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Research Effectiveness of Regeneral Brake Energy on Toyota Prius Vehicles by Matlab/Simulink

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Abstract. Regenerative brake control creates an optimal synergy between mechanical and electrical braking. Based on the study of vehicle dynamics under braking conditions propose a new control mode that ensures the best braking performance and maximum braking energy recovery. The implementation of the above control mode requires a combination of the traction control model and the brake control system. The HEV power distribution model is built using Matlab/ Simulink and the simulation results have shown a significant improvement in fuel consumption when using the regenerative braking system.

Introduction

For conventional vehicles, a considerable amount of energy is converted into heat consumed during braking [1, 2]. To save energy, HEV will combine both a mechanical braking system and an electric brake system to both achieve braking efficiency and make the most of regenerative energy. The electric motor converts kinetic energy into electrical energy to charge the battery during braking.

Therefore, regenerative braking is an indispensable element to improve the fuel economy of HEVs. Studies have shown that, depending on driving conditions and control modes, energy regeneration can add 8% to 25% to a vehicle's total energy use [3, 4]. The brake control mode has an important role in recovering as much energy as possible while maintaining the vehicle's stability during braking. Various studies have been carried out on regenerative braking systems to respond to brake control operations based on several rules [5], control strategies using fuzzy logic [6, 7], and control methods. neural network applications [8]. However, these studies mainly focus on improving energy recovery based on conventional factors without considering safety, reliability, and applicability criteria. expectations.

The brake control mode and brake force distribution in HEV proposed by the author in this paper have obtained maximum regenerative energy, safety, as well as easy application. Under braking conditions, the vehicle can achieve optimal regenerative energy efficiency. It can also prevent wheel locking and slippage by distributing the right braking force to the front and rear wheels according to operating conditions. Simulation results have demonstrated the effectiveness of the proposed brake control mode in ensuring safety, braking stability, and improving regenerative energy efficiency

Hybrid Vehicle Brake System

Structure. In hybrid vehicles, the system is combined by two components, the mechanical brake system, and the electric brake system, to optimize braking force and ensure maximum regenerative energy recovery while still ensuring safety. In particular, the braking system on current hybrid models can be controlled separately from the braking torque at the front and rear wheel positions, this system is often combined in the usual form of two. The front wheel uses a combination of electrical and mechanical brakes, while the two rear wheels only use mechanical brakes. Because of such a structure, the energy recovered from regenerative braking is only obtained from braking at the front wheel by an electric motor and charged to a high-voltage battery. This type of structure contributes to a more efficient distribution of braking force between the front and rear wheels. However, if the load placed on the front or rear wheels is changed, the braking performance will also be changed. To maintain vehicle stability during braking, the rear wheels must not be locked in front of the front wheels. Therefore, when studying brake control, it is necessary to study the distribution of braking force between the front and rear wheels, and the distribution of braking force between the mechanical brake system and the electric brake system.

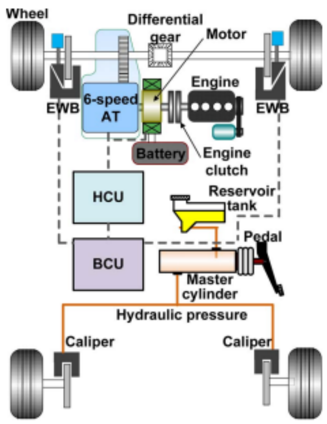

Figure 1. Brake system on HEV.

Facility in Terms of Brake Force Distribution. Figure 2 shows the load shift of the vehicle between the front and rear axles after the vehicle brakes on a flat road. Here it is assumed that rolling resistance and air resistance are ignored because they are very small compared to the braking force. Where j is the deceleration of the vehicle when braking, M is the mass of the vehicle, and the force exerted by the vehicle is shown by Equation 1.

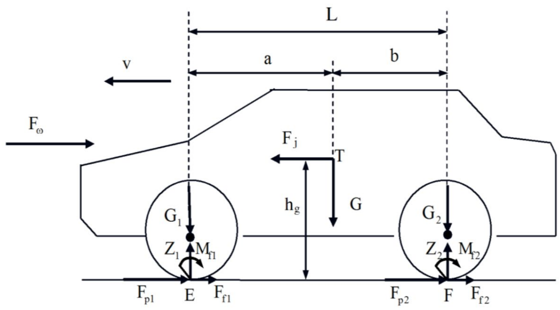

Figure 2. Forces acting on a car when braking on a level road.

$$F = M.j \tag{1}$$

Considering the change of vehicle load from the rear wheel to the front wheel is shown by equation (2) below, and the braking force between the rear wheel and the front wheel is obtained from equations (3) and (4). , where G_1 and G_2 is the load placed on the front and rear axles μ is the coefficient of traction between the wheel and the road surface

$$m = \frac{f.h_g}{L} \tag{2}$$

$$F_{p1} = \mu.(G_1 + m) = \mu.(G_1 + \frac{F.h_g}{L}) \tag{3}$$

$$F_{p2} = \mu.(G_2 + m) = \mu.(G_2 - \frac{F.h_g}{L}) \tag{4}$$

In order to achieve high efficiency and stability during braking, the controller must distribute the maximum braking force to the front wheel and the wrong wheel so that both can lock the wheel at the same time, but without any crash. slide icon. To distribute the braking force according to the ideal curve, it is necessary to determine the coefficient of friction between the wheel and the road surface. However, this coefficient of friction continuously changes with the state of the vehicle and depends a lot on the surface texture of the road surface, so it is difficult to determine this coefficient directly. Therefore, it is necessary to determine the ratio of brake force distribution of the front R_{p1} and rear wheels R_{p2}. These ratios are expressed as equations (5) and (6) and do not depend on the coefficient of friction.

$$R_{p1} = \frac{F_{p1}}{F_{p1}+F_{p2}} = \frac{M_1.g+m}{M.g} \quad (5)$$

$$R_{p2} = 1 - R_{p1} \quad (6)$$

From equations (5) and (6) it is found that the braking force depends only on the load and the acceleration slows down when braking. The braking torque at the front wheel and the rear wheel is determined according to equations (7) and (8)

$$M_{p1} = r.F_{p1} \quad (7)$$

$$M_{p2} = r.F_{p2} \quad (8)$$

To achieve high efficiency and stability during braking, the controller must distribute the maximum possible braking force to the front and rear wheels so that they can lock at the same time. To distribute the braking force along the ideal curve, we need to determine the coefficient of friction between the wheel and the road surface. However, because these coefficients of friction are constantly changing with the operating conditions of the vehicle, it is difficult to determine them directly. Therefore, we need to determine the ratio of brake force distribution of the front wheel (Rf) and the rear wheel (Rr). These ratios are expressed as equations (5), and (6) and they do not depend on the coefficient of friction. Where r is the tire radius [m], g = 9.81[m/s^2] is the acceleration due to gravity.

Consider the same case when the car brakes on a slope. The calculation of the distributed load is as shown in Figure 3, the deceleration is measured by the accelerometer (a_{sen}), equation (9). The braking force is determined by equation (10)

$$a_{sen} = g.\sin(\theta) + j \quad (9)$$

$$M.j = M.g.\sin(\theta) - F \rightarrow F = M.g.\sin(\theta) + M.j = M.a_{sen} \quad (10)$$

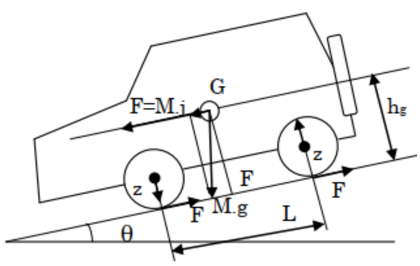

Figure 3. Kinetic model when braking on a slope.

Realizing that the load distribution is estimated by the signal provided by the accelerometer, the ideal braking force distribution can be realized even on flat or steep roads. From the above calculations, ideal braking force control can be achieved by estimating the actual vehicle weight and load distribution using accelerometers [8].

Optimum Control Mode for Energy Recovery During Regenerative Braking. The principle of the control mode is to distribute maximum braking force to the front wheel during braking. Also, ensure the rear wheel is not locked earlier than the front wheel by any coefficient of traction. The greater the braking force distributed on the front wheels; the more energy will be recovered to recharge the High-Pressure Battery. Braking performance requires that no wheels are locked and the braking force on the rear wheel must be higher than the ECE adjustment curve as shown in Figure 4. The braking force on the front and rear wheels depends on the deceleration rate of the vehicle. Vehicle and the coefficient of traction of the road surface [7].

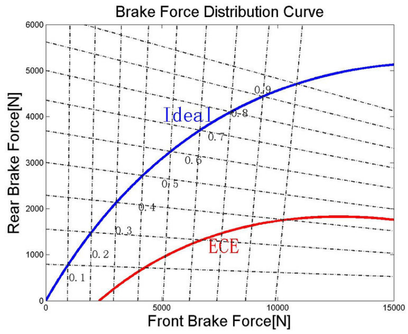

Figure 4. Ideal characteristic of brake force distribution between front and rear wheels according to ECE standards and ideal characteristics.

When the braking force is less than 0.2g (z = 0.2), all braking force will be allocated to the front wheel to use regenerative braking, no mechanical braking force is applied to the front or rear wheels. When the braking degree is more than 0.2g, the new mechanical brake system is started to work. Braking force will be distributed to the front and rear wheels according to the ideal distribution of braking force (I-curve).

At the same time, braking force on the front wheels will be distributed both electrically and mechanically with the maximum amount of energy recovered. The maximum braking power must not exceed the maximum power of the electric motor and the storage capacity of the battery. In addition, the minimum braking power on the rear axle must meet ECE standards. Therefore, the braking force on the front and rear wheels can vary within a certain range. This range is limited by the ideal brake force distribution curve and the ECE curve. However, depending on operating conditions, the braking force will be distributed to meet the maximum energy recovered from the front wheel.

Controller Design. In the research scope of this paper, brake control will focus on the maximum possible regenerative energy recovery efficiency and is controlled by several factors including vehicle speed, braking torque requirement and state of charge (SOC) of the high-voltage battery pack. The SOC of a high-voltage battery can affect the efficiency during the charging and discharging of the assembly. The optimal operation of high-voltage batteries should be controlled between 50% and 80%. The relationships between these elements will be implemented by the Fuzzy Logic controller [9].

Regarding the safety of automobile movement, if the required braking torque is large (in case of emergency), then the regenerative braking torque is now zero (mechanical brake only). Similarly, when the vehicle speed is high, also apply the mechanical brake only. If the vehicle speed is very low, the efficiency of the electric motor is very low, and the regenerative braking is not effective so it is not used [8].

To demonstrate the effectiveness of the brake controller, we use the actual vehicle with the specifications as shown in Table 1 to perform the simulation.

From the above analysis, we can see that the three inputs of the fuzzy logic controller include the required braking torque, SOC, and vehicle speed. To increase generality, all inputs and outputs should be normalized in the range [0, 1]. The definitions of these inputs are listed below. The braking torque is divided into 5 subfunctions in the range [-1, 0] as shown in Figure 5. The braking torque requirement is divided into 5 zones such as VH (very high braking torque), H (braking torque). High), M (Medium braking torque), L (low braking torque) and VL (very low braking torque).

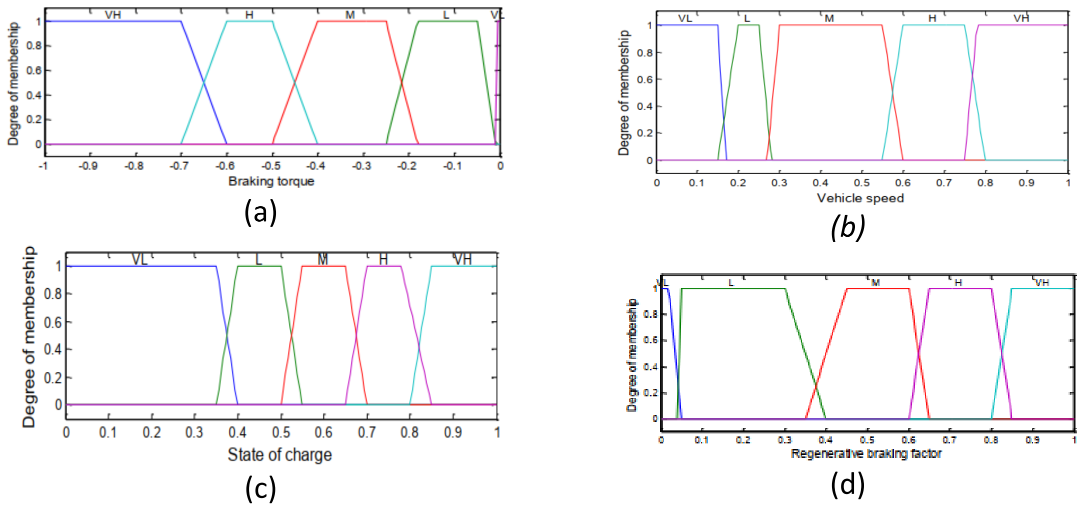

Figure 5. Signal control according to Fuzzy logic, (a) Braking torque; (b)Vehicle speed; (c) SOC, (d) Output signal.

Table 1. Specifications of vehicles included in the simulation.

Specifications	**Value**
Full load mass	1805 kg
The standard long	2.75 m
Car center of gravity	0.76 m
Distance from center of gravity to center of front wheel	0.982 m
Distance from center of gravity to center of rear wheel	1,768 m
Grip coefficient	0.22 -1

Similarly, the vehicle speed and input SOC also have five levels as shown in Figures 6 and 7 respectively. Since the optimal discharge-discharge process of the battery is between 50% and 70% of capacity, the SOC input is concentrated mainly in this region. The component functions are shown in Figure 5 (c).

The output of the brake controller is the ratio of the regenerative braking torque on the front axle to the total required torque. There are 5 component functions, VL, L, M, H, and VH, as shown in Figure 5 (d) .

The brake controller calculates the regenerative braking ratio on the front axle to ensure maximum regenerative energy while ensuring safety. The remaining braking force is distributed to the mechanical braking of the front and rear axles. Figure 9 shows the algorithm flowchart depicting the brake distribution on the front and rear wheels.

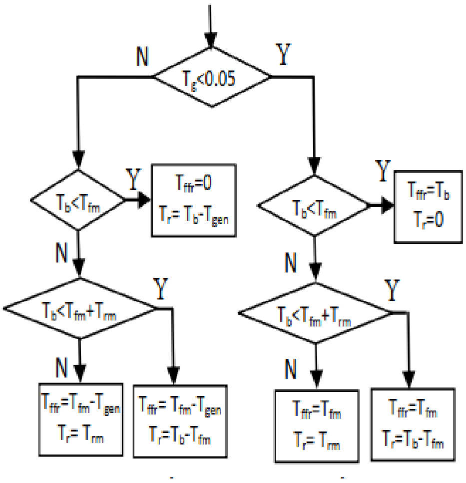

Figure 6. Flow chart of brake torque distribution on the front and rear axles.

In the algorithm flowchart, $T_b, T_{ffr}, T_r, T_{gen}, T_{fm}$, and T_{rm} are torque ratios, respectively.

Regenerative braking and required braking torque, required braking torque, front-wheel mechanical braking torque, rear-wheel mechanical braking torque, front – wheel regenerative braking torque, front-wheel maximum braking torque and rear axle maximum braking torque.

Simulation Results. The brake torque controller has been designed and simulated by Simulink/Matlab on the NEDC (New Europe Driving Cycle) test cycle. Figure 7 shows the desired actual speed of the vehicle and the calculated simulated speed asymptotically close to each other. Figure 8 shows a very high ratio of regenerative braking torque to required braking torque, which means that the brake controller recovers energy during braking very well. Figure 9, shows the change of battery charging status when the vehicle runs on the NEDC cycle. The battery always operates at its optimum range through these driving cycles. Finally, Figure 10 shows the operating points in the electric motor efficiency map. Operating points of a negative torque motor, i.e. the engine acts as a generator. The engine also operates in the high-efficiency area

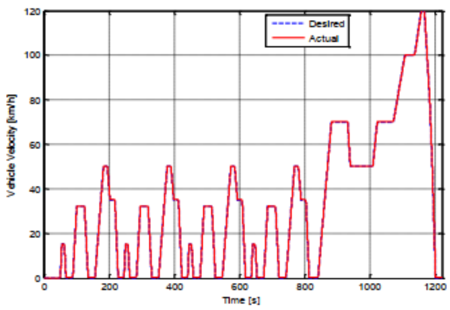

Figure 7. Simulated NEDC velocity.

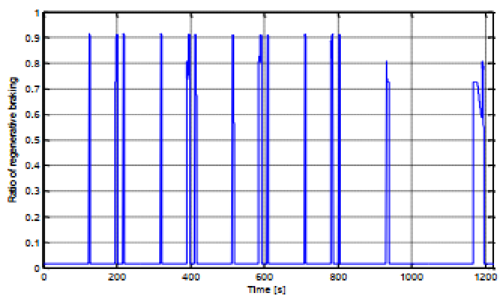

Figure 8. Ratio of regenerative braking torque and required torque.

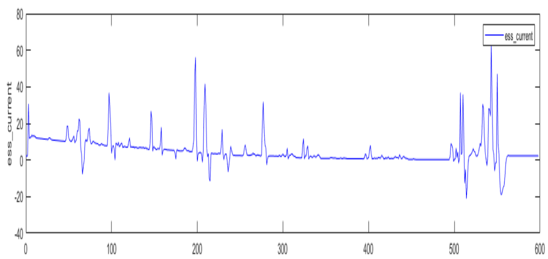

Figure 9. High voltage battery charging current charging status.

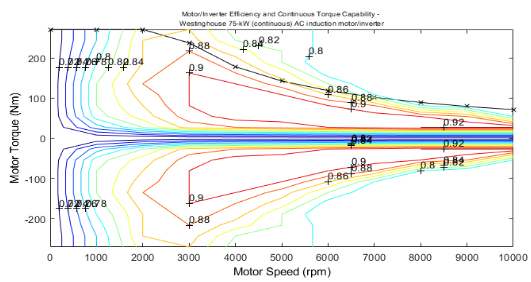

Figure 10. Operating points of electric motors.

From the above results, the model performed with the brake controller using fuzzy logic has achieved higher energy efficiency than the law-based brake controller, especially when the vehicle is operating in urban areas. In the urban driving cycle according to the US federal test cycle - UDDS (Urban Dynamometer Driving Schedule), the car using the regenerative brake controller using fuzzy logic saves 4.6% compared to the system using the controller. Law-based brake control. Similarly, in the NEDC driving cycle, the vehicle using the fuzzy logic regenerative braking system saves 5.25% compared to the braking system with the rule-based controller. All of the parameters are presented in detail between the two simulation cycles in Table 2.

Table 2. Fuel consumption with regenerative braking using the law-based controller and fuzzy logic controller.

CYCLE	*REGULAR (l/100Km)*	*FUZZY LOGIC (l/100 Km)*	*EFFICIENCY (%)*
UDDS	*4,45*	*4,24*	*2,1*
NEDC	*5,76*	*5,51*	*2.5*

Summary

The brake controller using fuzzy logic has been designed and simulated, the results of which have been demonstrated in hybrid electric-motor vehicles with high regenerative energy results. The regenerative brake controller recovered the most energy and ensured safety during braking. Applying fuzzy logic to design the brake controllers with the proposed control strategy got better performance and more fuel economy. The brake controller always meets the requirements of the control process according to the brake pedal signal, the battery always provides enough power to meet each operating mode of the HEVs, and always ensures the stability of the vehicle during braking.

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