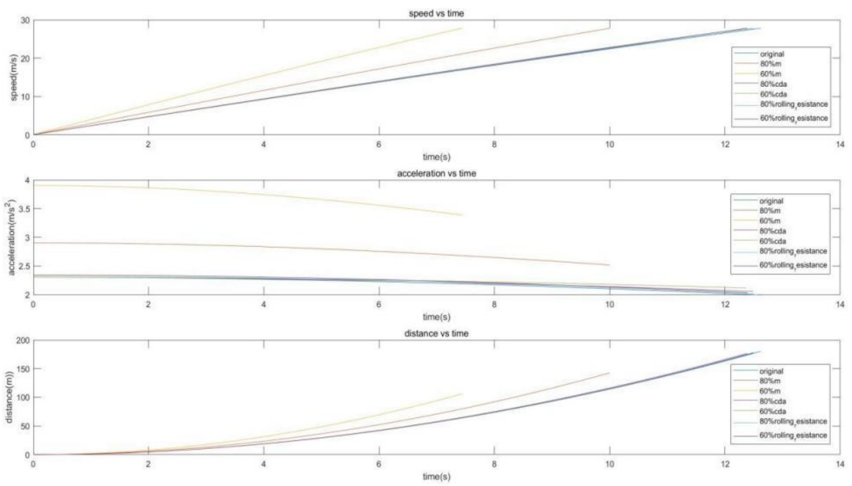


Figure 5: Velocity, acceleration and distance.

Figure 6 and 7 display the vehicle performance under conditions of a 40%, 60% reduction in mass, rolling resistance, and aerodynamic drag. Analyzing the graphical data presented, it is evident that mass significantly impacts a vehicle's dynamics across various performance metrics, including speed, acceleration, and distance over time. The simulations demonstrate that reductions in mass lead to marked improvements in distance traveled over a given time period. Specifically, the vehicle with 60% of the original mass displays a noticeably enhanced distance trajectory compared to the original mass scenario, which illustrates mass is the most effective factor among mass, aerodynamic drag and rolling resistance.

5. Conclusion

Amid the deepening crisis of fossil fuel depletion and the escalating severity of global warming, electrification is rapidly emerging as a pivotal trend in the advancement of technology. Consequently, electric vehicles (EVs) have progressively integrated into the fabric of everyday life. The central objective of this study is to conduct a thorough analysis of the acceleration characteristics of EVs, aiming to exhaustively examine the influence of various parameters on vehicular performance. This analysis is intended to provide automotive manufacturers with nuanced insights, enabling them to judiciously balance trade-offs in vehicle design. The goal is to enhance the user's driving experience by improving vehicle performance at the most economical cost. Throughout this study, we engaged in a comprehensive examination of the different forces of resistance encountered by a vehicle in motion, delving into their physical implications and contributory factors. This led to an analytical investigation of the power fluctuations occurring during vehicular operation, which, in turn, facilitated the derivation of the vehicle's acceleration and velocity profiles at successive time intervals. In the initial phase of our study, we utilized simulation techniques to predict the performance outcomes based on the vehicle's parameters. The findings from this research elucidate that the vehicle's total mass exerts a preponderant effect on its acceleration capabilities. In stark contrast to the mass, the influence of aerodynamic drag and rolling resistance on the vehicle's performance is markedly insubstantial. Consequently, vehicle design initiatives should place a significant emphasis on mass reduction, utilizing advanced lightweight materials wherever possible while uncompromisingly maintaining safety standards. Furthermore, our study suggests that rather than undertaking comprehensive vehicular redesigns to mitigate aerodynamic drag, it is more feasible and cost-effective to prioritize the enhancement of material selection for v

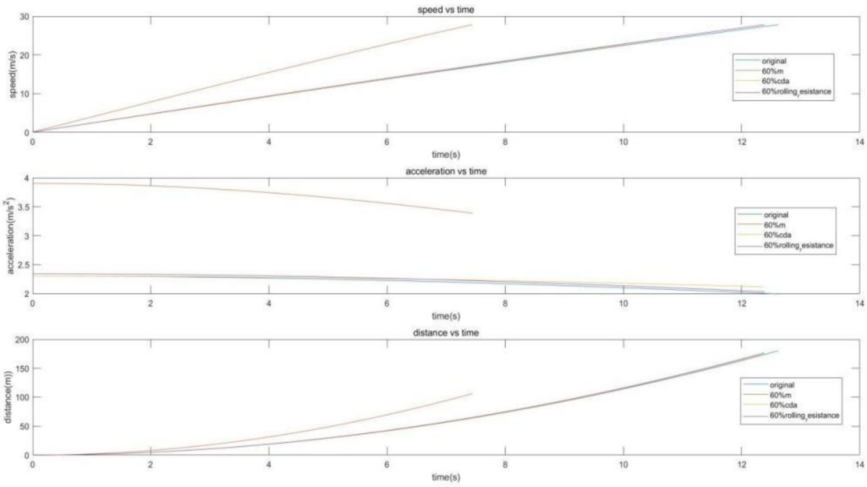


Figure 6: Result under 40% reduction.

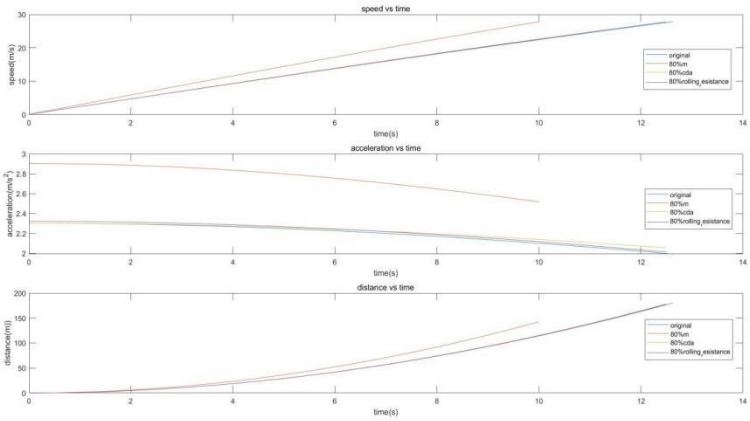


Figure 7: Result under 20% reduction.

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