Simulation Calculation and Experimental Study on Linear Braking Performance of New Energy Vehicles

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Abstract. The structure and characteristics of the braking system of the new energy vehicle are analyzed. The calculation model of the linear braking performance for the new energy vehicle is established. The parameters such as the adjustment frequency of the solenoid valve and the adjustment amplitude are determined. Finally, the road test is verified. The results show that compared with the road test results, the calculated error is less than 10%, and the model can be used to evaluate the braking performance of battery electric vehicles.

1. Introduction
The braking performance of the car means that the car can break and stop the vehicle within a short distance while driving. The stability of the vehicle can be maintained during braking. The car can be maintained at a certain speed when the vehicle is down. When the parking brake is applied on the ramp, the vehicle can remain stationary for a certain period of time [1]. Braking performance evaluation indicators for new energy vehicles include braking efficiency, constancy braking efficiency, and directional stability during braking.

2. New energy vehicle brake system structure and characteristics
Typical new energy system consists of a regenerative braking force system and a hydraulic braking system [2]. The system calculates the required braking force based on the degree to which the driver steps on the brake pedal and the applied force. This system then applies the required braking force (including the regenerative braking force and the braking force generated by the hydraulic braking system) and effectively absorbs energy. During normal braking, the hydraulic pressure generated by the master cylinder is replaced by a hydraulic signal instead of directly acting on the wheel cylinder. The actual hydraulic pressure of the hydraulic source is adjusted by adjusting the frequency and amplitude of the brake actuator solenoid valve acting on the wheel cylinder.

3. Interval function of linear braking performance of new energy vehicles
When the ESP system of the new energy vehicle does not work, the braking process of the car can be divided into four stages, as shown in Fig.1. The first stage is the reaction stage \( t_0 \), the driver detects the obstacle and decides the emergency braking, at the same time, moves the foot from the accelerator pedal to the brake pedal. The reaction time \( t_0 \) is mainly determined by the driver's reaction speed, and is related to the position of the accelerator pedal and the brake pedal, and generally is 0.3s to 1.0s. During the time
to, the car travels at the initial speed $u_0$, and the braking distance $S = t_0 \cdot u_0$, it is not included in the definition of the braking distance

![Figure 1. The relationship between braking deceleration and braking time.](image)

The second stage $t_1$ is the braking force increasing stage. Because there is a gap between the active part and the driven part of the brake, the ground braking force will take effect after a small period of time, but this small time is very short, and is ignored according to the reference [1]. As the driver steps on the brake pedal, the braking force continues to increase until the maximum value. If ESP does not work during this stage, the brake deceleration will increase linearly along the AB line until the B point begins to lock up. At this time, the deceleration value is $a_{\text{min}}$. If ESP is active at this stage, the car can obtain the best braking effect. Assuming that the control performance of the car is good, the maximum braking force of the brake increases to the maximum road braking force. Therefore, according to the force of the wheel during braking, the minimum value $a_{\text{min}}$ and the maximum value $a_{\text{max}}$ of the deceleration can be obtained as follows:

$$a_{\text{min}} = \varphi_s \cdot g$$  \hspace{1cm} (1)

$$a_{\text{max}} = \varphi_r \cdot g$$  \hspace{1cm} (2)

Where, $g$ is gravity acceleration and the value is 9.8kg/s$^2$.

During the braking force growth phase, the braking force increase of the brake is a linear function of time $t_1$, and the average braking force at this stage is:

$$F_{AB} = \frac{1}{t_1} \int_0^{t_1} mg \varphi_s \, dt = \frac{1}{2} mg \varphi_s$$  \hspace{1cm} (3)
According to Newton's second law, during the brake braking force growth phase, the average of the deceleration and the final speed of the second phase are:

\[
\begin{align*}
 a_{11} &= \frac{\overline{F}_{AB}}{m} = \frac{1}{2}g \varphi_s \\
a_{12} &= \frac{\overline{F}_{AB'}}{m} = \frac{1}{2}g \varphi_p
\end{align*}
\] (5)

\[
\begin{align*}
v_{11} &= v_0 - \int_0^{t_1} \frac{g \varphi_st}{t_1} dt = v_0 - \frac{1}{2}g \varphi_s t_1 \\
v_{12} &= v_0 - \int_0^{t_1} \frac{g \varphi_p t}{t_1} dt = v_0 - \frac{1}{2}g \varphi_p t_1
\end{align*}
\] (7)

According to the relationship of power and energy, the power done by the braking force on the car is equal to the increment of the kinetic energy before and after the brake, then:

\[
\begin{align*}
 \overline{F}_{AB} \cdot S_{11} &= \frac{1}{2}mg \varphi_s S_{11} = \frac{1}{2}mv_0^2 - \frac{1}{2}mv_{11}^2 \\
 \overline{F}_{AB'} \cdot S_{12} &= \frac{1}{2}mg \varphi_p S_{12} = \frac{1}{2}mv_0^2 - \frac{1}{2}mv_{12}^2
\end{align*}
\] (9)

Thus, the braking distance of the second stage [1] is:

\[
\begin{align*}
 S_{11} &= \frac{v_0^2 - v_{11}^2}{g \varphi_s} \\
 S_{12} &= \frac{v_0^2 - v_{12}^2}{g \varphi_p}
\end{align*}
\] (11)
The third stage is the continuous braking phase. Due to the intervention of the ESP (ABS) system, the acceleration change during the actual braking process is fluctuating [3], but the range of variation should theoretically fall within the interval \([a_{\text{min}}, a_{\text{max}}]\).

4. Determination and calculation of braking system parameters of new energy vehicles

In order to further accurately calculate the braking distance and braking deceleration, this paper considers the influence of ESP system parameters on braking distance and braking deceleration, that is the pressure regulating frequency \((\omega)\) and adjusting amplitude \((\delta)\) of the brake. Then use the cosine function to simulate the ESP brake pressure adjustment process and do coordinate transformation, as shown in Fig.2.

\[ a(t) = \frac{\delta}{2} \cos \omega t' \]
\[ a' = a - \left( a_0 - \frac{\delta}{2} \right) \]
\[ t' = t - t_1 \]

So there is:

Convert equation (13) to the original coordinate system:

\[ \frac{d^2 S_2}{dt^2} - (a_0 - \frac{\delta}{2}) - \frac{\delta}{2} \cos \omega(t - t_1) = 0 \]

Equation (14) is a computational model based on considering system parameters, where \(a\) is instantaneous deceleration.

For the integral of (14):

\[ v_2 - v_1 = (a_0 - \frac{\sigma}{2})(t - t_1) + \frac{\sigma}{2} \sin \omega(t - t_1) \]

According to the definition of braking distance, the car stops, so
\[ v_2 = 0 \]
\[ t - t_1 = t_2 \]

(16)

Where, \( t_2 \) is the continuous braking time of the car in the third stage.

According to the definition of average deceleration, the average deceleration \( (a_2) \) of the third stage is:

\[
a_2 = \frac{\int_{t_1}^{t_2} \left( a_0 - \frac{\sigma}{2} \right) + \frac{\sigma}{2} \cos \left[ \omega(t - t_1) \right] \, dt}{t_2 - t_1}
\]

(17)

It can be known from equations (13) to (17) that as long as the system parameters, peak adhesion coefficient and initial braking speed of the vehicle are determined, the braking distance, braking deceleration and braking time of the second stage can be determined by calculation. Thus, consider the system parameters, \( a \) is calculated as:

\[
a = \frac{g \varphi t_1}{2(t_1 + t_2)} + \frac{t_2}{(t_1 + t_2)(t_2 - t_1)} \int_{t_1}^{t_2} \left( a_0 - \frac{\sigma}{2} \right) + \frac{\sigma}{2} \cos \left[ \omega(t - t_1) \right] \, dt
\]

(18)

\[
s = \frac{v_0^2 - v_{11}^2}{g \varphi_p} + s_2
\]

(19)

The continuous braking process of the new energy vehicle (is the third stage of braking) is generally between 2s and 10 s. The minimum operating time of the solenoid valve of the pressure regulator is about 10 ms. during the control process, the magnetic valve moving frequency is 8 to 20 per second [4], so there is:

\[
\frac{\omega}{2\pi} = 8 - 20
\]

(20)

It can be known from equation (20), and the value of \( \omega \) is mainly based on the vehicle speed and the road surface. In this calculation, since the adjustment frequency of the dry road surface is smaller than the wet road surface, \( \omega \) is 50 on the dry road surface and is 100 on the wet road surface.

The value of \( \delta \) represents the magnitude of the change in brake deceleration. It is a concrete manifestation of the control reliability for the new energy vehicle control system and an estimate of the braking performance potential of the new energy vehicle. According to the concept of slip rate, the relationship between the sliding ratio and the adhesion coefficient is obtained by the function approximation method [1], and the equation (21) is obtained, as shown in Fig. 3.
According to the reference [13], when the slip ratio is 15%~20%, the braking force coefficient is the largest, and the best braking performance is obtained. Therefore, the new energy vehicle brake system is based on the sliding ratio of 15% to 20% as the control target. According to the equation (21), the above two kinds of road surfaces are calculated, wherein the optimal sliding ratio, the peak adhesion coefficient and the sliding adhesion coefficient are obtained according to the typical pavement experiment, are shown in Table 1.

![Figure 3. The relationship between sliding ratio and adhesion coefficient.](image)

**Table 1.** The typical road surface experiment data.

| Road surface          | \( s_p \) | \( \varphi_p \) | \( s_s \) | \( \varphi_s \) |
|-----------------------|-----------|----------------|-----------|----------------|
| Dry concrete road     | 0.17      | 0.9            | 1         | 0.75           |
| Wet concrete road     | 0.36      | 0.8            | 1         | 0.7            |

Therefore, the magnitude of the change in the braking deceleration can be obtained:

\[
\sigma = (\varphi(0.2) - \varphi(0.15)) \cdot g
\]  

Substituting the relevant data of Table 1 into equation (22), the calculation result of the variation range of the braking deceleration corresponding to the dry and wet concrete can be obtained, as shown in Table 2.
Table 2. The calculation result of system parameters.

| Road surface         | $\sigma$ | $\omega$ |
|----------------------|----------|----------|
| Dry concrete road    | 0.2647   | 50       |
| Wet concrete road    | 0.3333   | 100      |

5. Road test verification and error analysis

As shown in Table 3, it is calculated based on the “interval function of new energy vehicle braking performance” and the “calculation model of new energy vehicle braking performance considering system parameters”, where $A$ is the minimum value of the interval function and $C$ is the maximum value of the function, $B$ is the calculation result according to the equations (18) and (19).

Table 3. Simulation calculation of linear braking performance of new energy vehicles.

| Calculation condition | A         | B         | C         |
|-----------------------|-----------|-----------|-----------|
|                       | Initial speed(k m/h) | Braking distance (m) | Average deceleration (m/s$^2$) | Braking time(s) | Initial speed(k m/h) | Braking distance (m) |
| concrete road surface |           |           |           |           |                       |                      |
| dry                   | 100       | 49.13     | 8.293     | 3.349 7  | 51.382                 | 7.89                 | 3.55                 | 57.91                 | 6.981                 | 3.9796                |
| wet                   | 100       | 55.27     | 7.418     | 3.718 4  | 58.129                 | 7.00                 | 3.96                 | 63.17                 | 6.536                 | 4.2353                |
| dry                   | 130       | 80.97     | 8.409     | 4.294 2  | 84.946                 | 7.99                 | 4.66                 | 95.78                 | 7.063                 | 5.1131                |
| wet                   | 130       | 90.23     | 7.514     | 4.806    | 95.317                 | 7.08                 | 5.10                 | 102.1 3               | 6.609                 | 5.464                 |

From the calculation results, the values of braking distance and braking deceleration obtained by "the calculation model of braking performance of new energy vehicles considering system parameters" are between the maximum and minimum values of the interval function, as shown in Fig. 4. It shows that the modeling process is reasonable in theory.

![Figure 4. The Diagram of Simulation Calculation Results.](image)
The road test results of linear high-speed braking of a new energy vehicle on a concrete pavement are compared with the calculation results of the "calculation model of new energy vehicle braking performance considering system parameters". The test car enters the straight road (dry concrete and wet concrete respectively) at 100km/h and 130km/h, and brakes. The braking distance and the average braking deceleration in the test are compared with the calculation model in the text, as shown in Table 4.

Table 4. Road test results of a car in linear high-speed braking on concrete pavement.

| Calculation condition | Theoretical calculation result | Road test result | Error analysis |
|-----------------------|--------------------------------|-----------------|---------------|
|                       | breaking distance(m) | average deceleration(m/s²) | braking time(s) | breaking distance(m) | average deceleration(m/s²) | braking time(s) | Braking distance relative error(%) | Average deceleration relative error(%) | Braking time relative error(%) |
| concrete road surface |干燥 | 100 | 51.382 | 7.89 | 3.55 | 41.832 | 9.25 | 3.00 | 22.83 | -14.70 | 18.33 |
|                       |湿润 | 100 | 58.129 | 7.00 | 3.96 | 62.753 | 6.71 | 4.14 | -7.37 | 4.32 | -4.35 |
|                       |干燥 | 130 | 84.946 | 7.99 | 4.66 | 81.264 | 8.0 | 4.51 | 4.53 | -0.13 | 3.33 |
|                       |湿润 | 130 | 95.317 | 7.08 | 5.10 | 97.125 | 6.71 | 5.38 | -1.86 | 5.51 | -5.20 |

From the road test results in Table 4, the errors are all within 10%, which verifies that the modeling of the "interval function" and the "calculation method of new energy vehicle braking performance considering system parameters" is reasonable and feasible.

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References
[1] Yu Zhisheng. Automobile Theory [M]. China Machine Press, Beijing, 2018.
[2] Gong Yingwei, Zhang Beibei. Electric Vehicle Structure Principle and Maintenance [M]. China Machine Press, Beijing, 2018.
[3] Wang Xiaofeng. Automotive Chassis Design [M]. Tsinghua University Press, Beijing, 2018.
[4] Zhao Guozhu, Tang Jingyou, etc. ABS Control Strategy of Giving Priority to Regenerative Braking Torque for Electric Vehicles [J]. Mechanical Science and Technology for Engineering, 2019, (6): 1 – 4.
[5] Yang Ruiwei. Research on Detection Method of Automobile Braking Performance [J]. Light Industry Science and Technology, 2019, 35 (1): 52 – 54.
[6] SAE J1441, Subjective Rating Scale For Vehicle Handling. 2007 (4).