

Research on Braking Force Distribution Strategy of Composite Braking System of Electric Vehicle

Kuiyang Wang, Liang Zhu* and Shanfeng Wang

School of Automotive and Traffic Engineering
Jiangsu University of Technology
Changzhou 213001, China

*Corresponding author

Abstract—Based on analyzing the necessity of research on composite braking system of electric vehicle and its braking force distribution strategy, according to the ECE regulations and the requirements of braking stability, the optimized braking force distribution strategy and control logic are proposed for a certain type of selected electric vehicle with front wheels drive. The mathematical models of electric motor, battery, braking force distribution and so on of electric vehicle are established, and the simulation models of composite braking system of electric vehicle are established based on MATLAB/Simulink software. The simulation analyses on the change curves of braking speed, braking deceleration, braking distance, battery SOC, braking total energy and recycling energy with the change of braking time are carried out respectively when the initial speed is 20km/h and 50km/h and the braking intensity is 0.1 and 0.3. The simulation results validate that the braking force distribution strategy and mathematical models proposed are correct and feasible, which provide a theoretical basis for the follow-up study.

Keywords—electric vehicle; composite braking system; braking force distribution strategy; simulation analysis

I. INTRODUCTION

The mechanical friction brake is the main braking mode of vehicle. In the braking process, the kinetic energy and potential energy of vehicle are converted into heat energy through mechanical friction to achieve the purpose of decelerating or braking the vehicle. The motor regenerative braking, which can turn some of braking energy into electric energy using the motor and the electric energy may be recycled to the storage battery or the super capacitor, is one of the important measures of saving energy and improving continued driving range of electric vehicle. Therefore, the composite braking system with mechanical friction braking and regenerative braking is an inevitable combination of electric vehicle's braking system [1].

However, when the regenerative braking works, its braking torque will be applied to the power transmission system of electric vehicle. At the same time of generating electric energy, it will provide auxiliary braking torque to electric vehicle and the control logic and braking force distribution strategy of friction brakes will be interfered. The braking feeling, braking efficiency and braking stability of electric vehicle will be affected. Therefore, it is necessary to study on the braking force distribution strategy between regenerative braking of motor and friction brake.

At present, a wide range of researched on the composite braking system of electric vehicle have been carried out at

home and abroad, and a certain research foundation and progress have been obtained [2][3]. Three typical braking force distribution strategies were proposed by Yimin Gao et al, which were the braking force distribution strategy with parallel connection, braking force distribution strategy for maximum energy recovery and braking force distribution strategy for optimal braking performance [4][5]. In the paper, the optimized braking force distribution strategy and control logic are proposed based on the ECE regulations and the requirements of braking stability, the mathematical models of electric motor, battery, braking force distribution and so on of electric vehicle are established, and the simulation models are established based on MATLAB/Simulink software, which provide a theoretical basis for the follow-up study.

II. PARAMETERS OF SELECTED ELECTRIC VEHICLE

The electric vehicle selected in this paper is a front drive vehicle, which is provided energy by single battery. And there are no transmission device and no super capacitor device in it. The relevant parameters of selected electric vehicle are shown in Table 1. The relevant parameters of electrical motor and battery of selected electric vehicle are shown in Table 2.

TABLE I. PARAMETERS OF SELECTED ELECTRIC VEHICLE

Parameters	Numerical Values
Total mass (m)	1200kg
Wheelbase (L)	2.34m
Wheel radius (r)	0.28m
Centroid height (h_g)	0.5m
Distance from centroid to front axle (a)	1.06m
Distance from centroid to rear axle (b)	1.28m
Main reduction ratio (i_0)	3.55
Maximum speed (u_a)	80km/h

TABLE II. PARAMETERS OF ELECTRICAL MOTOR AND BATTERY

Parameters	Numerical Values
Rated speed (N_n)	3000r/min
Rated power (P_n)	25kw
Rated torque (T_n)	90N·m
Peak rotational speed (N_{max})	5000r/min
Peak power (P_{max})	45kw
Peak torque (T_{max})	200N·m
Rated total voltage (E)	324V
Rated capacity (Q)	100A·h

III. DESIGN OF BRAKING FORCE DISTRIBUTION STRATEGY

The constraint formula of ideal braking force distribution curve is as follows [6]:

$$F_{\mu 2} = \frac{1}{2} \left[\frac{G}{h_g} \sqrt{b^2 + \frac{4h_g L}{G} F_{\mu 1}} - \left(\frac{Gb}{h_g} + 2F_{\mu 1} \right) \right] \quad (1)$$

where $F_{\mu 1}$ is the braking force of front wheel brake, $F_{\mu 2}$ is the braking force of rear wheel brake, G is the total weight of electric vehicle.

The constraint formulas of ECE (Economic Commission for Europe) regulations are as follows [6]:

$$\begin{cases} F_{\mu 1} = \frac{z + 0.07}{0.85} \frac{G}{L} (b + zh_g) \\ F_{\mu 2} = Gz - F_{\mu 1} \end{cases} \quad (2)$$

where z is the braking strength. Based on the ECE regulations and the curve of ideal braking force distribution, the optimized braking force distribution strategy suggested is shown in Figure 1.

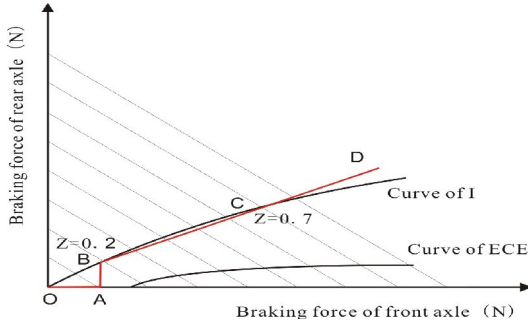


FIGURE 1. OPTIMIZED DISTRIBUTION STRATEGY

The braking forces of front axle and rear axle are assigned according to the curve of OABCD.

A. Line Segment of OA

The strength of braking is greater than zero and less than 0.107, the maximum braking force provided by the motor is 1268N, and the corresponding braking strength is 0.107. At this time, the braking force of vehicle is provided all by front axle, it is just needed to control the braking force of motor, and the braking force of rear axle is 0. The math formulas of braking force of motor (F_e), braking force of front axle brake (F_f) and braking force of rear axle brake (F_r) are as follows.

$$\begin{cases} F_e = Gz \\ F_f = Gz - F_e \\ F_r = 0 \end{cases} \quad (3)$$

B. Line Segment of AB

The strength of braking is greater than 0.107 and less than 0.18. This moment, because the motor can't provide all the required braking force, the electric vehicle is in the composite braking state. In order to make the front wheels of electric vehicle not to be locked on the road surface of low adhesion coefficient, the front axle is no longer applied friction braking force, the partial braking force which exceeds the maximum braking force of motor will be provided by friction brakes of rear axle. The math formulas of braking force of motor (F_e),

braking force of front axle brake (F_f) and braking force of rear axle brake (F_r) are as follows.

$$\begin{cases} F_e = F_{e \max} \\ F_f = 0 \\ F_r = Gz - F_e \end{cases} \quad (4)$$

C. Line Segment of BC

The strength of braking is greater than 0.18 and less than 0.7. In order to make better use of the pavement adhesion coefficient, the curve is close to the curve of I (Ideal braking force distribution curve). And the curve is located under the curve of I in order to prevent the rear axle locked firstly. The math formulas of braking force of motor (F_e), braking force of front axle brake (F_f) and braking force of rear axle brake (F_r) are as follows.

$$\begin{cases} F_e = F_{e \max} \\ F_f = \frac{(Gz - 385.78)}{1.369} - F_e \\ F_r = Gz - F_e - F_f \end{cases} \quad (5)$$

D. Line Segment of CD

The strength of braking is greater than 0.7, which belongs to the emergency braking state. At this time, in order to ensure the braking safety, the braking of electric motor is not involved in braking, and there is only mechanical friction brake on the electric vehicle. Therefore, the math formulas of braking force of motor (F_e), braking force of front axle brake (F_f) and braking force of rear axle brake (F_r) are as follows.

$$\begin{cases} F_e = 0 \\ F_f = \frac{Gz - 385.78}{1.369} \\ F_r = Gz - F_f \end{cases} \quad (6)$$

IV. MATHEMATICAL MODELS AND SIMULATION MODELING

A. Model of Electric Motor

The permanent magnet brushless DC motor is taken as the driving motor in the electric vehicle. The corresponding characteristic curves of the torque, power and speed are shown in Figure 2.

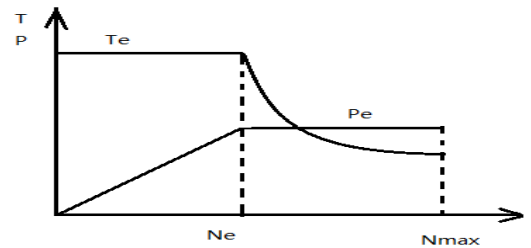


FIGURE II. CHARACTERISTIC CURVES

The relationship between the speed of electric motor and the speed of vehicle is shown as below.

$$n = \frac{u_a i_0}{0.377r} \quad (7)$$

where n is the speed of electric motor, u_a is the speed of vehicle. The maximum braking torque of the motor is shown as below.

$$T_{\max} = \begin{cases} T_e, n \leq N_e \\ \frac{9550P_e}{n}, n > N_e \end{cases} \quad (8)$$

The maximum braking force of the motor is as follows.

$$F_{e\max} = \frac{T_{\max}}{r\eta_T} \quad (9)$$

where η_T is the efficiency of mechanical transmission. Based on Simulink software, the simulation model of motor is established as shown in Figure 3.

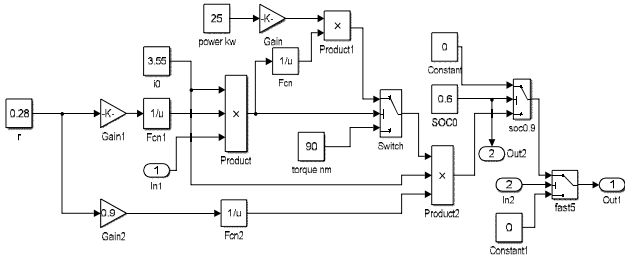


FIGURE III. MODEL OF ELECTRIC MOTOR

B. Model of Storage Battery

The charging power of storage battery is as follows.

$$P_b = U * I = U * \frac{E - U}{R} \quad (10)$$

where P_b is charging power, U is charging voltage, I is charging current, and R is the internal resistance of battery.

It can be obtained from the above formula:

$$U^2 - E * U + P_b * R = 0 \quad (11)$$

So then:

$$U = \frac{E - \sqrt{E^2 - 4P_b R}}{2} \quad (12)$$

$$I = \frac{E - \sqrt{E^2 - 4P_b R}}{2R} \quad (13)$$

The calculation formula of SOC is as follows.

$$SOC = SOC_0 + \frac{\eta_{\text{charge}} \int Idt}{Q_{\text{ALL}}} \quad (14)$$

where SOC_0 is the initial value of SOC, η_{charge} is the charging efficiency, and Q_{ALL} is the total power of battery. The simulation model of battery is shown as Figure 4.

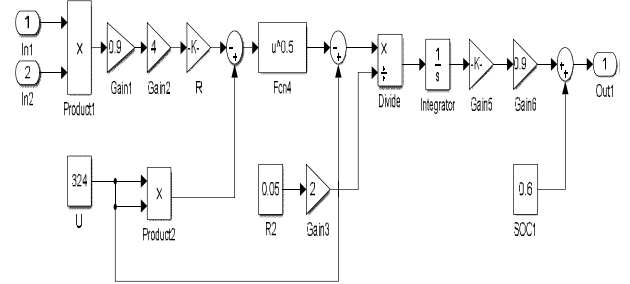


FIGURE IV. MODEL OF STORAGE BATTERY

C. Simulation Model of Braking Force Distribution Strategy

The simulation models of braking force distribution strategy are established as follows.

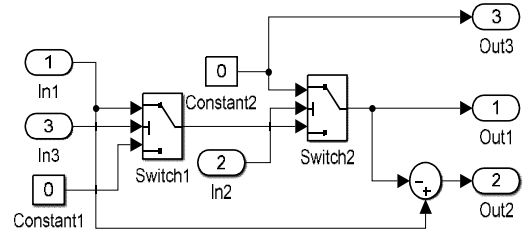


FIGURE V. MODEL WHEN $0 < Z \leq 0.107$

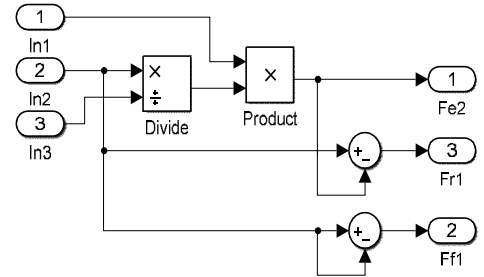


FIGURE VI. MODEL WHEN $0.107 < Z \leq 0.18$

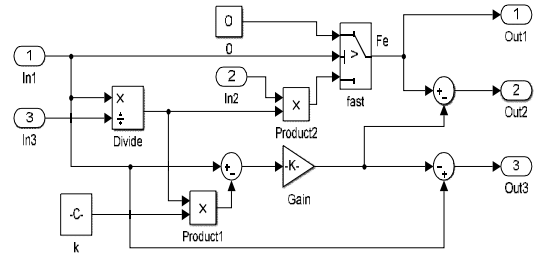


FIGURE VII. MODEL WHEN $0.18 < Z$

D. Overall Simulation Model of Electric Vehicle

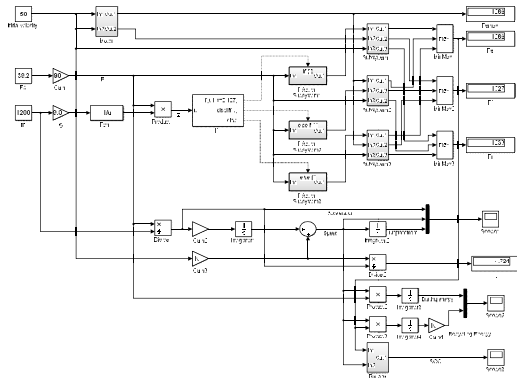


FIGURE VIII. OVERALL SIMULATION MODEL

V. SIMULATION AND ANALYSIS

A. Initial Velocity is 20km/h

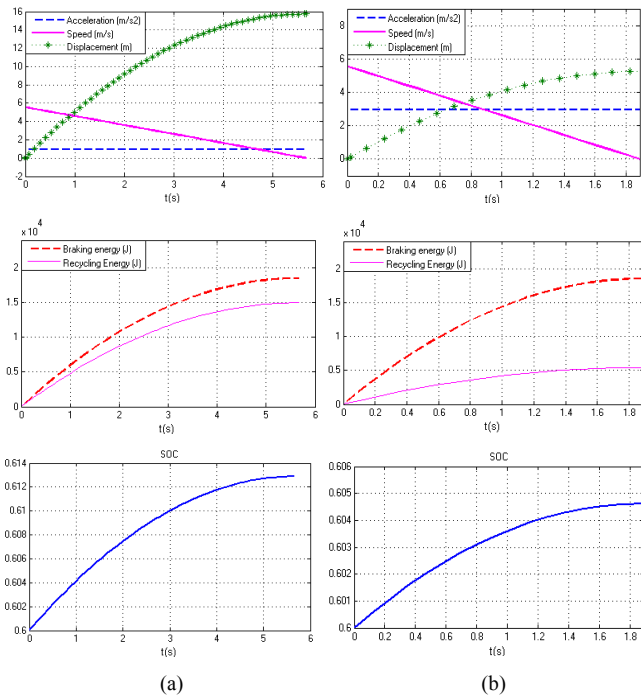


FIGURE IX. CURVES : (A)WHEN $Z = 0.1$, (B) WHEN $Z = 0.3$

B. Initial Velocity is 50km/h

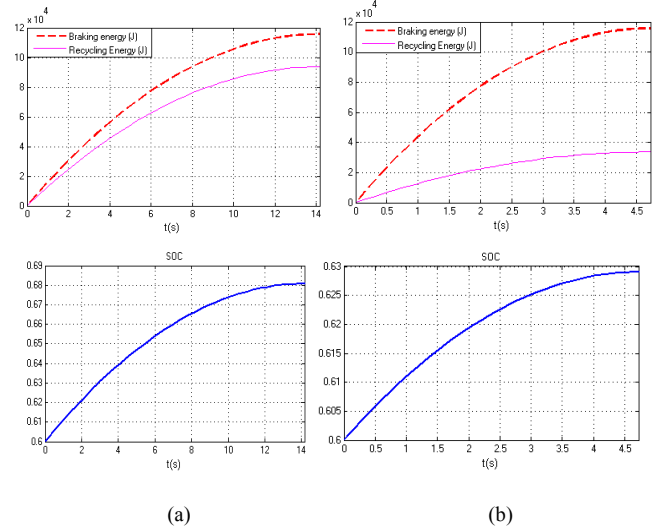
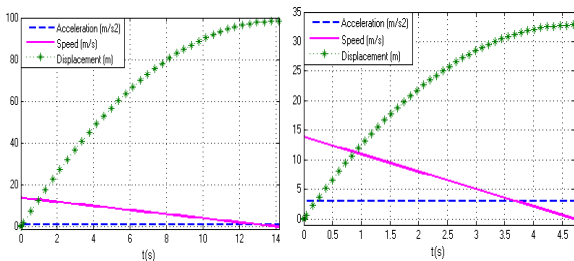


FIGURE X. CURVES : (A)WHEN $Z = 0.1$, (B) WHEN $Z = 0.3$

When the initial velocity is 20km/h, with the change of braking time, the relationship curves of braking speed, braking deceleration, braking distance, storage battery SOC, braking energy and recycling energy are shown in Figure 9. When the braking strength is 0.1, the braking time is 5.669 seconds, the braking distance is longer, close to 16 meters, the total braking energy is about 18.5KJ, and the energy recovery is about 15KJ, the energy recovery accounted for the vast majority of braking energy. But due to lack of initial kinetic energy, the maximum value of SOC is only 0.613. When the braking strength is 0.3, the braking time is 1.89 seconds, the braking distance becomes shorter. Due to the mechanical friction brakes to participate in the braking process at this time, the recovery energy and its ratio for total braking energy decline.

When the initial velocity is 50km/h, with the change of braking time, the relationship curves of braking speed, braking deceleration, braking distance, storage battery SOC, braking energy and recycling energy are shown in Figure 10. When the braking strength is 0.1, the braking time is 14.17seconds. Because the initial kinetic energy becomes larger, the brake distance becomes longer, close to 100 meters. This moment, due to the braking of electric motor works alone, the most of the braking energy is recycled, the maximum value of SOC is about 0.68. When the braking strength is 0.3, the braking time is 4.724 seconds, the braking distance becomes shorter, approximately 32.5 meters. This moment, due to the friction brakes to participate in the braking process, the recovery energy and its ratio for total braking energy decline, the maximum value of SOC is only 0.628 and its added value accounts for about 35% in contrast to small braking strength.

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