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Research on Control Strategy of Regenerative Braking and Anti-lock Braking System for Electric Vehicle

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Abstract

In order to guarantee the premise of braking stability and improve the rate of energy recovery, a modified control strategy based on ideal braking force distribution for the integrated system was proposed, including the coordination control of ABS braking mode. In the study of motor characteristics, battery charging characteristics and ECE regulations, motor regenerative braking torque calculation method was proposed. Control strategy was simulated through AMESim and Simulink co-simulation. A simulation analysis of regenerative braking system performance has been completed in different velocity, braking severity and soc of batteries and three driving cycles. Through urban bus cycle, the correctness of the simulation model has been verified. The simulation results indicate that the vehicle can achieve a better rate of energy recovery and a longer driving range with ensuring braking stability.

Keywords: electric bus; regenerative braking; braking force distribution; anti-lock braking; control strategy

1 Introduction

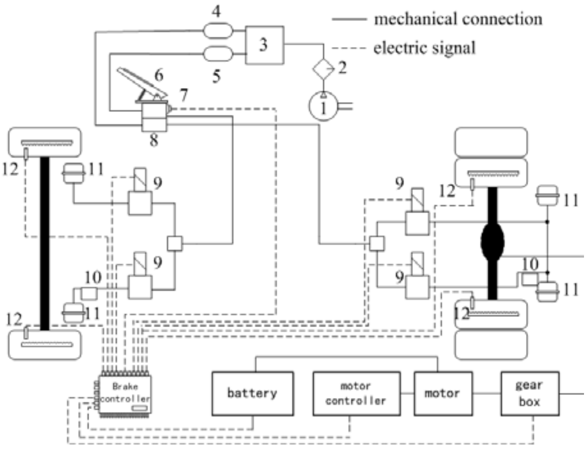
Most traction, which created from engine in public transportation under urban driving circle, becomes fricative heat and loses, because of traffic jam, low velocity, frequent starts and stops. This leads to low energy utilization efficiency, and then research and application for electric bus turn into an emphasis in studies for new energy vehicles. Ratio of braking energy and total driving energy is 48.3% in the case of FUDS (Federal Urban Driving Schedule) driving cycle, while the ratio is 53% in the case of 10-15 driving cycle [1]. Utilization of Regenerative braking system could reclaim partial energy during braking process and extend driving range.

In recent studies for regenerative braking control strategy, the stress is braking force distribution, and control strategy needs to consider braking torque of motor, harmonious management of regenerative braking system and ABS, charge-discharge characteristic in battery, etc [2]. Currently, most electric buses adopt parallel regenerative braking control strategy, which means mechanical braking system and motor braking system function simultaneously. However, this system has problems, such as: constantly operational mechanical subsystem, uncontrollable air braking force, limited recovered energy and easily locked driving axle[3,4].

Based on the original pneumatic brake system, an integrated system of regenerative braking and anti-lock braking has been proposed by increasing the braking controller and pressure sensors. In the study of motor characteristics, battery charging characteristics and ECE regulations, motor regenerative braking torque calculation method was proposed. Motor regenerative braking torque was adjusted by introducing vehicle speed impact factor, battery SOC impact factor, braking strength impact factor. Control strategy was simulated through AMESim and Simulink co-simulation.

2 Structure of Integrated System

The proposed integrated system is an improvement of ABS system. As what is shown in Figure1, equipment of data acquisition is composed of pedal displacement sensor , wheel speed sensor and pressure sensor. Braking controller is the core of the integrated system, and could get information of SOC, gears, motor speed, wheel speed, braking pedal displacement and pressure through CAN bus, and could give ABS valves instruction to make them on/off and control battery controller to make on or off.



1 air compressor; 2 air receiver; 3 Four-circuit protection valve； 4/5 air receiver for front/rear axle; 6 braking pedal; 7 pedal displacement sensor; 8 braking valve;9 ABS valve; 10 pressure sensor; 11 gas chamber; 12 wheel speed sensor

Fig. 1 Structure diagram of integrated system

During braking process, braking controller obtains related information for calculation of braking force distribution by CAN bus, determines braking mode in accordance with control strategy embedded in controller to make the ABS valves on/off and to accurately regulate air pressure and to realize appropriate distribution of front and rear braking force and motor braking force. The motor functions as generator, and the current is stored in battery when the motor provides braking force.

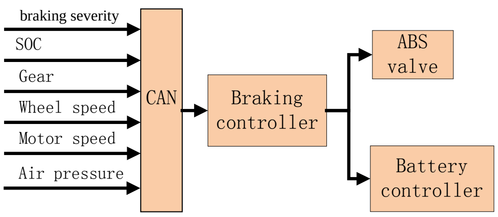


Fig. 2 Input and output of integrated system

3 Control Strategy

3.1 Calculation of motor regenerative braking torque

For regenerative braking control system, the key point is distribution between braking force of front and rear axle, motor braking force and air braking force of driving axle. The strategy should pursue the most amount of recovered energy while guaranteeing braking stability, braking comfort and other safety factors. For regenerative braking control system, the key point is distribution between braking force of front and rear axle, motor braking force and air braking force of driving axle. Calculation of motor regenerative braking torque should include motor characteristics, battery charging characteristics and ECE regulations.

ECE R13 regulation has clear requirements in braking forces of front and rear axle in two-axle vehicles, as follows[5]:

$$\begin{cases} \varphi_f > \varphi_r & 0.15 \le z \le 0.3 \\ z - 0.08 \le \varphi_f \le z + 0.08 & 0.15 \le z \le 0.3 \\ \varphi_r \le z + 0.08 & 0.15 \le z \le 0.3 \\ \varphi_r \le (z - 0.02)/0.74 & 0.3 \le z \le 0.61 \\ \varphi_f \le (z + 0.07)/0.85 & 0.2 \le z \le 0.8 \\ \varphi_r \le (z + 0.07)/0.85 & 0.2 \le z \le 0.8 \end{cases} \tag{1}$$

φ_f is adhere to the coefficient utilization of front axle, φ_r is adhere to the coefficient utilization of rear axle z is braking severity.

So expressions of φ_f and φ_r are put intoequations.1, the relationship between brake force distribution coefficient and braking severity.

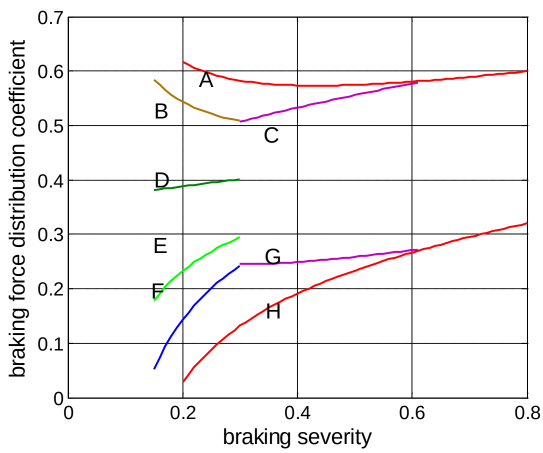


Fig. 3 The relationship between braking force distribution coefficient and braking severity

As shown in Fig. 3, line A is upper control line, line G is under control line, line B is serious upper control line of front axle, line D is serious under control line of rear axle, line E/F are serious control line of rear axle, and line C is control line of anti-lock order. When $0 \le z \le 0.15$, there is no serious requirement; $0.15 < z \le 0.3$, brake force distribution coefficient should be in line B and line

C; $0.3 < z \le 0.8$, braking force distribution coefficient should be in line A and line F.

When the vehicle speed is too low, soc is too high or braking severity is too high, in order to protect the battery system will be no work. So the factor of vehicle speed, soc and braking severity are proposed.

The factor of vehicle speed is defined as follow:

$$w_v = \begin{cases} 0 & 0 \le v < 5km/h \\ 1 & v \ge 5km/h \end{cases} \tag{2}$$

The factor of soc is defined as follow:

$$w_{SOC} = \begin{cases} 0 & 0 \le soc < 0.2 \\ 1 & 0.2 \le soc < 0.9 \\ 0 & 0.9 \le soc \le 1 \end{cases} \tag{3}$$

The factor of braking severity is defined as follow:

$$w_z = \begin{cases} 1 & 0 \le z < 0.7 \\ 0 & 0.7 \le z \le 1 \end{cases} \tag{4}$$

So current motor regenerative braking torque is defined as follow:

$$T_{motor\_reg} = w_v \cdot w_{SOC} \cdot w_z \cdot \min\left\{T_{motor\_\max}, T_{battery}, T_{ECE}\right\} \tag{5}$$

T_{motor_reg} is current motor regenerative braking torque, $T_{motor\_\max}$ is regenerative braking torque of motor, $T_{battery}$ is regenerative braking torque of motor, T_{ECE} is regenerative braking torque of motor.

3.2 Control Strategy on distribution between front and rear axle

A modified control strategy based on ideal braking force distribution for the integrated system was proposed. This strategy is based on the ideal braking force distribution control strategy, and can adjust the pressure of front axle and rear axle to compensate motor regenerative braking force through the ABS valve.

$$\beta_{front} = \begin{cases} 0 & 0 \le z < 0.1 \\ \dfrac{(z-0.1)(2b+0.4hg)}{z \cdot L} & 0.1 \le z < 0.2 \\ \dfrac{(b+z \cdot hg)}{L} & 0.2 \le z < 1 \end{cases} \tag{6}$$

β_{front} is braking coefficient of front axle, hg height of center of mass, L is wheel base.

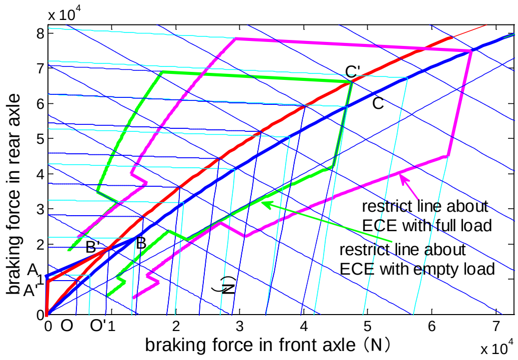


Fig. 3 The relationship between braking force distribution coefficient and braking severity

As shown in Fig. 3, when the rear braking force demand is less than the maximum braking force, rear braking force is all provided by the motor regenerative braking; when the rear braking force is greater than current regenerative braking force of motor at the moment, the motor provides maximum braking force, the rest of the braking force is provided by the rear axle braking force.

3.3 Control logic of braking controller

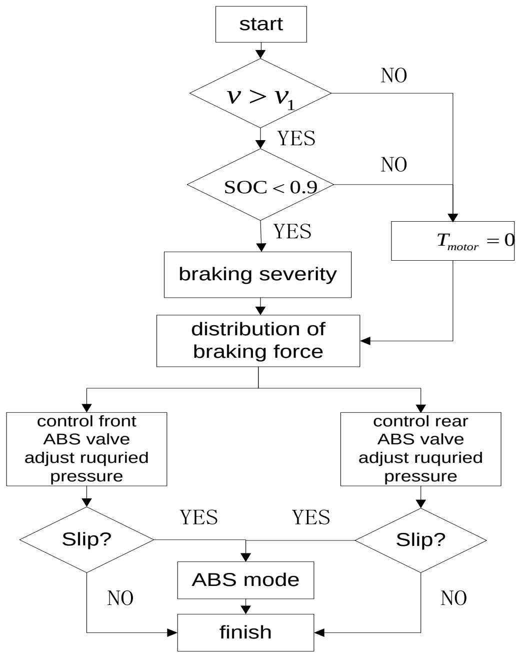


Fig. 4 Logic diagram of control strategy

Fig.4 has shown the logic diagram of control strategy. While low velocity, charging efficiency of motor is very low, motor cannot afford braking torque. Therefore, control logic in this paper introduces min valid velocity called v_1. Only when velocity is larger than v_1, regenerative braking starts effective; while battery has higher soc, braking force of motor will be canceled to protect battery from overcharge. According to the braking severity, distribution between motor braking and gas braking are completed, then the demand of the front and back pressure is calculated, and through adjusting the ABS valve on and off to work it precisely.

While there have slips in front and rear wheels, ABS mode will be effective and its logic tree is shown in Figure 5. It adopts dual-logic-threshold control algorithm for wheel acceleration and reliable slip rate[6].

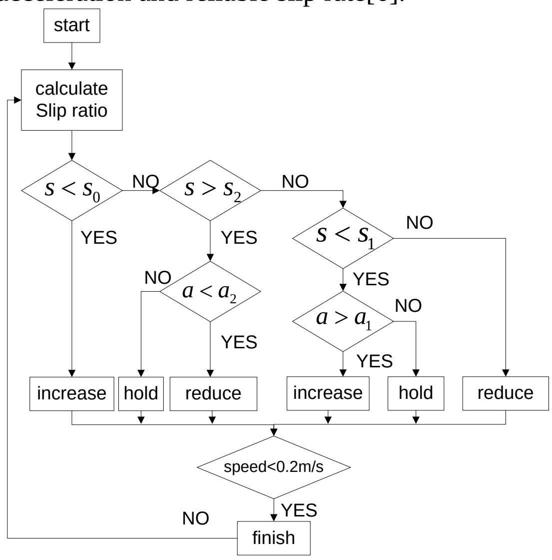


Fig. 5 Logic of ABS model

s_0 is lower control limit of slip rate. s_1 is upper control limit of slip rate. s_2 is trigger threshold of slip rate. a_1 is upper control limit of wheel deceleration. a_2 is lower control limit of wheel deceleration.

4 Modeling

To verify control strategy of regenerative braking and anti-lock braking system, vehicle models are established under matlab/simulink and AMESim, including three degrees of freedom vehicle model, motor model, battery model, driver model, transmission system model , controller model, and air brake system model, and co-simulation is realized. Simulation model for whole vehicle as follow:

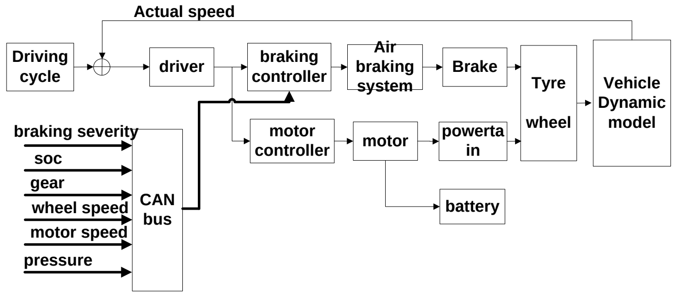


Fig. 6 Simulation model for whole vehicle

4.1 Vehicle dynamic model

3-DOFs vehicle dynamic model has been used and shown in Fig.7, which considers 1 DOF for longitudinal motion and 2 DOFs for wheel running. Fundamental formulas for vehicle dynamic model are as follow[7]:

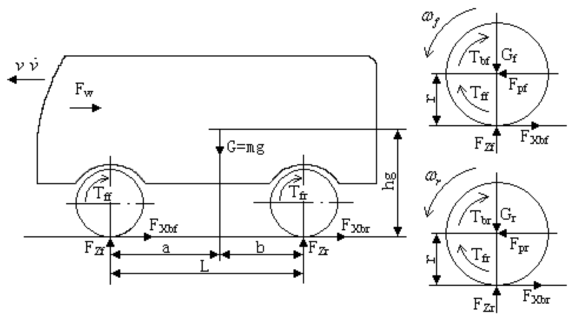


Fig. 7 3-DOFs Vehicle Dynamic Model

$$\begin{cases} I_w \dot{\omega}_i = F_{Xbi} \cdot r - T_{bi} - T_{fi} \\ m\dot{v} = -\left(F_{Xbf} + F_{Xbr} + F_f + F_w\right) \end{cases} \tag{7}$$

Where, I_w is wheel moment of inertia. ω_i is wheel angular velocity. F_{Xbi} is ground braking force. T_{bi} Is braking torque provided by mechanical braking and motor braking. T_{fi} is tire rolling resistance moment. F_f is rolling resistance. F_w is air resistance, which represents front and rear wheel when the subscripts i are f and r .

4.2 Tire model:

$$\varphi(s) = \varphi_o + A\sin \left\{B\arctan[Cs - D(Cs - \arctan(Cs))]\right\} \tag{8}$$

Where, φ_o is adhesion coefficient when wheel runs, which generally is assumed to be 0. A, B, C and D are relative parameters. s is slip rate.

4.3 Battery model

PNGV model has been adopted and this model simplifies actual battery into equivalent circuit shown below.

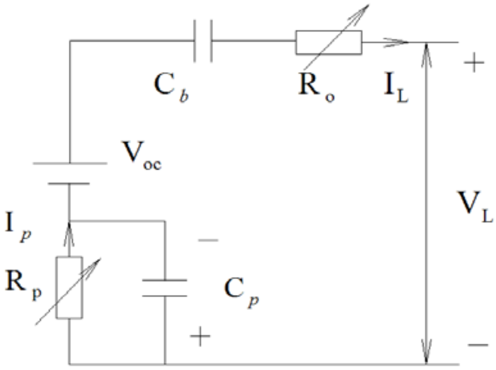


Fig.8 PNGV dynamic battery model

$$\begin{cases} V_L = V_{oc} - \dfrac{1}{C_b}\int I_L dt - R_o I_L - R_p I_p \\ \dfrac{dI_p}{dt} = \dfrac{I_L - I_p}{\tau} \\ \tau = R_p \cdot C_p \end{cases} \tag{9}$$

V_{oc} is open-circuit voltage of battery in specified state of charge. R_o is internal resistance. R_p is polarization internal resistance. C_p is polarization capacity. I_L is load current. I_p is current flowing in polarization internal resistance. V_L is terminal voltage of battery. C_b is equivalent capacity which describe the variation of open-circuit voltage of battery changing along with integration of load current.

4.4 Air Braking System Model.

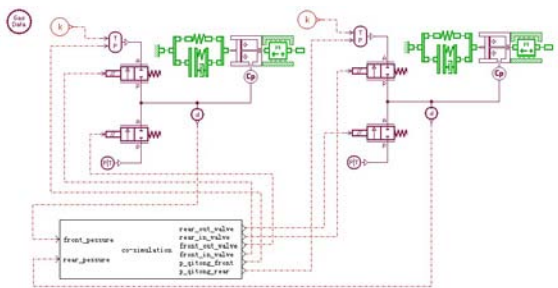


Fig. 9 Air Braking System Model

The model is built by AMESim software, which is a top-ranking, acknowledged simulation platform acknowledged and has high accurate models. ABS of front and rear wheels and air braking system are built, and we could get accurate air chamber pressure curve after united simulation with Simulink. Electromagnetic valve in ABS valve, gas tanks of front and rear axles and braking air chamber all adopt submodule in AMEsim to build models[8].

4.5 Motor model

The rated power is100 KW, and peak power is 150 KW. The rated torque is 477.8Nm, and peak torque is 850Nm. The rated speed is 2000 r/min, and peak speed is 4500 r/min. The characteristic of motor could be shown as follow:

$$T = \begin{cases} T_N & (n < n_N) \\ 9549\dfrac{P_N}{n} & (n < n_N) \end{cases} \tag{10}$$

Where, T_N is rated torque of motor. P_N is rated power of motor. n is rated speed of motor.

The motor characteristic curve and motor efficiency are shown below:

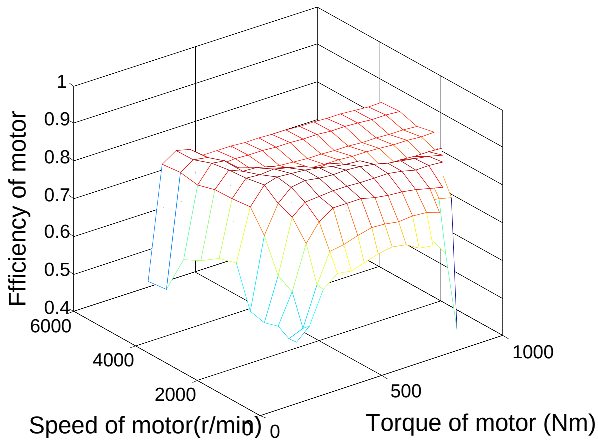


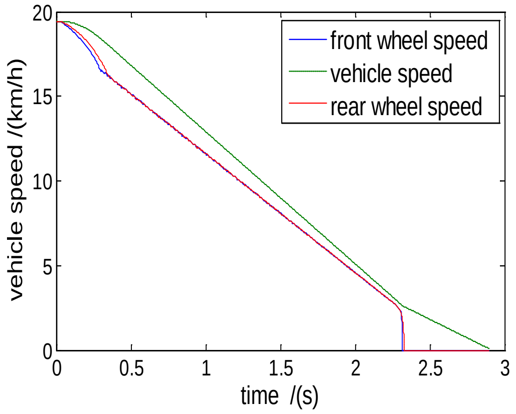
Fig. 10 Efficiency of motor

5 Results

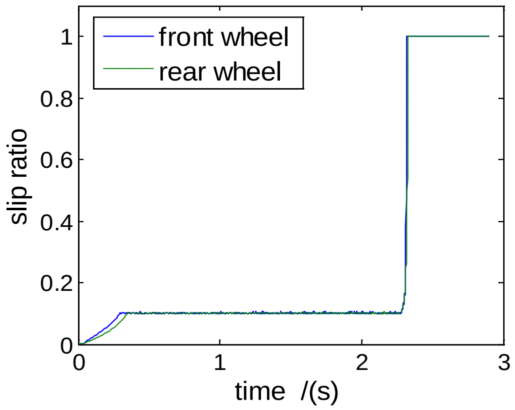
According to the characteristics of the vehicles, different initial speed (40 km/h and 70 km/h), initial soc(0.5 and 0.7), and braking severity(0.1, 0.2, 0.4 and 0.9) are choose to simulate braking characteristics. At the same time in driving cycle simulation, China typical city cycle, the London bus cycle and Beijing transit cycle are choose.

5.1 Simulation of braking characteristics

Fig.11 shows simulations results (v=70km/h soc=0.7、z=0.9). In fig11(a), wheel speed curve and vehicle speed has separated obviously, and the reason is that braking severity is very high(0.9), braking controller turn into ABS model. In fig11(b), slip ratio of front and rear wheel is near the optimal slip ratio, because in ABS model, pressure in braking line is adjusted through ABS valve open or close frequently.



(a) Change of vehicle speed and wheel speed



(b) Change of slip ratio

Fig. 11 Simulation results

(v=70km/h soc=0.7、z=0.9)

Table1: rate of recovery(70km/h)

Braking severity	Soc=0.7	
	Final soc	Rate of recovery（%）
0.1	0.7111	27.90
0.2	0.7053	13.31
0.4	0.7028	7.035
0.9	0.7	0

Table1 is rate of recovery in the condition that soc is 0.7 and velocity is 70km/h. Rate of recovery increased by 27.90%. From the data, rate of recovery decreases with increase of braking severity. Because in control strategy, smaller braking severity means regenerative braking takes up more scale.

5.2 Simulation of driving cycle

China typical city cycle, the London bus cycle and Beijing transit cycle are choose to verify the effects of control strategy with initial soc is 0.2. Fig. 12 is change of soc in China typical city cycle. There is a obvious change between with recovery and no recovery. Rate of recovery can be calculated through these data.

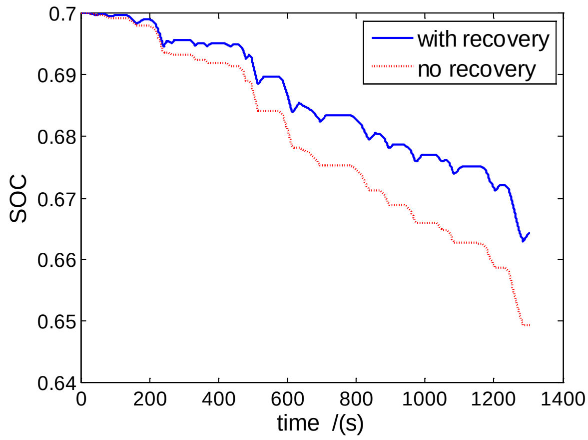


Fig. 12 Change of soc in China typical city cycle

Table2 is rate of recovery in different driving cycle. The data shows that rate of recovery has an obvious increase in all of three driving cycles, especially under London bus driving cycle in which the rate of recovery can be 38.72% because of the low average speed, frequent braking and small braking intensity.

Table2: rate of recovery in different driving cycle

Driving cycle	Ultimate soc		Rate of recovery（%）
	no recovery	with recovery	
China typical city cycle	0.6492	0.6637	28.56
London bus cycle	0.5907	0.6330	38.72
Beijing transit cycle	0.6592	0.6737	35.57

Rate of contribution for driving range is proposed. Specific standards are set as follows: the initial soc is 1, electric car is tested to complete driving cycles, end with soc = 0.2 , then driving distance is calculate. Through comparing distance with recovery or not, rate of contribution for driving range is get.

$$\eta_{reg\_总} = \frac{s_{有回收} - s_{无回收}}{s_{无回收}} \qquad (11)$$

$\eta_{reg\_总}$ is rate of contribution for driving range, $s_{有回收}$ is driving distance with recovery，km, $s_{无回收}$ is driving distance no recovery, km.

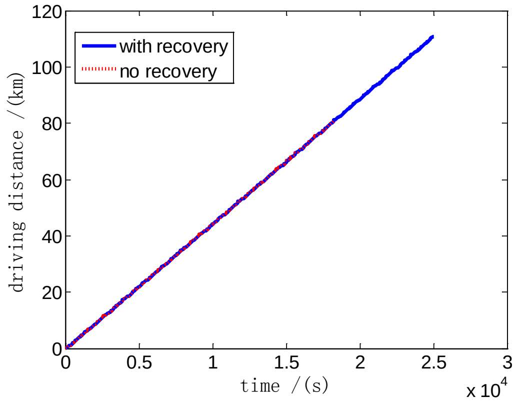


Fig. 13 Driving range in China typical city cycle

Fig. 13 is driving range in China typical city cycle. From the picture, two curves are coincident in general， because in driving cycles, through adjustment (PI) of driver' model , the velocity at same moment is same more or less. Driving range is integration of velocity to time, so the trend of driving range between with recovery or not is similar.

Table3: rate of contribution in different driving cycle

Driving cycle	Driving range（km）		Rate of contribution（%）
	no recovery	with recovery	
China typical city cycle	80.70	110.95	37.48
London bus cycle	79.00	118.3	49.75
Beijing transit cycle	96.9	141.5	46.03

Table3 is rate of contribution in three different driving cycle. In China typical city driving cycle, driving range has increased by 37.48%, so the effect of control strategy is very obvious. At the same time results show that rate of contribution for three cycles has a larger difference. Because comparing with China typical city driving cycle, braking severity of the other two cycles is smaller (less than 0.1), so motor regenerative braking is made full use, mechanical braking is less.

Acknowledgments

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