Regenerative Braking Control Strategy of Electric Truck Based on Braking Security

Shiwei Xu, Ziqiang Tang, Yilin He and Xuan Zhao

Abstract In order to improve the energy efficiency of electric vehicles, a regenerative braking control strategy of electric truck was developed to improve energy recovery based on braking security. After the prerequisites, the restrictions of ECE regulations, battery and motor were completed to ensure the braking security, the regenerative braking force allocation strategy was designed. Then a co-simulation of Cruise and Matlab of this control strategy was executed in Japan1015 operating cycle to evaluate the strategy effects. Simulation results show that the strategy proposed in this paper can recover as much as 11.48 % braking energy in Japan1015 cycle under braking security requirements. So this regenerative braking control strategy can significantly improve the economic performance for electric vehicles.

Keywords Automotive engineering · Electric truck · Regenerative braking · Braking stability · Co-simulation

1 Introduction

According to recent studies of electric vehicles, regenerative braking seems to be a most promising technology to improve the driving range because it can recover the energy wasted on braking energy. So far main focus has been placed on factors that affect the electric power on recovering the braking energy, such as motor and battery. However, there is not enough attention paid to the braking stability. Since

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the capacity of regenerative braking is restricted by velocity, maximum torque of motor and maximum charge current of battery, it is crucial to make a suitable division percentage of motor braking and mechanical braking for regenerative braking. More recently, the division of braking force has been investigated in some studies. Hellgren [1] conducted a research on the effect of motor, battery and structure of braking system; however, the division of braking force was not mentioned. References [2, 3] conducted studies on distribution of braking force under considering the restriction of electric power; however, the application of these theories are needed to improve because all of these theories were proposed on ideal situation. Therefore, in order to recover the braking energy as much as possible, the issues, the principle of braking force distribution strategy and maintaining the braking stability warrant further attention.

In this paper, considering the security requirements, a regenerative braking control strategy of electric truck was proposed. The structure of the paper is organized as follows: Sect. 2 introduces the requirement of braking security restrictions, which are consist of ECE R13, battery and motor, Sect. 3 describes the regenerative braking control strategy, Sect. 4 presents the co-simulation, simulation results and the analysis, Sect. 5 is the conclusion.

2 Constraints of the Regenerative Braking Under Braking Security Requirements

2.1 ECE R13 Brake Regulations

I curve is the ideal braking forces distribution curve applied on front and rear wheels. However, in practice, the braking force distribution generally cant be employed as 'I curve'. ECE R13 brake regulations enacted by Economic Commission have proposed clear requirements for the front and rear braking forces of biaxial vehicle [5]: For truck, the adhesion utilization coefficient of front wheels should exceed the adhesion utilization coefficient of rear wheels with various loading conditions; when the friction coefficient φ is between 0.2 to 0.8, the requirements of the braking intensity should meet $z \geq 0.1 + 0.85(\varphi - 0.2)$. According to this requirement, rear wheels must have a certain braking force if the front wheels locked to maintain vehicle stability and high braking efficiency. The related curve between the smallest ground braking force of rear wheels and that of front wheel is called M curve, and the braking forces distribution curve should be higher than the M curve, M curve determined by formula (1) and (2).

$$F_{br} = \frac{z + 0.07}{0.85}\frac{G}{L}(L_a - zh_g) \tag{1}$$

$$F_{bf} = G_Z - F_{br} \tag{2}$$

From the ECE brake regulations, it can be concluded that the ideal security range of braking force distribution should distribute between the I curve and M curve, however, even if the braking force allocation curve is above I curve but below the ECE regulations rear axles upper limit [4], the truck braking security will also be guaranteed. So considering these restrictions, the actual regenerative braking force allocation curve should be located in the region between M curve and ECE regulations rear axles upper limit curve.

2.2 Battery

For regenerative braking system, maximum charging current, maximum charging power, the battery state of charge(SOC) are the major restriction factors. Both of the charging current and charging power of regenerative braking cannot exceed the maximum charging current and the maximum allowable charging power of batteries. Battery SOC cannot operate beyond the active battery charging region. Here, the active battery charging region is from 30 to 90 % [5]. For most batteries, the charging power P_{bat} can be expressed as

$$P_{bat} = (U_{OC} + IR)I \tag{3}$$

Where U_{OC} is the open circuit voltage in V, and R is the internal resistance of the battery in Ω. I is the current of the charging current in A, which is calculated as:

$$I = I_0 e^{-\sigma t} \tag{4}$$

Where I_0 is the maximum initial charging current in A, while σ is the attenuation coefficient, which is also called as the charge acceptance ratio. The battery charge power calculated by the formula (3) and (4) limits the maximum regenerative braking force, which is:

$$F_{reg1} \leq \frac{P_{bat}}{v\eta_t \eta_m \eta_b} \tag{5}$$

Where F_{reg1} is the maximum motor regenerative braking under the limitation of the battery charging power in N; v is the velocity in km/h; η_t is mechanical transmission efficiency; η_m is the power generation efficiency of motor; η_b is battery charging power.

2.3 Motor

As motor is a main factor affecting the energy recovery, the regenerative braking torque provided by it is affected by the motor torque characteristics, motor speed characteristics, vehicle velocities and other factors [6]. When the motor is working in the generator state, the torque output characteristics are basically similar to the output characteristics of the motor state, which can be expressed as:

$$T_{reg1} = \begin{cases} 9550P_N/n_b & n \leq n_b \\ 9550P_N/n & n > n_b \end{cases} \tag{6}$$

Where T_{reg1} is the motor regenerative braking torque in N.m; P_N is the motor rated power in kW; n_b is the motor base speed in r/min.

When the vehicle braking at a low velocity, the regenerative braking capacity will decrease with the vehicle velocity decreasing due to the lack of kinetic energy. In order to ensure safety, the regenerative braking force provided by motor is set as zero when the motor speed drops to 500 r/min, so the amendment formula is turned into:

$$T_{reg} = \lambda(n)T_{reg1} \tag{7}$$

Where λ (n) is the correction factor associated with the motor speed:

$$\lambda(n) = \begin{cases} 0 & n \leq 500r/min \\ 1 & n > 500r/min \end{cases} \tag{8}$$

From the above analysis, the maximum motor regenerative braking force on driving wheel under the generator power limits is obtained as:

$$F_{reg2} = \frac{T_{reg}i}{r}\eta_t \tag{9}$$

Where i is the total ratio of power train; r is the wheel radius in m. During the braking, in order to ensure the brake safety, the braking force distribution ratio needs to be adjusted when the maximum motor regenerative braking force can't satisfy the required braking force on the drive wheels.

In summary, the motor maximum regenerative braking force is determined by battery charge power and motor generator power, which is:

$$F_{regmax} = min(F_{reg1}, F_{reg2}) \tag{10}$$

3 Regenerative Braking Control Strategy

3.1 Braking Force Allocation Strategy

In order to maximize the recovery of braking energy, the braking force allocation strategy is established within the range of the safety brake force distribution [7].

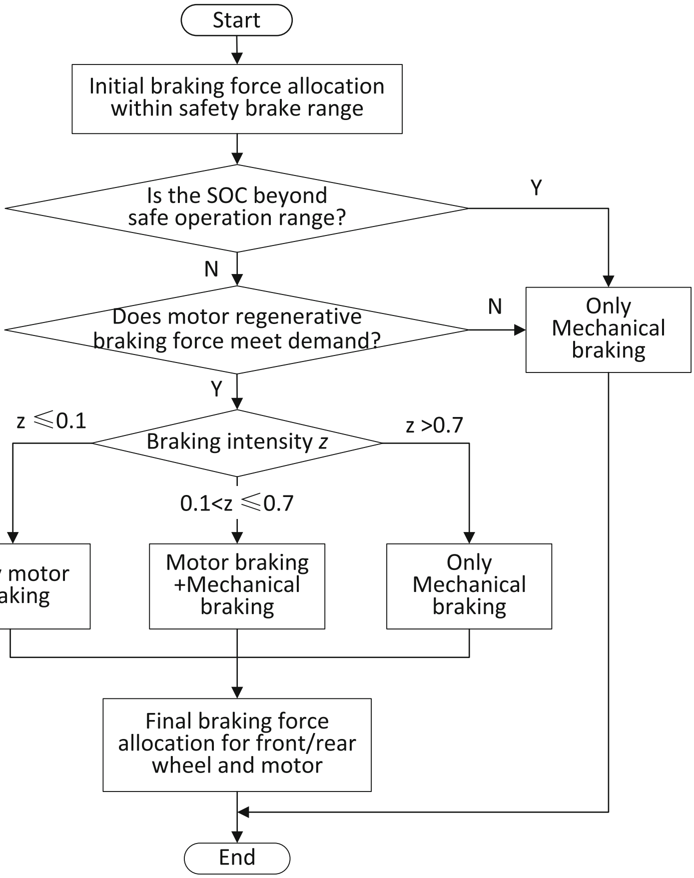

Fig. 1 Control flow of the braking force distribution

One way to improve braking energy recovery rate is to increase motor braking force in conjunction with a decrease of mechanical braking force [8]. The braking force allocation strategy are shown in Fig. 1.

Specific steps are presented as follows: Firstly, the initial braking force distribution ratios of front wheel and rear wheel are gotten within the braking safety range. Secondly, a judgment, whether the battery SOC is beyond safe operation range or not, should be made. If yes, it means the regenerative braking will damage the battery, so the regenerative braking should be stopped and only mechanical braking supplies the whole braking force. Otherwise, the flow enters the next step. Thirdly, we should judge if the motor regenerative braking meets demand or not. If not, the motor braking force will be too small to supply enough braking force, so the whole braking force also should be supplied by mechanical braking solely. Otherwise, the flow enters the next step. Fourthly, braking intensity z should be classified. If $z \leq 0.1$, it means the motor braking can meet the whole braking force so that there is only motor braking

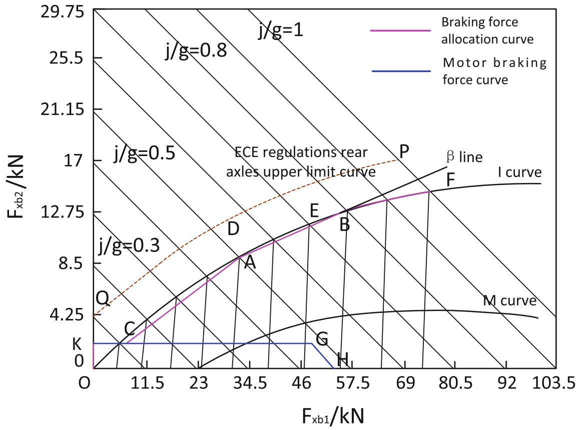

Fig. 2 Sketch of the braking force allocation strategy

supplying braking force. If $0.1 < z \leq 0.7$, it seems that only motor braking cannot meet the whole braking force so the mechanical braking will supply the rest braking force. If $z > 0.7$, this case is the emergency braking, then only mechanical braking is employed to ensure the braking safety. Finally, the final braking force allocation for front/rear wheel and motor can be deduced.

In order to facilitate the practical application, the varied proportional valves hydraulic distribution curve like β line is commonly used in modern vehicles to replace I curve and also utilized in this paper. Moreover, as shown in Fig. 2, the Line OKCABF is used as the actual braking force allocation curve of the truck in this paper. When the braking intensity is no more than 0.1, the motor braking force can meet the whole braking force and thereby the actual braking force allocation curve is coincident with motor braking force curve. Then, when the braking intensity is between 0.1 and 0.7, the whole braking force consists with motor braking force and mechanical braking force, and the curve is varying along with β line to get a good braking security. Then again, when the braking intensity exceeds 0.7, ABS or other braking security electric equipment are activated and the curve will follow the idea I curve.

3.2 Regenerative Braking Control Process

Regenerative braking control system structure were shown in Fig. 3. From the structure, it can be revealed that during braking process, the total target braking force was obtained by the pedal travel, and the motor braking force was determined by velocity, battery SOC and so on. Then the actual regenerative braking force and mechanical braking force were determined in the braking force allocation strategy module, and these signals were sent to the corresponding control module. All signals were transported through the CAN bus between modules.

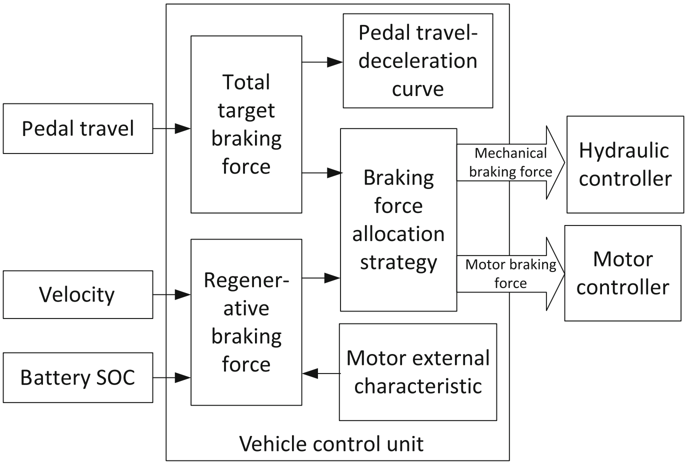

Fig. 3 Regenerative braking control system structure

4 Simulation Results and Analysis

To evaluate the results of regenerative braking control strategy in this paper, the co-simulation of Cruise and Matlab is executed in Japan1015 operating cycle [9], and the results were compared with non-braking energy recovery strategy. In the operation cycle, all of the initial battery SOC were set to 80 %. The parameters of the electric truck are shown in Table 1.

Figure 4 shows the speed track curve at Japan1015 cycle, which suggests that the braking strategy developed in this paper can meet the operation cycle conditions. In Figs. 5 and 6, the current and SOC change under regenerative braking strategy are compared with non-braking energy recovery strategy. In Fig. 5, the current value was positive in some braking conditions with the regenerative braking strategy, which implies that parts of electric energy were recovered. Figure 7 shows that the battery SOC can decrease more slowly under regenerative braking strategy owing to the

Table 1 Parameters of the electric truck

Parameters	Value
Length × Length × height (mm)	7830 × 2470 × 2760
Front body over-hang (mm)	1480
Rear body over-hang (mm)	1830
Wheel base (mm)	4600
Curb weight (kg)	10800
Gross mass (kg)	16000
Maximum velocity (full load) (km/h)	80

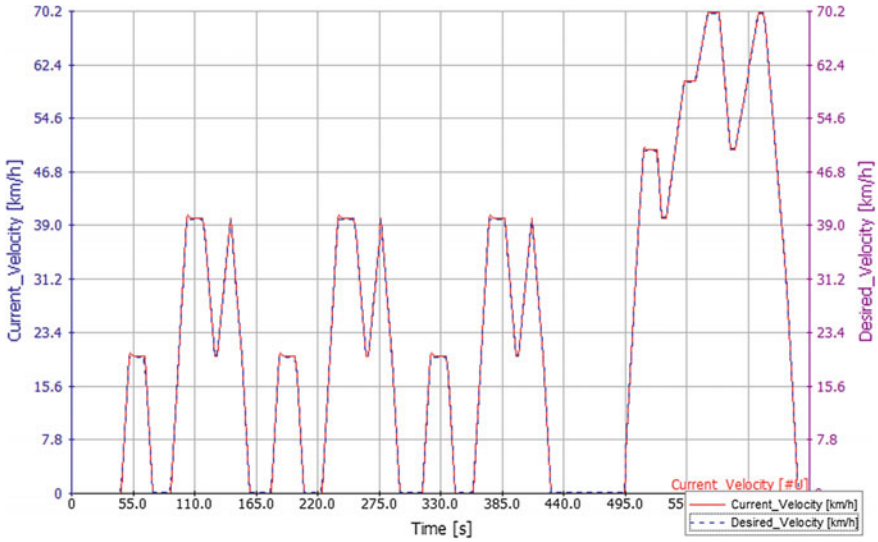

Fig. 4 Speed track curve at Japan 1015 cycle

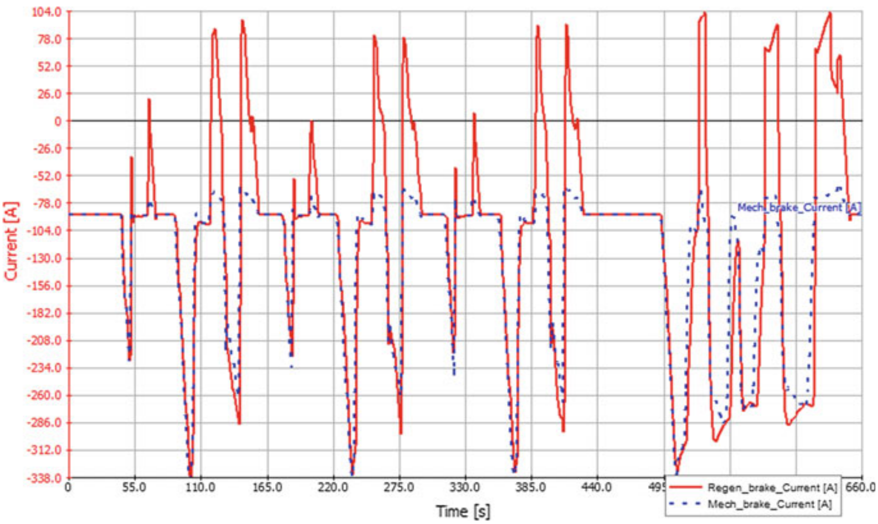

Fig. 5 Current change curves at Japan 1015 cycle

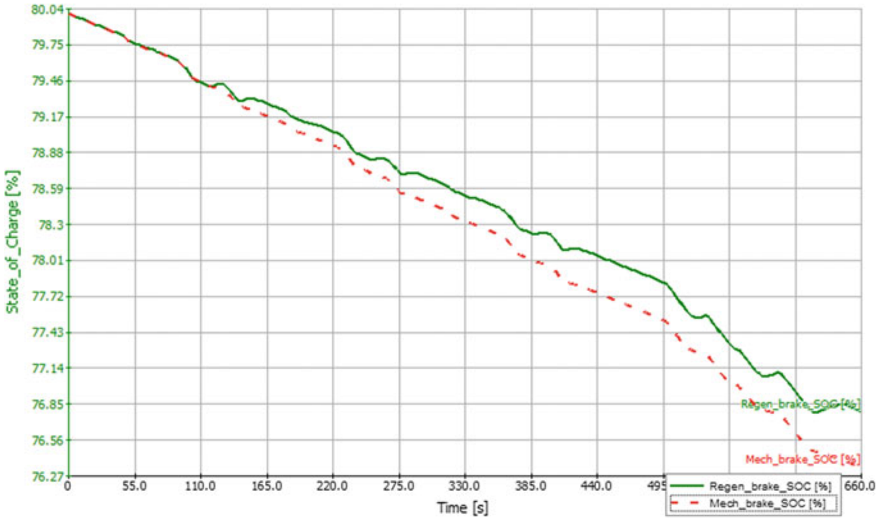

Fig. 6 Battery SOC change curves at Japan 1015 cycle

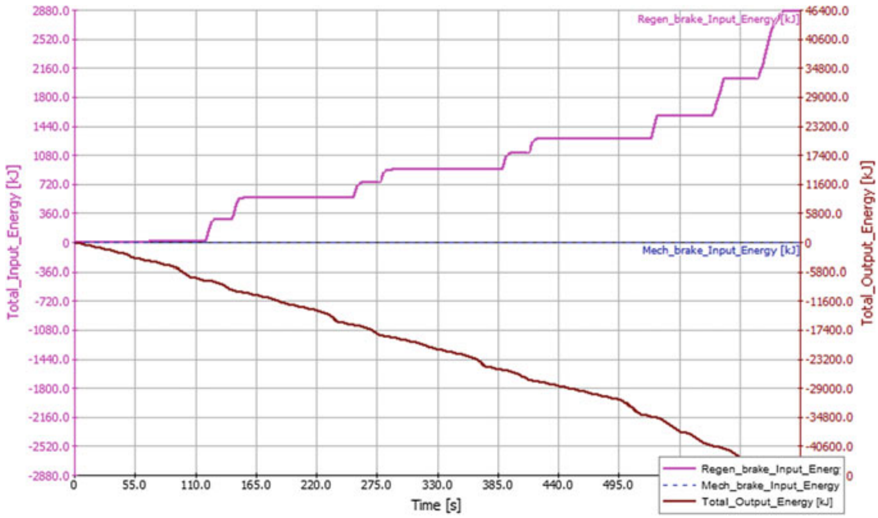

Fig. 7 Energy input and output curves at Japan1015 cycle

Table 2 Comparison between regenerative braking strategy and non-braking energy recovery strategy at Japan1015 driving cycle

Item	Regenerative braking strategy	Non-braking energy recovery strategy
Distance (m)	4163.77	
End SOC (%)	76.6	75.59
battery output energy (kJ)	23965.6	23965.6
battery input energy (kJ)	2752.09	0
energy recovery rate in battery (%)	11.48	0

electric energy recovery, and the end SOC is 76.6 %, which is higher than 1.01 % that using non-braking energy recovery strategy. The energy input and output are shown in Fig. 6. Figure 6 presents that regenerative braking strategy can recover 2752.09 kJ energy while consuming 23965.6 kJ energy in the whole driving cycle, and the energy recovery rate in battery can reach to 11.48 %. The comparison of performance between regenerative braking strategy and non-braking energy recovery strategy in Japan1015 driving cycle are as shown in Table 2. The results indicate that the regenerative braking strategy proposed in this paper can perform a good effect on braking energy recovery, and it could be concluded that using the proposed strategy can improve the economic performance of electric truck. Therefore, regenerative braking is also a useful method to reduce the energy consuming due to the recovery of braking energy.

5 Conclusion

Regenerative braking shows great promise for improving the driving range of electric vehicle. In this paper, a regenerative braking control strategy of electric truck based on braking security was proposed with the considerations of the restrictions of ECE regulations, battery and motor. Then the regenerative braking force allocation strategy was designed, and a co-simulation of Cruise and Matlab about this control strategy was conducted in Japan1015 operating conditions to evaluate the strategy effects. Simulation results show that the regenerative braking control strategy proposed in this paper can recover as much as 11.48 % braking energy in the operating cycle. Consequently, it is affirmed that this regenerative braking control strategy has a great ability to improve the economic performance of electric trucks. In the future, how to recycle more energy under the large braking intensity needs increasing attention.

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References

1. Hellgern J, Jonasson E (2007) Maximisation of brake energy regeneration in a hybrid electric parallel car. J Int J Electr Hybrid Veh 1:95–121
2. Ko J, Ko S, Son H (2015) Development of brake system and regenerative braking cooperative control algorithm for automatic-transmission-based hybrid electric vehicles. J. IEEE Trans Veh Technol 64:431–440
3. Junzhi Z, Yutong L, Chen L (2014) New regenerative braking control strategy for rear-driven electrified minivans. J. Energ Convers Manag. 82: 135–145 (in Chinese)
4. Yimin G, Ehsani M (2001) Electronic braking system of ev and hev-integration of regenerative braking. In: Future transportation technology conference, SAE International, Costa Mesa, pp. 2001–2478
5. Han J, Park Y (2014) Cooperative regenerative braking control for front-wheel-drive hybrid electric vehicle based on adaptive regenerative brake torque optimization using under-steer index. J Int J Automot Technol 15:989–1000
6. Hongwei G, Yimin G, Ehsani M (2001) A neural network based srm drive control strategy for regenerative braking in EV and HEV. In: Electric machines and drives conference 2001 (IEMDC 2001), IEEE International, IEEE Press, Cambridge, pp 571–575
7. Yin G, Jin J (2013) Cooperative control of regenerative braking and antilock braking for a hybrid electric vehicle. J. Math Probl Eng 7:1–9
8. Maia R, Silva M, Arajo R (2015) Electrical vehicle modeling: a fuzzy logic model for regenerative braking. J. Expert Syst Appl 42:8504–8519
9. Farhad S, Vahid E, Hassan N (2008) Effect of different regenerative braking strategies on braking performance and fuel economy in a hybrid electric bus employing CRUISE vehicle simulation. In: 2008 SAE International Powertrains, Fuels and Lubricants Congress, Shanghai, pp 2008-01-1561