Development of TCS Slip Control Logic Based on Engine Throttle Control

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Slip control systems are used to prevent wheel slipping and to improve acceleration performance, stability and steerability on slippery roads through the engine torque and/or brake torque control. This paper mainly deals with the engine control algorithm via adjustment of the engine throttle angle. The slip control algorithm developed in this research includes a control gain scheduling part and a road estimating part to enhance control performance. Various actual vehicle tests have been carried out on low friction roads in order to verify the developed slip control algorithm. The test results show that the controlled vehicle is superior to the non-controlled vehicle in acceleration performance and stability.

Key Words: Slip Control, Traction Control System(TCS), Throttle Control, Road Estimation

1. Introduction

Vehicle active safety systems have been developed thanks to the recent advances in control and electronics technologies. One of such active safety systems, a Traction Control System (TCS), improves the vehicle acceleration performance and stability, particularly on low-friction roads. The TCS is classified into slip control and trace control parts. The slip control system is the one that improves acceleration performance by preventing any excessive slip developed at start-off or during acceleration on low-friction or split-μ roads. On the other hand, the trace control system enables the vehicle to follow the desired course by preventing excessive lateral acceleration of the vehicle while the vehicle is accelerated during turning.

The TCS can be implemented by either an engine control or a brake control approach. In some cases, the above two approaches are simultaneously used for better performance, but most TCSs implement one method for an economic reason. In this research, the engine control-based TCS is mainly dealt with. Furthermore, the engine torque is to be controlled by adjusting the throttle valve opening, although it can also be controlled by adjustment of the amount of injected fuel and/or ignition timing. (Ise et al., 1990 and Yamada et al, 1991)

In this research, the control logic for the TCS slip control system was developed. The developed algorithm shows robustness over various types of roads at a wide range of vehicle velocities. Two features of the logic are as follows; one is the function to adjust the target slip ratio based on the determination of the roads and the other is the function to vary the control gains according to the vehicle velocities. The developed TCS slip control system was tested on the proving ground for various types of roads and driving conditions.

Chapter 2 deals with the concept of TCS and the engine-based TCS slip control logic that is applied to the vehicle test. Chapter 3 explains the test equipment and the test method. Chapter 4 provides the test results for various types of the roads and Chapter 5 concludes this paper.

2. TCS Slip Control Algorithm

This chapter provides a brief introduction to

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the TCS slip control and the developed control logic that is applied to the vehicle test.

2.1 Introduction to TCS slip control

In general, the acceleration performance of a vehicle is limited by two factors. (Gillespie, 1992) The first factor is the power produced by the engine and delivered to the driving wheels through the powertrain. This driving torque is converted to tractive force used to overcome the various loads and to accelerate the vehicle if there is a sufficient friction between the tire and the road. The second factor limiting the acceleration capability is the maximum traction limit that the tire-road contact can support. This factor is especially important on low-friction roads such as snowy, icy and rainy roads. In this case, the maximum tractive force is limited by the friction force (i. e., the product of the friction coefficient and the normal load due to the vehicle weight) between the tire and the road, regardless of the amount of power delivered from the powertrain. Therefore, part of the driving torque coming from the engine is converted into tractive force, and the remaining torque causes the driving wheels to spin excessively, thus resulting in the decrease of friction coefficient. As a result, the tractive force is further decreased and then the acceleration performance deteriorates. Thus, it is important that the maximum friction coefficient be maintained on the low-friction roads. (Wong, 1978)

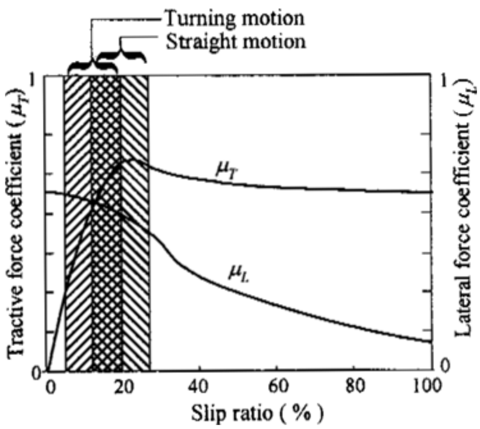

Fig. 1 Tractive and lateral force coefficients as a function of slip ratio.

Among many factors which affects the friction coefficients, one factor that can vary during the vehicle operation with relative ease is the slip ratio that is defined as

$$\lambda = 1 - \frac{V_v}{V_w} \times 100(\%) \qquad (1)$$

where λ denotes the slip ratio, V_w the velocity of the driving wheel (angular velocity of driving wheel(ω_w) $\times$ tire radius(r_w)), V_v the vehicle velocity, respectively. Figure 1 shows the tractive and lateral force coefficients as a function of slip ratio. Note that the friction force is the resultant force of the tractive and lateral forces, but in the longitudinal slip control system the tractive force coincides with the friction force. As shown in Fig. 1, the tractive force becomes 0 when λ=0% and maximum around λ=10~20%. The slip ratio corresponding to the maximum tractive force depends on the road conditions and types of tires. On the other hand, the lateral force which maintains directional control of the vehicle decreases steadily with increasing λ.

In order to improve acceleration performance, the tractive force coefficient should be maximized. Excessive engine power caused by the driver's indiscreet operation of the accelerator pedal tends to decrease the tractive friction coefficient. Thus, some means to ensure the optimal slip ratio for the maximum tractive force regardless of the driver's action is needed, and this is implemented by the slip control function of the TCS.

The basic approach to the slip control system is as follows. (Song, 1998) From the definition of the slip ratio (i. e., Eq. (1)), the target driving wheel velocity is determined by

$$V_w^* = V_v / (1 - \lambda^*) \qquad (2)$$

where λ^* is the optimal slip ratio for the current road condition, the vehicle velocity V_v is estimated from the driven wheel velocities. It is noted that both the driving and driven wheel velocities are measured by use of the wheel speed sensors that are integral parts of the ABS system. Then the velocity error defined as $e = V_w^* - V_w$ is estimated and the PI control scheme is utilized to minimize the velocity error. That is, the PI controller computes the throttle angle to achieve the

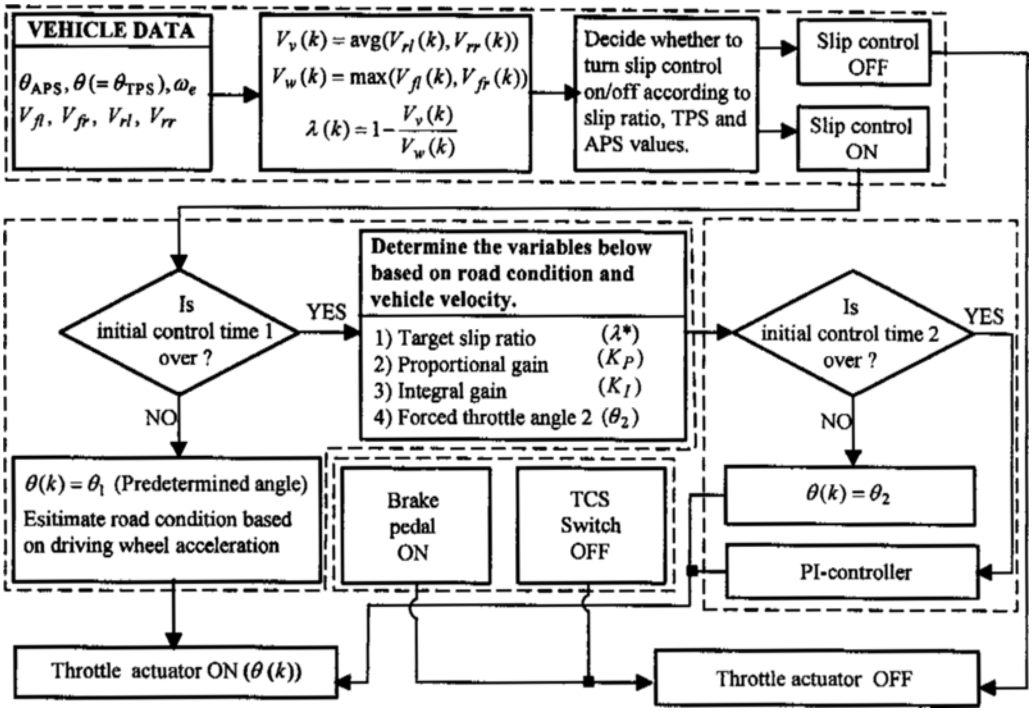

Fig. 2 Block diagram of TCS slip control algorithm.

desired slip ratio and this angle is implemented by means of throttle actuators that are mostly driven by an electric motor.

2.2 TCS slip control algorithm

The slip control system through the throttle control attempts to maintain the optimum slip ratio that maximizes the tractive force between the road and the driving wheels. Therefore, the driving wheel and vehicle velocities used to define a slip ratio are chosen as the control variables.

Figure 2 illustrates the block diagram of the overall TCS slip control algorithm, where the front wheel drive vehicle with manual transmission is assumed. The slip control algorithm developed in this research consists of 3 major parts; control decision part, initial control part, and main control part. The control decision part determines whether a slip control function is activated or not by analyzing the information from various vehicle sensors. The purpose of the initial control part is to quickly decrease excessive slip at the beginning of the slip control and estimate the road types. Finally, the main control part is to implement the digital PI controller to achieve the maximum acceleration performance and stability after reduction in the initial excessive slip. In what follows, details of 3 major parts will be given.

The control decision part monitors the amount of slip from the information based on the 7 measurement data and is continually operated not only during the slip control action but also during normal driving conditions. These 7 data are APS (Accelerator Position Sensor), TPS (Throttle Position Sensor), engine RPM sensor and 4 wheel speed sensors. The APS measures the throttle angle θ_{APS} set by the accelerator pedal position, while the TPS measures the throttle angle $\theta(=\theta_{APS})$ set by the throttle actuator system. Note that the throttle angles for the fully-closed and wide open throttle positions are defined as 0° and 90°, respectively. Thus, θ is less than θ_{APS} during the slip control action, but both angles become equal when it is not activated. On the other hand, ω_e represents the rotational speed of the engine, V_{fl} and V_{fr} represent the velocities of the front left and right wheels (here, the driving wheels), V_{rl}

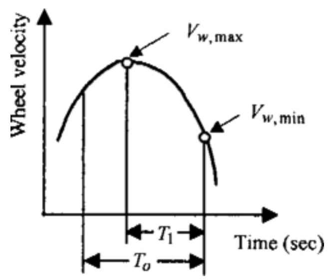

Fig. 3 Maximum and minimum wheel velocites for computation of deceleration.

and V_{rr} represent those of the rear left and right wheels, respectively.

The vehicle velocity is computed as an average of the rear wheel velocities (assuming the front wheel drive vehicles). Since slip may occur at only one driving wheel (e. g., on the split road), the higher one of the two is taken as the driving wheel velocity for computation of the slip ratio. The slip ratio is then given by Eq. (1) from the measured driving wheel and vehicle velocities. When the slip control is not in action, it is initiated if the computed slip ratio $\lambda(k)$ at time k is greater than the predetermined value $\lambda_{control}$. Once the slip control is activated, the slip ratio quickly reduces and then $\lambda(k)$ is less than $\lambda_{control}$.

In the beginning of the initial control part, the throttle valve is forced to close to the predetermined angle θ_1 (about 4°) for T_0 seconds in order to reduce excessive slip. Since an excessively quick reduction in the throttle angle may affect the ride comfort, the throttle angle is gradually reduced to θ_1 through 7 steps. At the very beginning, the driving wheel velocity first increases due to the time delay associated with the engine and power train even after the sharp decrease in the throttle angle, but it eventually decreases. For this period, the maximum and minimum wheel velocities are measured and the average deceleration a1 is computed as

$$a_1 = (V_{w,max} - V_{w,min}) / T_1 \qquad (3)$$

where T_1 is the time between the maximum and minimum velocities. Notice that T_1 is the integer multiple of the sampling period T_s of the control system which is 20msec in this case. Then, based on the amount of deceleration a1, the road is divided into three types as shown in Table 1. For example, reduction of the throttle angle to θ_1 makes the wheel velocity drop much more quickly in road C (i. e., higher friction coefficient) than in road A (i. e., lower friction coefficient).

Table 1 Surface conditions of the various roads.

	Road A	Road B	Road C
Friction coefficient	0.05~0.2	0.2~0.4	0.4~0.6

Once the road type is estimated, the corresponding target slip ratio is also determined from the look-up table. Lower target slip ratio is assigned to the road with a lower friction coefficient.

After the initial control part makes the vehicle stable by reducing excessive slip, the main control part attempts to improve acceleration performance. First, the target wheel velocity $V_w{}^*$ is computed by Eq. (2) with the target slip ratio λ^* determined in the previous stage based on the specific road type. Then the throttle angle is computed by the PI controller to minimize the error $e = V_w{}^* - V_w$.

$$\theta(k) = \theta(k-1) + (K_P + K_I)e(k) - K_P e(k-1) \quad (4)$$

where K_P and K_I represent the proportional and integral gains, respectively. Note that the value of K_P is adjusted so that K_P decreases as the vehicle velocity increases. The reason is as follows. For a high vehicle velocity, the error e also becomes large. Thus, the computed throttle angle may have large variation with a large value of K_P. It may have an adverse effect on the ride comfort due to great change in the engine output.

The value of the throttle angle of Eq. (4) is sent to the throttle actuator in which the position control system regulates the throttle valve to the desired throttle angle. During this process, the throttle angle is gradually increased and thus the vehicle is accelerated.

3. Test Vehicle and Test Method

3.1 Test vehicle

Figure 4 shows the setup of the test vehicle used in this test. As shown in the figure, the system

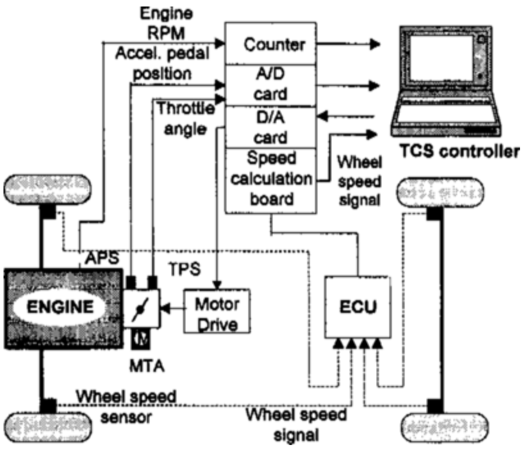

Fig. 4 Configuration of the TCS slip control system.

consists of the TCS slip controller which takes charge of the slip control function, the throttle actuator system where the DC motor and throttle valve are connected by the 4-bar linkage and the data acquisition board which collects the data from various sensors. A Notebook computer was used as a main controller that computes the target throttle angle and performs various auxiliary functions.

The throttle actuator system developed for the TCS is integrated with the ordinary throttle body. (Song et al., 1997) That is, a single throttle system functions either as an ordinary throttle body linked to the accelerator pedal or as an electric throttle system controlled by the throttle actuator system. In the throttle actuator system, the throttle valve is directly linked to the accelerator pedal and rotates between the fully-closed throttle (i. e., $\theta=0°$) and the wide open throttle (i. e., $\theta=90°$). The throttle valve position is limited to the throttle angle position set by the accelerator pedal and the fully-closed position, but within these limits the throttle valve can freely rotate to the angle set by the throttle actuator system. When the slip control function is not further required, the motor is deenergized and the traction spring returns the throttle valve to the throttle angle set by the accelerator pedal position. Hence, the main purpose of the throttle actuator system is to position the throttle valve to the angle commanded by the TCS slip controller. In order to drive a DC servo motor, a PWM signal generator and a PWM amplifier based on H-bridge configuration were built and interfaced to the motor. The TCS slip controller uses 20kHz PWM frequency to avoid audio frequency range in which this signal may be a source of audible noise.

The data acquisition board collects various data. The APS and TPS signals are analog and are converted by A/D converters. The signals from four wheel speed sensors are in the form of pulses, and thus the period between the pulses are measured and the velocities are estimated.

3.2 Test method

The acceleration test method was adopted in order to evaluate the acceleration performance. (SAE, 1996) In this method, the operator drives the engine at the speed of about 5,000rpm by pressing the accelerator pedal while holding down on the brake pedal and then releases the brake to accelerate the vehicle abruptly from a stand-still position. The velocity and the travelling distance in 9 seconds are measured and these values are used to evaluate the acceleration performance for the controlled and non-controlled vehicles.

Three types of roads summarized in Table 1 were tested. Road A and B simulate the icy and snowy roads, respectively, and Road C represents a wet asphalt. The weight of the test vehicle is about 1,200kg and the total weight including the operators and test equipment was approximately 1,350kg.

4. Test Result and Consideration

Vehicle tests were conducted for various roads with different friction coefficients mentioned in Table 1, and some typical results are shown below. Figure 5 shows the vehicle responses on Road B when the slip control was not in action. For safety reasons, the throttle valve was limited to about 20°, and the engine and transmission was abruptly connected by the clutch operation when the engine speed reached 5,000rpm. As shown in the figure, excessive slip occurred at the driving wheels and thus sufficient tractive force could not

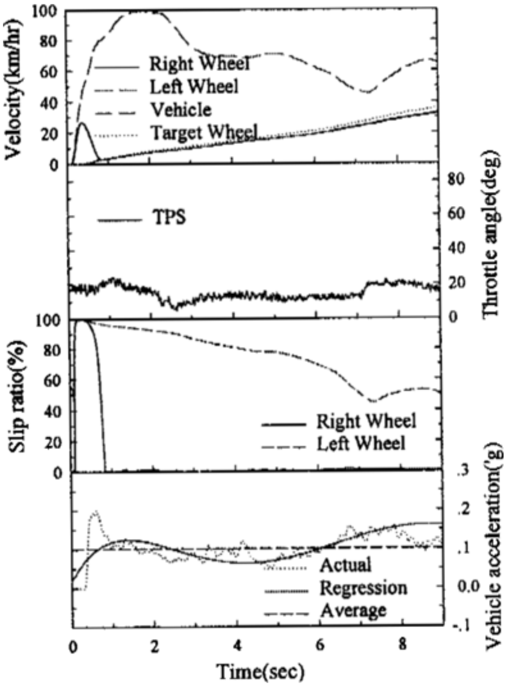

Fig. 5 Vehicle responses when the slip control system is not in action on Road B.

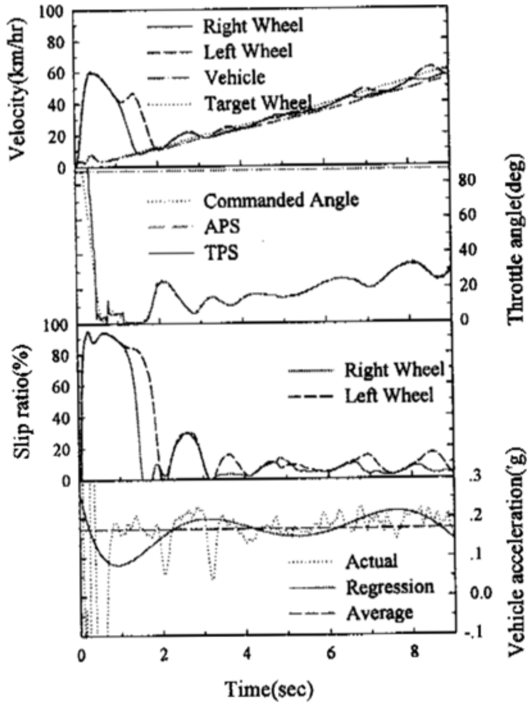

Fig. 6 Vehicle responses when the slip control system in action on Road B.

be developed. As a result, the average acceleration was about 0.10g for 9 seconds, and the vehicle velocity reached about 32km/h in 9 seconds.

Particularly, the sensitivity of the driving wheel to the low friction roads is so great that the velocity difference between the left and right wheels became very large even in this apparently uniform road. In Fig. 5, the velocity of the left front wheel is much larger than that of the right front wheel. The friction coefficients for both wheels are slightly different even for the uniform road. Although this amount of difference in friction does not affect the driving on normal roads, it can greatly affect the driving on low friction roads. That is, the wheel with a higher friction produces a higher velocity than the other and this difference is amplified by a differential action. Due to this velocity difference, the yawing phenomenon occurs, which usually happens when the vehicle turns, so the vehicle's directional stability deteriorates.

Figure 6 shows the vehicle responses when the slip control logic is applied. In this test, the throttle was forced to be held at wide open throttle throughout the test. This is the worst case and thus seldom happens in a real driving situation on the low-friction roads. Due to this extreme condition, excessive slip occurs, thus leading to the slip ratio of 90%. However, as the slip control function is activated, the throttle angle quickly decreases close to the fully-closed throttle position and then it gradually increases for acceleration performance. Compared with the non-controlled results shown in Fig. 5, the average acceleration becomes 0.16g, thus showing improvement by 60%. This is achieved by reducing the excessive slip and maintaining the optimal slip ratio corresponding to the best tractive force. Consequently, the vehicle velocity reaches approximately 55km/h in 9 seconds.

In addition to the acceleration performance, the vehicle stability improves by reducing the slip ratio. At the high slip ratio, the lateral force coefficient is so low that the lateral force is insufficient to maintain directional stability of the vehicle. However, directional stability can be maintained if the slip ratio is optimally controlled.

The plot of the vehicle acceleration in Fig. 6 shows a large variation, while such variation is not shown in Fig. 5. Such variation is due to the pitching motion of the vehicle since for the controlled vehicle the throttle angle reaches a wide open position and thus the engine output response get violent. Such a vibration at the startup of the vehicle may cause ride discomfort. However, the above test condition is very extreme, and in a real driving condition no one tends to press the accelerator pedal to the bottom and such a problem is not likely to take place.

The initial control part in the beginning of the slip control successfully estimated the actual road type. The data obtained from the tests conducted on Road A and the split road (composed of Road B and wet asphalt) show the similar results and the controlled vehicle yields much better acceleration performance than the non-controlled one. On Road A, the velocities of the non-controlled and controlled vehicles were 22km/h and 47km/h, while on the split road were 28km/h and 57km/h, respectively.

Figure 7 shows the vehicle responses on the split roads. As shown in the figure, the right driving wheel is on Road B while the left driving wheel is on the wet asphalt. Without any control action, the vehicle tends to rotate toward the lower-friction road since the tractive force on the higher-friction road is greater than that on the lower-friction road. However, The vehicle responses show that excessive slip at the lower-friction road has been substantially reduced by means of slip control. It is usually known that a brake-control approach is more effective on the split roads than an engine-control approach since the former can have the individual control for the driving wheels. The engine-control approach alone can also have a substantial effect on directional stability on the split roads.

Figure 8 represents the driving distances for the non-controlled and controlled vehicles for 9 seconds. As shown in the figure, the controlled vehicle shows much better acceleration performance than the non-controlled one.

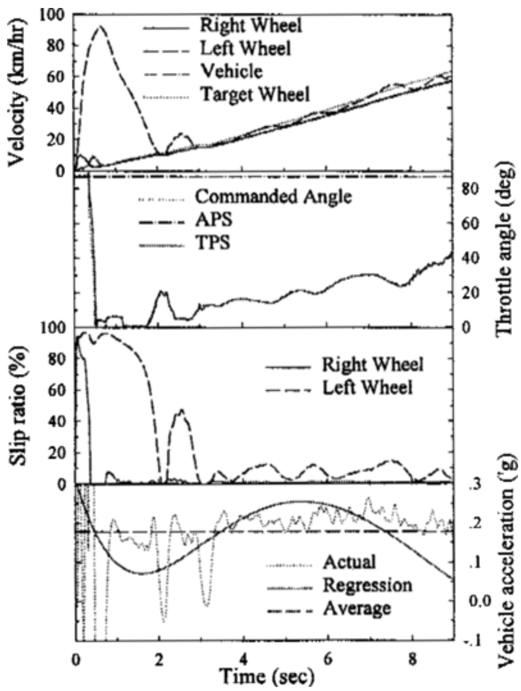

Fig. 7 Vehicle responses with the slip control system in action on split roads composed of Road B and wet asphalt.

5. Conclusions

In this paper, the engine-based TCS slip con-

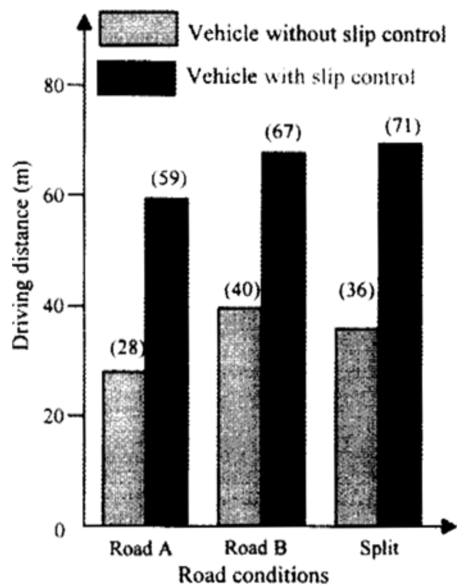

Fig. 8 Comparison of a controlled and a non-controlled vehicles.

trol algorithm was proposed and verified by various vehicle tests. From this study, the following conclusions can be drawn:

(1) The vehicle with the developed slip control algorithm shows better performance in acceleration and directional stability compared with that of the non-controlled vehicle.

(2) Road estimation and target slip ratio adjusting parts and control gain decision part in the proposed scheme show robustness to various types of roads at a wide range of vehicle velocities.

(3) The yawing phenomenon due to the difference in tractive forces of the driving wheels on split roads may increase the accident possibility, but slip control system can reduce this significantly.

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