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A Novel Parallel Regenerative Braking Control Strategy

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Abstract. A novel parallel regenerative braking control strategy which suits Electric Vehicles (EV) with Front-wheel drive pattern was introduced. This strategy met ECE regulations and ensured that all wheels were always in unlocked conditions. Feasibility and superiority were proved through theoretical analyses and simulations basing on the platform in the software of MATLAB/SIMULINK. The results indicate that this strategy can not only recover considerable braking energies, but also reduce the braking distance.

Introduction

Nowadays, traditional engine automobiles (TEA) have contributed to lots of environmental problems, such as the air deterioration and the scarce of petroleum resources [1]. So the researches of EV are becoming the hot topics because of the green advantages [2]. At the same time, the EV can recover the braking energies through regenerative braking [3]. Currently, there are two kinds of regenerative braking control strategies: the parallel one and the wire controlled one [4]. The wire controlled one could achieve the ideal braking force distribution function and recover lots of energies [5]. However, it has more complex control system and it costs much higher. In contrast, the parallel one can recover the braking energies with slight modifications [6].

Parallel Regenerative Braking Control Strategy

The ratio of front braking force to the rear braking force in TEA is a fixed value (β_0).

$$\beta_0 = F_{uf}(t) / \left(F_{uf}(t) + F_{ur}(t)\right). \tag{1}$$

As is shown in Eq.1, $F_{uf}(t)$ is front braking force originated from brake system; $F_{ur}(t)$ is rear braking force.

The braking force distribution coefficient changes when the regenerative braking force is added.

$$\beta_{ev} = \left(F_{uf}(t) + F_{re}(t)\right) / \left(F_{uf}(t) + F_{re}(t) + F_{ur}(t)\right). \tag{2}$$

As is shown in Eq.2, $F_{re}(t)$ is braking force provided by the motor.

According to the Eq.1 and Eq.2, Eq.3 is concluded.

$$\beta_{ev} \ge \beta_0 . \tag{3}$$

Constraints of ECE Regulations. The severity of braking (z) is one of the braking efficiency evaluating indicators.

$$z = v_t' / g . \tag{4}$$

As is shown in Eq.4, v_t is the instantaneous velocity of the vehicle; g is the acceleration of gravity.

Utilization adhesion coefficient is the minimum pavement adhesion coefficient when all the wheels are unlocked and the severity of braking is a fixed value. The following equations show the utilization adhesion coefficient of front wheels (φ_f) and the utilization adhesion coefficient of rear wheels (φ_r).

$$\varphi_f = L\beta z / \left(b + zh_g\right). \tag{5}$$

$$\varphi_r = L\left(1-\beta\right) z / \left(a - zh_g\right). \tag{6}$$

As is shown in Eq.5 and Eq.6, L is the wheel base; a is the distance between center of mass and front wheels; b is the distance between center of mass and rear wheels; h_g is the height of center of mass.

ECE R13 has clear requirements for the passenger cars.

When $z \ge 0.1$, utilization adhesion coefficient should meet the following restrictions.

$$\varphi_f \ge \varphi_r. \tag{7}$$

$$\varphi_f \le \left(z + 0.07\right) / 0.85. \tag{8}$$

$$\varphi_r \le \left(z + 0.07\right) / 0.85. \tag{9}$$

When $0.3 \le z \le 0.4$, utilization adhesion coefficient should meet the following restrictions.

$$\varphi_f \le \left(z + 0.07\right) / 0.85. \tag{10}$$

$$\varphi_r \le z + 0.05. \tag{11}$$

According to these restrictions, the range of braking force distribution could be concluded.

Table 1 Range of braking force distribution

Severity of braking	Lower limit value	Upper limit value
$z \ge 0.1$	$\left(b + z_t h_g\right) / L$	$\left(b + z_t h_g\right)\left(z_t + 0.07\right) / \left(0.85Lz_t\right)$
$z \ge 0.1$	$\left[0.85Lz_t - \left(a - z_t h_g\right)\left(z_t + 0.07\right)\right] / \left(0.85Lz_t\right)$	$\left(b + z_t h_g\right)\left(z_t + 0.07\right) / \left(0.85Lz_t\right)$
$0.3 \le z_t \le 0.4$	$\left[Lz_t - \left(a - z_t h_g\right)\left(z_t + 0.05\right)\right] / \left(Lz_t\right)$	$\left(b + z_t h_g\right)\left(z_t + 0.07\right) / \left(0.85Lz_t\right)$

If $\beta_{ev} \in \left[\beta_{\min}(z_t), \beta_{\max}(z_t)\right]$, the control strategy would meet the ECE regulations. Then the range of regenerative braking force can be concluded.

$$F_{re}(t) \le \left[\left(\beta_{\max}(z_t) - 1\right) F_{uf}(t) + \beta_{\max}(z_t) F_{ur}(t)\right] / \left(1 - \beta_{\max}(z_t)\right). \tag{12}$$

Constraints of Braking Distance Assurance. When the front wheels or the rear wheels are in critical locking states, the hydraulic-brake system would be in pressure holding condition. If regenerative braking force is added at this time, the Antilock Braking System (ABS) would make the hydraulic-brake system in pressure reduction condition. Then the mechanical braking force would decrease. The braking distance would increase during this period, if the available regenerative braking force cannot compensate the drops of mechanical braking force. So in order to ensure the braking distance, restrictions should be carried out when the ABS is to work.

The synchronizing adhesion coefficient (φ_0) is the adhesion coefficient when the front and rear wheel lock at the same time.

$$\varphi_0 = \left(L\beta_0 - b\right) / h_g. \tag{13}$$

Brake efficiency (E) is the ratio of maximum severity of braking to the ground adhesion coefficient when the front and rear wheel are not locked.

$$E \le 1. \tag{14}$$

$$E = \begin{cases} b / L / \left(\beta - \varphi hg / L\right), & \varphi < \varphi_0 \\ 1, & \varphi = \varphi_0 \\ a / L / \left[\left(1-\beta\right) + \varphi hg / L\right], & \varphi > \varphi_0 \end{cases}. \tag{15}$$

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Eq.16 shows the maximum severity of braking when all the wheels are unlocked.

$$z_{\max}(\varphi) = \varphi E(\varphi). \tag{16}$$

Then the maximum braking force can be concluded when all the wheels are unlocked.

$$F_{b\_\max}(\varphi) = Mgz_{\max}(\varphi). \tag{17}$$

The following equation shows the maximum braking force on front wheels when all the wheels are unlocked and the rear braking force is the allowed maximum value.

$$F_{bf\_\max}(\varphi) = \beta_0 F_{b\_\max}(\varphi) = \beta_0 Mgz_{\max}(\varphi). \tag{18}$$

Then the range of regenerative braking force can be concluded.

$$F_{re}(t) \le F_{bf\_\max}(\varphi) - F_{uf}(t) = \beta_0 Mg\varphi E(\varphi) - F_{uf}(t). \tag{19}$$

Constraints of Purpose of Preventing Front Wheels Locking. The relations between braking force and hydraulic pressure can be concluded when all the wheels are unlocked.

$$F_{bf}(t) = F_{uf}(t) + F_{re}(t). \tag{20}$$

$$F_{br}(t) = F_{ur}(t). \tag{21}$$

Eq.22 shows the relation between front braking force and rear braking force when the rear wheels are unlocked.

$$F_{br}(t) = \left(L - \varphi h_g\right) F_{bf\_lock}(t) / \left(\varphi h_g\right) - Gb / h_g. \tag{22}$$

The instantaneous maximum front braking force can be concluded from Eq.22.

$$F_{bf\_lock}(t) = \left(F_{ur}(t) + Gb / h_g\right) / \left[\left(L - \varphi h_g\right) / \varphi h\right]. \tag{23}$$

Then the range of regenerative braking force can be concluded.

$$F_{re}(t) \le F_{bf\_lock}(t) - F_{uf}(t) = \left(F_{ur}(t) + Gb / h_g\right) / \left[\left(L - \varphi h_g\right) / \varphi h_g\right] - F_{uf}(t). \tag{24}$$

Control Strategy. In order to ensure the braking distance after the regenerative braking force is added, the motor would not supply the braking force when the severity of braking reaches the unlocked maximum and the ABS is in pressure holding state.

Eq.25 shows the instantaneous allowed regenerative braking force maximum.

$$F_{re\_\max}(t) = \min \left\{ \begin{array}{l} \dfrac{\left(\beta_{\max}(\mathrm{z}_t) - 1\right) F_{uf}(t) + \beta_{\max}(\mathrm{z}_t) F_{ur}(t)}{1 - \beta_{\max}(\mathrm{z}_t)}, \\ \left(\beta_0 Mg\varphi E(\varphi) - F_{uf}(t)\right), \\ \left[\dfrac{F_{ur}(t) + Gb / h_g}{\left(L - \varphi h_g\right) / \varphi h_g} - F_{uf}(t)\right] \end{array} \right\}. \tag{25}$$

However, the motor cannot supply sustainable regenerative braking force all the time. Fig.26 shows the detailed conditions.

$$F_{re}(t) = \begin{cases} F_{re\_available}(t), & F_{re\_available}(t) \le F_{re\_\max}(t) \\ F_{re\_\max}(t), & F_{re\_available}(t) > F_{re\_\max}(t) \end{cases}. \tag{26}$$

As is shown in Eq.26, $F_{re\_available}(t)$ is the instantaneous available regenerative braking force provided by the motor.

Fig.1 shows the control strategy. The dashed area is the working area where the motor joins.

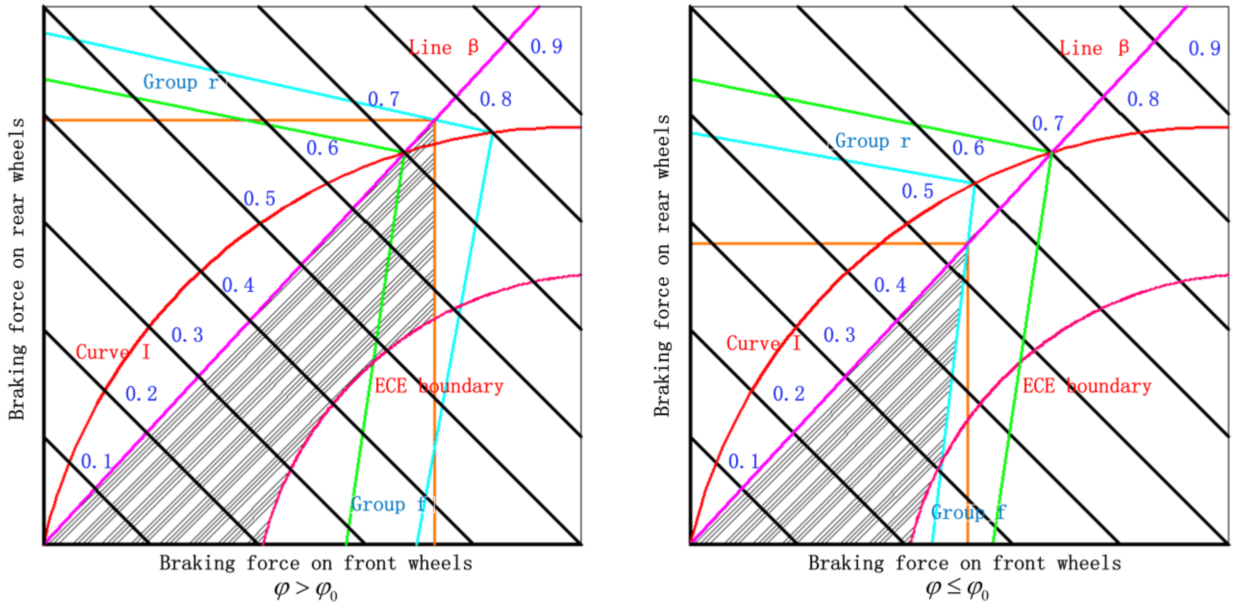

Fig.1 Parallel regenerative braking control strategy

Braking Distance Under the Novel Strategy

Eq.27 shows the instantaneous velocity of the car during the braking process.

$$v_t = v_0 - \int z_t g dt . \tag{27}$$

As is shown in Eq.27, v_0 is the initial velocity.

Supposing the TEA and the EV start to brake at the same time, the velocity of TEA is v_{tv_tvlock}, when the front or rear wheels are in critical locking states. At this time, the velocity of EV is v_{ev_tvlock}. According to Eq.27, it can be concluded that v_{tv_tvlock} is higher than v_{ev_tvlock}. When the velocity of TEA is v_{ev_tvlock}, the EV and the TEA are in critical locking states. Supposing the time is t_1, when the velocity of TEA is v_{ev_tvlock}. And the stopping time of TEA is t_{tvstop}. Supposing the time is t_2, when the velocity of EV is v_{ev_tvlock}. And the stopping time of EV is t_{evstop}. Then Eq.28 and Eq.29 can be concluded.

$$t_{evstop} - t_2 = t_{tvstop} - t_1 . \tag{28}$$

$$\int_0^{v_{ev\_tvlock}} v_t dt = \int\int_{t_2}^{t_{evstop}} z_{\max} g dt^2 = \int\int_{t_2}^{t_{tvstop}} z_{\max} g dt^2 . \tag{29}$$

The process of deceleration from v_0 to v_{ev_tvlock} can be divided into N pieces. And each piece can be regarded as a linear process. During the t part, the brake distance is $(v_t + v_{t+1})\Delta t_t / 2$. During this period, the severity of braking of EV (z_{t_ev}) is not lower than that of TEA (z_{t_tv}). Then Eq.30 is concluded.

$$\Delta t_{t\_ev} \le \Delta t_{t\_tv} . \tag{30}$$

Eq.31 and Eq.32 show the braking distance during the whole braking period.

$$Distance\_ev = \sum_{t=0}^{N} (v_t + v_{t+1})\Delta t_{t\_ev} / 2 + \int\int_{t_2}^{t_{evstop}} z_{\max} g dt^2 . \tag{31}$$

$$Distance\_tv = \sum_{t=0}^{N} (v_t + v_{t+1})\Delta t_{t\_tv} / 2 + \int\int_{t_1}^{t_{tvstop}} z_{\max} g dt^2 . \tag{32}$$

Eq.33 shows the braking distance relations between TEA and EV.

$$\begin{cases} Distance\_tv - Distance\_ev > 0, & \int F_{re\_t}(v)dt > 0 \\ Distance\_tv - Distance\_ev = 0, & \int F_{re\_t}(v)dt = 0 \end{cases}. \tag{33}$$

In sum, it can be concluded that the braking distance of EV is lower than that of TEA if the regenerative braking forces are added.

Braking Models

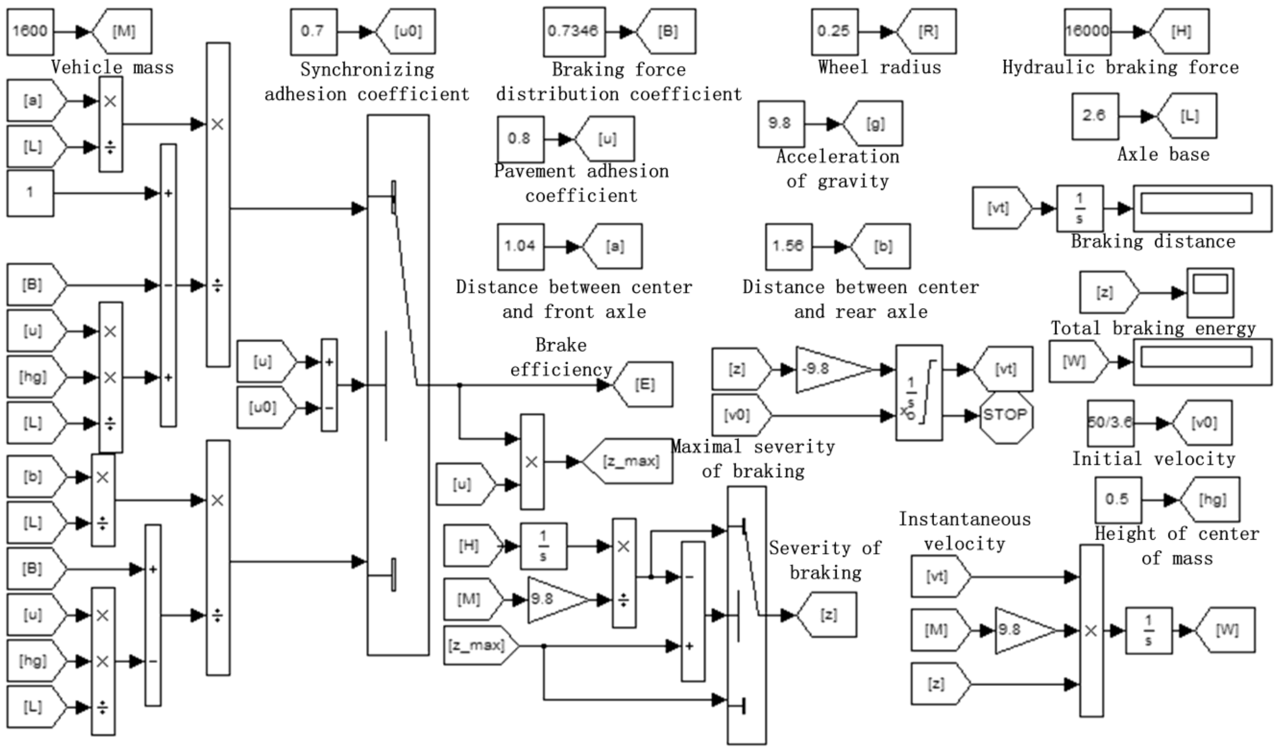

Fig.2 Braking model of TEA

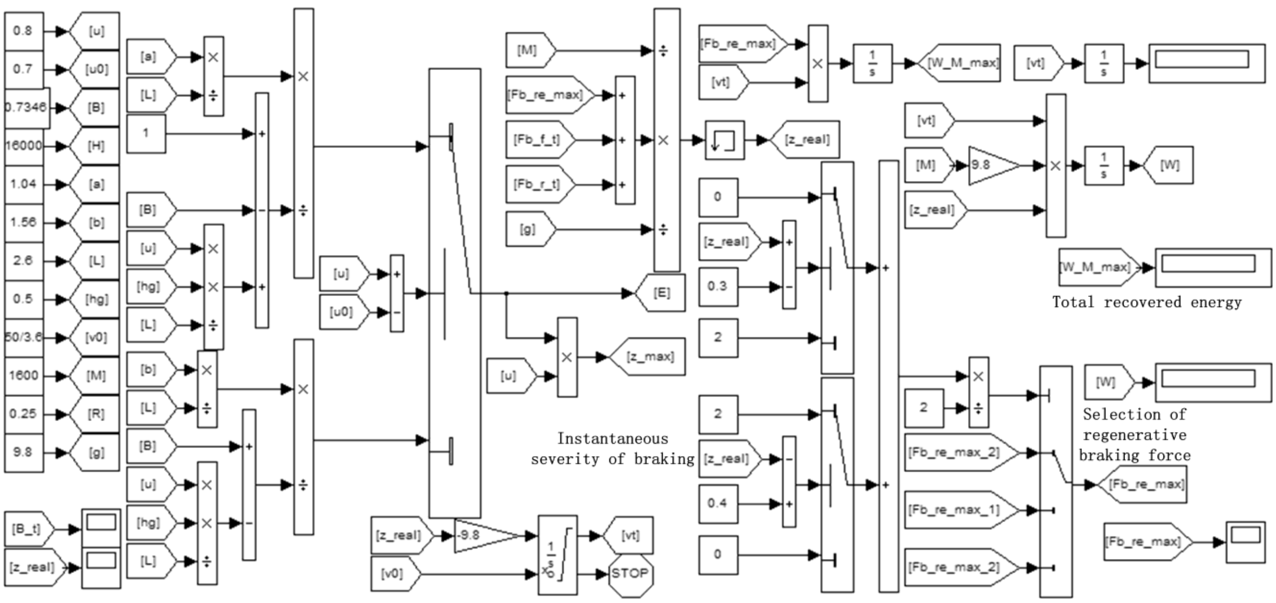

Fig.3 Main module of EV braking model

Braking Model of TEA. Fig.2 shows the braking model of TEA. The maximum braking severity can be calculated according to the comparison between synchronizing adhesion coefficient and pavement adhesion coefficient when all the wheels are unlocked. Braking rate module is used to simulate the process of depressing the brake pedal by the driver. Instantaneous braking severity can be calculated according to the driver's commands and the maximum braking severity. Then the instantaneous velocity and the braking distance can be calculated.

Braking Model of EV. Fig.3 shows the main module of EV braking model. The motor in this model can supply the demand regenerative braking force all the time. So the braking distance and the recovered energy are the optimum values. The instantaneous braking severity module is changed because the regenerative braking force is added on front wheels. The demand regenerative braking force can be selected according to the braking severity. And the total recovered energy can be calculated according to the regenerative braking force and velocity.

Fig.4 shows the restriction module. The hydraulic braking force on front and rear wheels can be calculated by the driver module. The maximum instantaneous front braking force is calculated according to the instantaneous rear hydraulic braking force. The allowed maximum of front braking force is calculated according to the maximum braking severity.

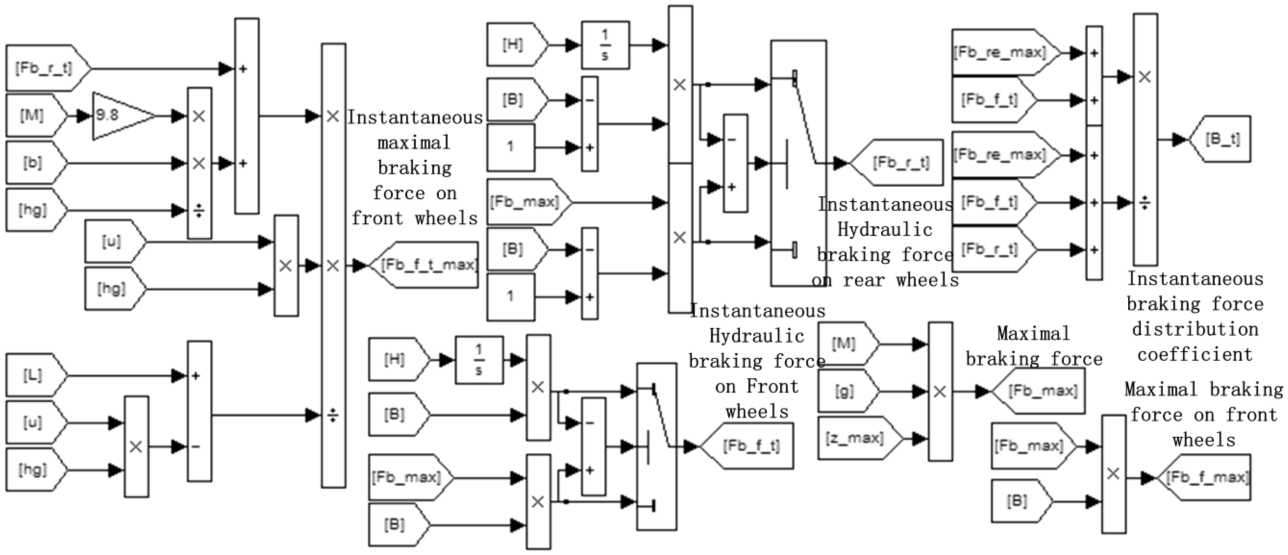

Fig.4 Restriction module

Fig.5 shows the regenerative braking module. The maximum braking force distribution coefficient can be calculated according to the braking severity. The instantaneous maximum regenerative braking force is the minimum among the three restrictions.

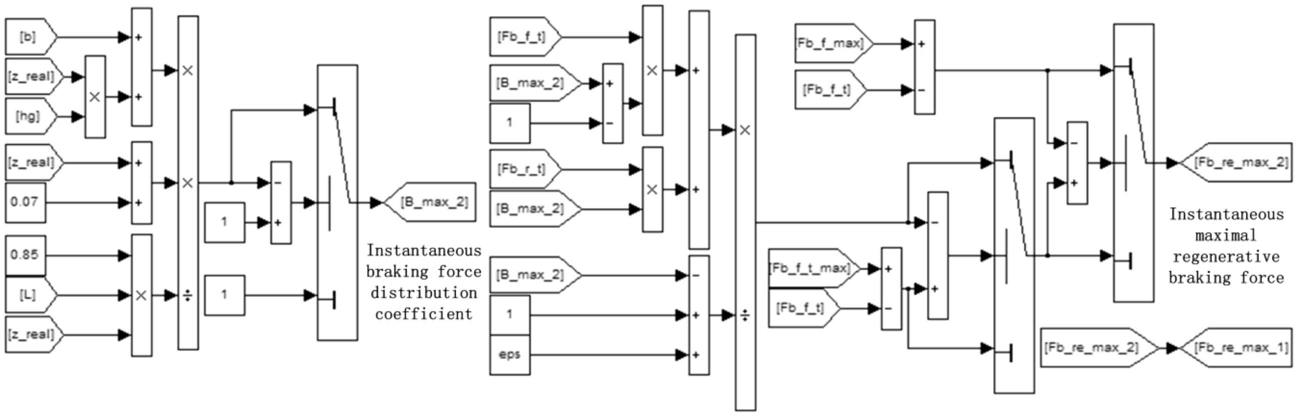

Fig.5 Regenerative braking module

Simulation Results Analyses

The whole EV model is simulated in a certain EV. The parameters in the EV model are determined by the EV structure. Table 2 shows the EV parameters.

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Table 2 EV parameters

Mass of EV	1600 [kg]
Initial velocity	50 [km/h]
Distance between mass center and front axle	1.04 [m]
Distance between mass center and rear axle	1.56 [m]
Height of center of mass	0.5 [m]
Tyre radius	0.25 [m]
Synchronizing adhesion coefficient	0.7
Pavement adhesion coefficient	0.8

Fig.6 and Fig.7 show the simulation results. It can be concluded that the braking force distribution coefficient decreases and the braking severity increases with the rise of rear braking force. There are several vibrations at first and the braking force distribution coefficient is very high. This is because the hydraulic braking forces are too low at the beginning and the regenerative braking force changes quickly. Then the variation trends of distribution coefficient and braking severity are stable.

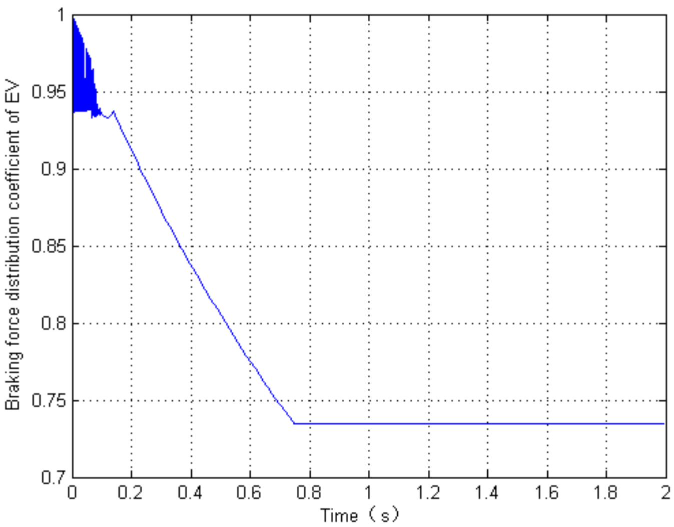

Fig.6 Instantaneous distribution coefficient

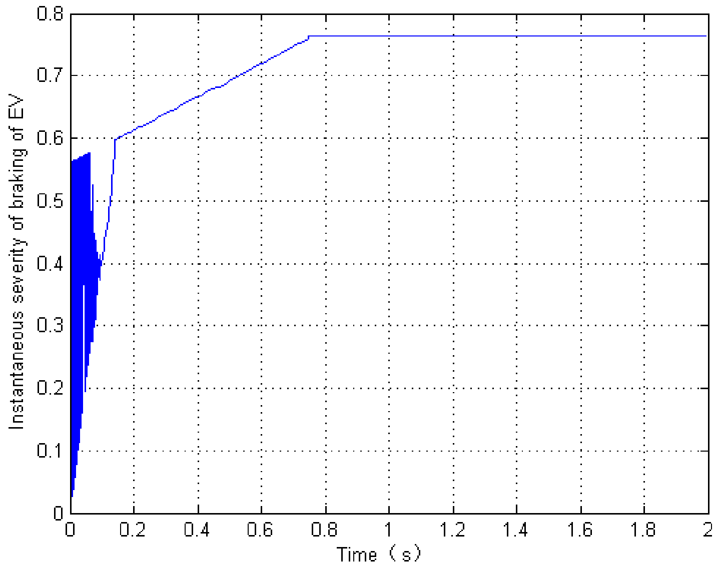

Fig.7 Instantaneous braking severity

The braking process of EV and TEA with the same parameters are also simulated under different initial velocities. Table 3 shows the results.

Table 3 Braking results of EV and TEA

Initial velocity [km/h]	Braking distance of TEA [m]	Braking distance of EA [m]	Decrement rate of braking distance	Recovery rate of braking energy
80	41.15	35.93	12.7%	15.3%
70	32.37	27.83	14.0%	17.4%
60	24.63	20.72	15.9%	20.0%
50	17.91	14.67	18.1%	23.6%
40	12.23	9.638	21.2%	28.6%
30	7.584	5.647	25.5%	36.3%
20	3.967	2.690	32.2%	49.1%

From the table, it can be concluded that the EV with this strategy can recover considerable braking energies and reduce the braking distance at the same time which means that this strategy is feasible. The recovery rate of braking energy and the decrement rate of braking distance increases when the initial velocity decreases. This is because the regenerative braking participates more during the whole braking process. So this strategy suits the passenger cars driven on urban conditions better.

Summary

This novel parallel regenerative braking control strategy meets the ECE regulations and can ensure that all the wheels are unlocked. The theoretical derivations indicate that this strategy can reduce the braking distance on the premise of recovering braking energies. In addition, the simulation results show that this strategy has more advantages if the EV driven on urban conditions equips it.

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