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Original Research Article

Development of Test Methodology to Reveal Effects of Changes in Damping Capacity of Damper on ABS Braking Performance

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Abstract

This paper aims to develop ABS test methodology for determining the effects of changes in damping capacity of shock absorber on ABS braking performance of a passenger vehicle. For this aim, the performance tests of ABS are separately conducted on wet and slippery surfaces of rough road by using three different damper stages. Thereby, the effects of all stages of damper on ABS braking performance are individually investigated. The test results show that this test methodology provides the effects of changes in damping capacity of damper on braking performance of ABS to be occurred in accordance with the changes in braking distance.

Keywords: Experiment, Methodology, damper, ABS.

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1. Introduction

Antilock Brake System (ABS) is one of the most important vehicle safety systems. At present, this importance considerably increases, because ABS has been used as a standard in all vehicles. ABS considers that maximum effective braking can only occur, when the braking force applied to the wheel matches the grip imposed between the tire and road surface. For this, ABS controls slip ratio by modulating brake pressure. Thereby, ABS aims to sufficiently exploit from available braking force potential based on the changes in road grip [1,2]. In here, it is remarkable point that the road grip strongly depends on the vertical load acting on the wheel. The vertical loads are differently distributed on wheel during cornering and longitudinal motions of vehicle. Therefore, the braking force distribution and braking performance of ABS vary according to the motions of vehicle. This requires the performance of ABS to be measured in different test conditions. For this reason, a number of braking tests are conducted during straight line, transition, curve, J-turn and single lane change. In order to simulate every road conditions for the straight line braking tests of ABS, the different road surface types are designed. These road surface types are dry asphalt, wet asphalt, wet polished concrete, wet epoxy (asphalt covered with a coating used on factory floor) and loose gravel. The wet polished concrete simulates a heavily worn road. The wet epoxy road types show badly worn wet roadways. The loose gravel road simulates uneven roads. As for the transition road tests, they represent a situation where the friction coefficient changes during ABS-braking. The aim of these tests is to evaluate system response to a sudden change in road surface [3,4,5].

In addition to these ABS-braking maneuvers, other braking tests are conducted for special aims. One of the most important of these is the tests based on the effects of damper on braking performance with ABS or without ABS. Vaculin et al. investigate the influence of deteriorated suspension components on ABS braking by measuring the elastokinematic properties of a vehicle suspension [6]. The results indicate that the influence of the worn components on the braking performance of the vehicle with ABS is more significant than that without anti-lock brakes. They also determine that the stopping distance is longer with defective shocks. Calvo et al. focus on the influence of worn damper on braking performance. For this, several shock absorber conditions are considered from new to high wear stages in certain steps to simulate progressive wearing. They conduct smooth and rough road tests. The results indicate that the shock absorber status has a significant influence on the stopping distance under rough road conditions. Also, they reorted that this influence is not significant when the damping coefficient is within the acceptable values suggested by the authors [7]. As a result, a number of different test methodologies are used for exploring ABS performance. This shows that ABS performance is very important for vehicle safety.

In addition, the recent studies indicate that the changes in damping capacity of dampers have a considerably important effect on ABS braking [8,9,10,11]. Also, many automotive companies integrate the suspension system of vehicle into ABS braking system for safer vehicle. This shows that the ABS-braking performance of the vehicles, which have this integration, gains great importance. Thus, in this study, it is aimed to determine the influence of damping capacity changes on ABS braking performance. For this, firstly, the dampers are set to respectively three different damping stages. Then, the rough road is designed. For this, the wooden planks are transversely mounted to the road surface underneath the rubber carpet. The wavelength of the rough road is determined according to the resonance frequency of axle-wheel assembly. After designing the test road, ABS road tests are conducted for hard, medium-hard and soft dampers on wet and slippery road surfaces. Finally, the test methodology to detect the effects of damping capacity changes on ABS braking performance is developed.

2. Experimental Materıal and Methods

2. 1. Test Road

In order to conduct ABS braking tests, the rubber carpet which has 80 m length and 6 m width is covered onto the road as shown in Fig. 1a. This test road contains two different areas.

a b

Figure 1. (a) Rough ABS test road (b) Test areas of test road and the car position on the test road

These are smooth and rough areas as shown in Fig. 1b. The smooth area is used for initiating braking maneuver with ABS. The rough area is designed for performing a hard environment of braking with ABS. The smooth area has same friction coefficient as rough area. When the rubber carpet is dry, the friction coefficient is 0.8 at smooth and rough areas. When this carpet is wetted by only water, the friction coefficient approximately is 0.6 and the test road becomes wet. Also, when the road is wetted by soapy water, the friction coefficient of the road is decreased to 0.3 and the test road becomes slippery.

In here, in order to obtain the rough road area as shown in Fig. 1, the wooden planks are transversely mounted to the road surface underneath the rubber carpet. The distance between the right-most position of the left-hand side bump and the left-most position of the right-hand side bump determines wavelength. It is experimentally described with the resonance frequency and vehicle speed as follows:

$$L = \frac{1}{f} V_x \qquad (1)$$

Where L is wavelength of test road, f is the resonance frequency of the axle mass (unsprung mass) mounted to suspension system and V_x is the vehicle speed. According to Eq. (1), in order to determine the wavelength of the road, the resonance frequency and the braking initial speed of the vehicle body should be calculated. Firstly, the resonance frequency of unsprung mass is determined using test equipment as shown in Fig.2a. The ride vibrations are described as oscillations of the vehicle in the frequency range from 1 to 25 Hz [12]. Also, they state that the higher frequency suspension modes such as tire hop near 15 Hz are more evident in the undulated road surface. In order to determine the resonance frequency of unsprung mass, test equipment is used as shown in Fig.2a.

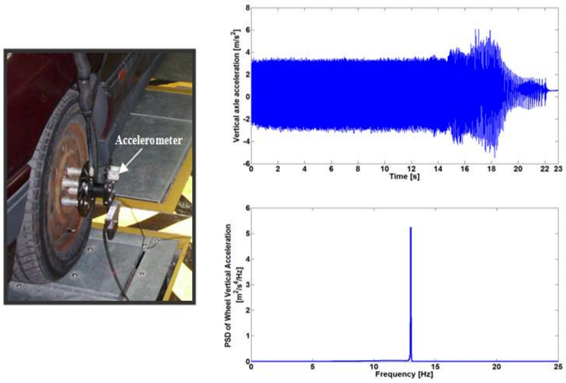

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Figure 2. (a) Measurement equipments of wheel vertical acceleration (b) Time response and PSD results of wheel vertical acceleration for medium-hard damper

The vertical axle acceleration is measured with medium-hard damper as shown in top graph of Fig. 2b. The PSD (Power Spectral Density) of measured acceleration signal is obtained by filtering with low pass butterworth filter as shown in Fig.2c. The cut-off frequency of the filter is selected as 25Hz, since the axle resonance frequency occurs 7-20 Hz frequency ranges. Thus, PSD graph shows that the resonance peak occurs at 13 Hz. This indicates that the highest vibration energy of wheel occurs at this frequency and this frequency is resonance frequency of unsprung mass.

The other essential variable to determine the wavelength of the test road is braking initial speed of the vehicle. In order to determine the braking initial speed, the additional tests are conducted. In this study, it is aimed that the suspension system is excited on rough area of test road during braking with activated ABS. For this reason, the additional ABS tests are conducted to determine the vehicle speed at which the ABS-braking can continue until end of rough area. For this, the wet and slippery road tests are separately conducted. After additional tests, the vehicle speed is monitored as 95 km/h. The lower vehicle speed than 95 km/h causes the vehicle to stop at middle of rough area. Also, the higher vehicle speed than 95 km/h causes the vehicle to stop at outside of rough area. For this reason, the braking initial speed is considered as 95 km/h. Therefore, only this vehicle speed enables safe and effective braking to excite the suspension system on the covered rough region for hard, medium-hard and soft shock absorbers. As a result, the wavelength of test road is calculated with the resonance frequency (13 Hz) and braking initial speed (V=95km/h=26.38 m/s) by substituting into Eq. (1). As for height of the planks, it is determined by using the static tire deflection under static load with nominal tire pressure (30 psi or 2.06 Bar). These results are given in Table 2.

Table 1. The wavelength and amplitude of rough road with the natural frequency of suspension system

Resonance frequency of unsprung mass	The braking initial speed	The wavelength of road	The amplitude of road
13 Hz	95 km/h	2.092m	0.026m

Thereby, the test road profile exciting all dampers at resonance frequency is designed as shown in Fig. 3.

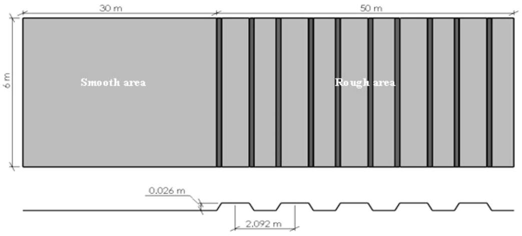


Figure 3. Structure and roughness profile and of test road

2.2. The measurement system of test vehicle

In this experimental study, the angular speed of wheel, vehicle speed, brake pressure, effective rolling radius and vertical axle acceleration are measured. Also, circumferential speed of wheel, wheel acceleration, friction coefficient and vehicle braking deceleration are obtained by using measured parameters. In here, the circumferential speed of wheel and circumferential acceleration of wheel are obtained by using angular speed of wheel. The brake pressure enables brake pressure change rates to be obtained. The braking acceleration of vehicle is derived from vehicle speed. Also, the changes in damping force are reflected to friction coefficient, the circumferential speed and acceleration of wheel by using effective rolling radius and vertical axle acceleration. All measurement devices and measured parameters are shown in Fig. 4.

The angular speed signal of the wheel is measured from the connection to ABS speed sensor. The vehicle speed is measured using the speed measurement device (Microsat model) with magnetic GPS antenna which is mounted onto the test vehicle via the MicroSAT interface box as shown in Fig. 4. The device has 0-1854 km/h measurement range and 0.1 km/h velocity accuracy. The brake pressure is measured using pressure transducer. The pressure transducer has 1-400 bar measurement range and 0.5ms response time. It is connected to the hydraulic modulator output related to the left front wheel with a T apparatus as seen in the Fig. 4. The effective rolling radius is measured by non-contact laser height sensor. The sensor has 100-350 mm measurement range and 0.1mm resolution. This sensor is mounted to the wheel lug nuts via adjustable mounting collets. Thus, it is exactly located to the wheel centre. Thereby, it can rotate with respect to the wheel's y-axis. To restraint this rotation in the vehicle body (vertical) z-direction, the height sensor is connected to the vehicle body with a rod. The vertical acceleration of the axle is measured by using the accelerometer. The accelerometer has 0-10g measurement range and it is mounted on the same apparatus as the height sensor as shown in Fig. 4.

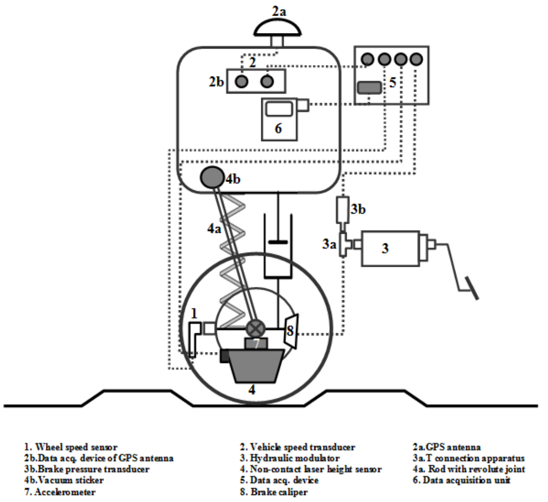


Figure 4. Experimental design and measured parameters during ABS test

The circumferential speed of wheel, brake pressure change rates, wheel rotational acceleration and friction coefficient have been obtained from the measured variables as follows:

The circumferential speed of wheel V_w is calculated by reflecting the measured effective rolling radius to the wheel angular speed as follows:

$$\mathrm{V_w} = \dot{\varphi}_m R_{\mathrm{m,e}} \tag{2}$$

where $\dot{\varphi}_m$ is the measured wheel speed and $R_{m,e}$ is measured effective rolling radius. The brake pressure change rate is calculated by using measured brake pressure as the following[1]:

$$\pm \Delta P_b = \dot{P}_b = \frac{d(P_{m,b})}{d(t)} \tag{3}$$

where $P_{m,b}$ is the measured brake pressure and t is time which is taken until the vehicle speed is reduced from 95 km/h to 0 km/h. Also, the circumferential acceleration of wheel is obtained by using the measured angular speed of wheel and effective rolling radius as follows[1]:

$$a_w = \frac{d\dot{\varphi}}{dt} R_{m,e} = \ddot{\varphi} R_{m,e} \tag{4}$$

The changes in friction coefficient are calculated to investigate the changes in road-tire contact occurring during braking with ABS. The friction cofficient is calculated as follows:

$$\mu(\lambda) = \frac{M\dot{V}_x}{F_{z,l} - m_W\, g} \tag{5}$$

3. Setting of Damper Stages

In the experimental study, the major purpose is to excite three different dampers on the rough area during braking with activated ABS. To achieve these damping stages, the valve model is used as shown in Fig. 5. In this model, firstly, the valve is pushed to down, and thus the motion of the valve is resisted in high pressure section. Then, when the sufficient pressure difference is obtained, the oil is allowed to pass through a small hole.

As a result, the pressure, acting on the piston annulus area A_p or rod cross-sectional area, creates a force F_d in adverse direction of piston motion [13]. In this way, the damping coefficient of the damper is obtained as the following:

$$c_d = \frac{\rho A_p^{\,3} v_d}{2 A_v^{\,2}}$$

(6) According to the Eq. (6), the damping capacity of damper is varied by changing either the piston annulus area or the effective flow area as mechanical means. In this study, the effective flow area is changed by keeping constant the piston annulus area. For this purpose, the shock absorber which has the valves with flat shim is used so that it is relatively easy to change the effective flow area by using different shim thicknesses. The pressure difference across the valve strongly depends upon the shim thickness. For this reason, only if the shim thickness allows to the liquid to pass, the pressure difference can be occurred and the damping force can be produced. Therefore, damping capacity is varied by changing effective flow area with different shim thicknesses and different numbers of shim. The valve positions of each damper are shown in Fig. 5.

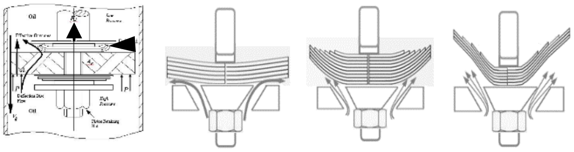
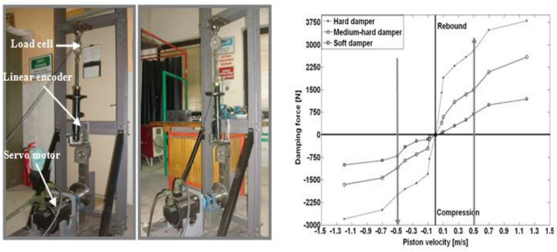


Figure 5. The valve model and valve positions for hard, medium-hard and soft dampers

Hard damper stage is obtained by increasing thickness of shim and decreasing the number of shims as shown in Fig. 5a. For soft damper, the thickness of shims is considerably decreased, but the less shim is used relative to that of medium-hard damper as shown in Fig. 5c. As for medium-hard damper, it is already available on the test vehicle. In addition, the medium hard damper has more number of shim than that of soft, but it has same shim thickness as shown in Figs. 5b and 5c.

4. Damping Characteristics of the Dampers

The damping characteristics of the achieved dampers are given in Fig. 6. The dampers are tested as shown in Fig.6a. In this test, the dampers are excited by a shock absorber tester driven by servo motor. The achieved damping force vs piston velocity graphs are given in Fig.6b. Also, the arrows in Fig.8b show how direction the thickness of shim increases or the number of shims decreases. The damping characteristics are described with relationships between damping force and piston velocity for three damper stages as shown in Fig. 6b. The relationship between force and piston velocity of these dampers is degressive and depends strongly on the direction of motion of the piston as shown in Fig. 6b. Thus, the different damping forces can be obtained for same damper, as the piston velocity changes.



a b

Figure 6. (a) Shock absorber tester (b) The damping characteristics for hard, medium-hard and soft dampers

5. Experimental Procedure

The measurements are performed by braking the vehicle with ABS at 95 km/h over rough area. Before measurements, the vehicle has been accelerated to predetermined speed (95 km/h). When the vehicle reaches to the smooth area at this speed, the force required to activate ABS is applied to brake pedal by the test driver. Then, the rough area is transited with activated ABS. Therefore, the vehicle is allowed to come to a complete stop with ABS on rough area. In this way, the ABS-braking maneuver is continued until the end of rough road. The braking experiments with activated ABS have been repeated five times under wet road conditions and five times under slippery road conditions. The test matrix related to these experiments is shown in Table 2.

Table 2. Test Matrix for ABS tests

Braking initial speed (95 km/h)				
Experiment	**Road Type**	**Brake Pedal Force**	**Number of test cycles**	**Dampers**
Test 1	Wet	Constant during braking with ABS	5	Medium-hard
Test 2	Slippery	Constant during braking with ABS	5	
Test 3	Wet	Constant during braking with ABS	5	Hard
Test 4	Slippery	Constant during braking with ABS	5	
Test 5	Wet	Constant during braking with ABS	5	Soft
Test 6	Slippery	Constant during braking with ABS	5	

In all ABS braking tests, the vehicle is braked in the cool down areas of the experimental facility. In this way, the bad effects of hard braking on braking system are eliminated. Also, the wooden planks are not worn out during the test, because the wooden planks are mounted to the road with concrete screw and the carpet is covered onto the planks. Thus, the effects of wooden plank-wear on braking performance are minimized. As a result, these precautions provide that ABS is operated under equal road conditions for all damper stages. They can enable adaptation to the wet and slippery rough test conditions for each shock absorber.

6. Experimental Results and Discussions

6.1. Braking distance results

In order to assess experimental results, time responses of wet and slippery road conditions are analyzed. The validation of the analysis results is discussed using the changes in braking distance as shown in Table 3.

Table 3. Braking distances on wet and slippery rough road for dampers

Road type	Shock Absorbers Braking distance [m]		
	Hard	Medium-hard	Soft
Wet rough road	73.04	64.90	78.75
Slippery rough road	83.67	91.96	95.58

According to Table 3, the wheel load effects of medium-hard damper have obtained the shortest braking distance 64.90m at 4.92s on wet road. However, hard damper has increased the braking distance by 13.09 % at 6.03s. Also, soft damper has greatly increased the braking distance by 21.3 % at 6.33s.

As for slippery road results, hard damper obtains the shortest braking distance 83.67m at 6.03s. Medium-hard damper increases the braking distance by 9.90 % at 6.32s. Also, soft damper leads the braking distance to be increased by 14.23 % at 6.47s. Therefore, the longest braking distance is caused by soft damper, regardless of the changes in road surface. In addition, it is a remarkable point that the medium-hard damper causes braking effect of the wheel to considerably decrease during transition from wet road to slippery road.

6.2. Brake pressure results for wet rough road

Brake pressure results are analyzed by using MATLAB [14]. The validation of the analysis results is discussed using the changes in braking distance as shown in Tables 4. Also, in order to reflect the damping characteristics of damper to brake pressure change rate results with braking distance, the damping forces are considered at high and low piston velocities. In this study, the first half of braking maneuver is considered as high piston velocity area, while the second half is considered as low piston velocity area. Also, the wheel load effect term is often used for expressing effect of damping force on wheel load. This term describes how the damper changes wheel load. Thus, as the damping force of damper increases, the wheel load effect increases. However, if the damping force decreases, the wheel load effect decreases.

Thereby, Fig. 7 shows the brake pressure results achieved on wet rough road for hard, medium-hard and soft dampers. As shown in Fig. 7a, if the damper is set to medium-hard stage on wet road, the brake pressure is applied at high levels. Also, brake pressure is reduced and built-up at lower speeds than that of other dampers. This is valid for all piston velocities as shown in Fig. 7b.

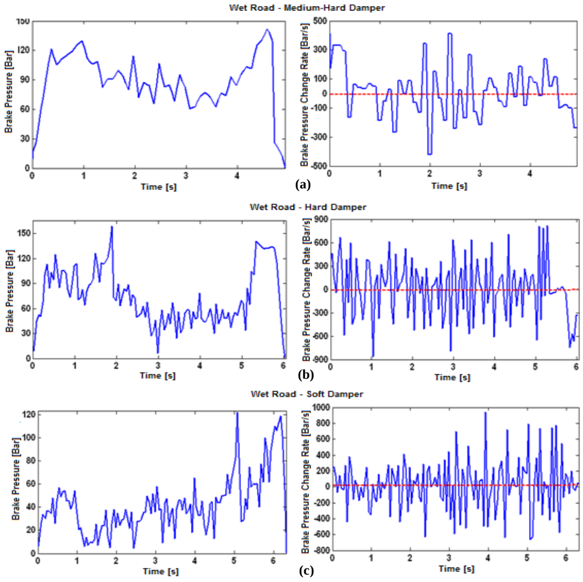


Figure 7. Brake pressure and the brake pressure change rates for hard, medium-hard and soft dampers under wet rough road condition

If the damper is set to hard stage, the brake pressure level is increased at high piston velocity, whereas the low piston velocity causes brake pressure level to considerably reduce as shown in Fig. 7a. Furthermore, if the damper is set to soft stage, the brake pressures are applied at low level due to high piston velocity, but the brake pressure level becomes high at low piston velocity as shown in Fig. 7c. Also, according to Figs. 7a and 7c, the decreases in piston velocity with hard and soft dampers cause the brake pressure to be built-up and reduced at high speeds. Furthermore, soft damper causes the oscillatory build-up and reductions due to low piston velocity as shown in Fig. 7c.

Therefore, the brake pressure change results of wet road indicate that irrespective of the changes in piston velocity of damper, medium-hard damper provides sufficient wheel load effect by maintaining the tire-road contact up to the end of braking maneuver. Also, if hard damper is used, the wheel load effect is sufficient at high piston velocity. However, at low piston velocity, the wheel load effect of hard damper causes the brake pressure level to suddenly reduce due to high change speeds of brake pressure. As for soft damper, the wheel load effect of soft damper leads the tire-road contact to be extremely deteriorated at high piston velocity area of damper. In addition, the wheel load effect obtained with low piston velocity of soft damper causes the brake pressure to unsteadily change.

6.3. Brake pressure results for slippery rough road

Fig. 8 shows the brake pressure results of hard, medium-hard and soft dampers on slippery road. It is remarkable point that slippery road condition causes the brake pressure level of all dampers to decrease at beginning of ABS-braking maneuver. As shown in Fig.8a, medium-hard damper causes the brake pressure to remain at low level during all ABS-braking maneuver, irrespective of the changes in piston speed. According to Fig. 8b, hard damper enables the brake pressure to be built up at high speed and reduced at low speed of piston. This is also performed with low brake pressure level. As the piston velocity gradually decreases, not only brake pressure level but also the magnitude of build-ups and reductions become high. If the damper is set to soft stage, the brake pressure is suddenly increased and decreased as shown in Fig. 8c.

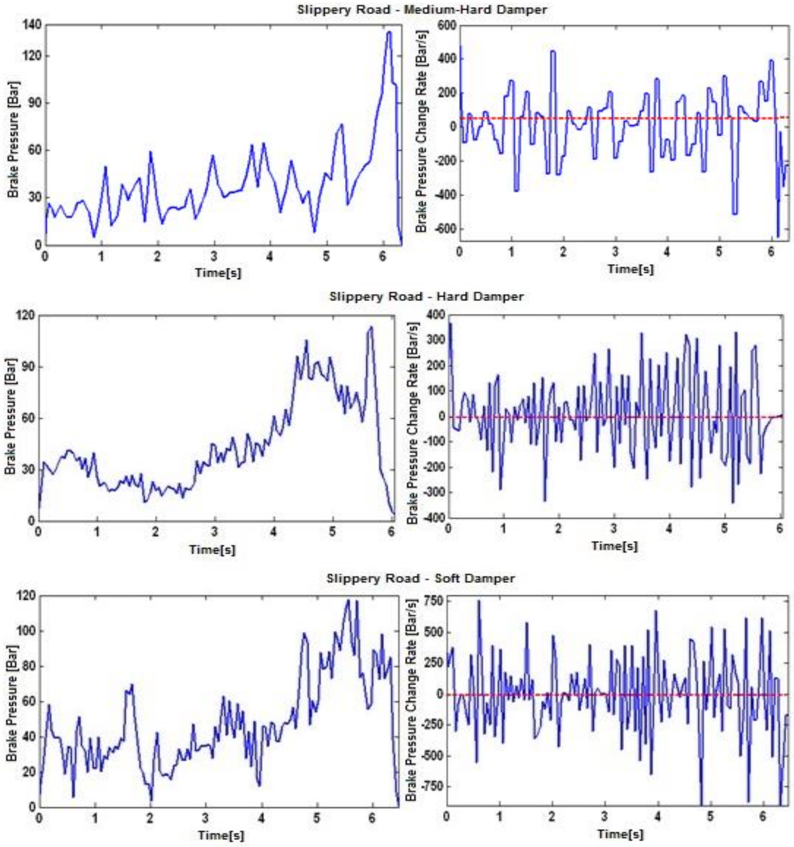
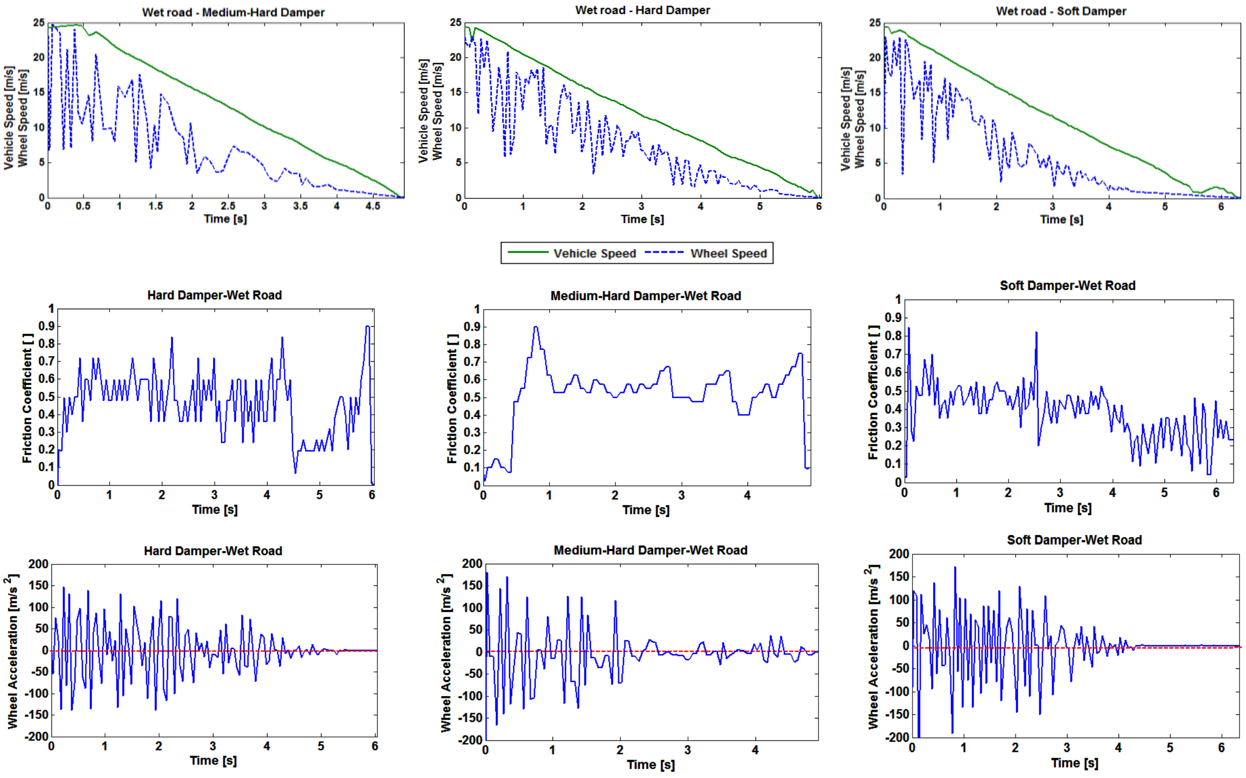


Fig. 8. Brake pressure and the brake pressure change rates for hard, medium-hard and soft dampers under slippery rough road

6.4. Results of ABS-braking performance parameters

In order to reveal the interaction between the changes in brake pressure and ABS performance parameters, the changes at the wheel and vehicle speeds, wheel acceleration and adhesion coefficient are investigated as shown in Figs. 9 and 10.



(a) (b) (c)

Figure 9. ABS braking performance parameters for hard, medium-hard and soft dampers under wet rough road condition

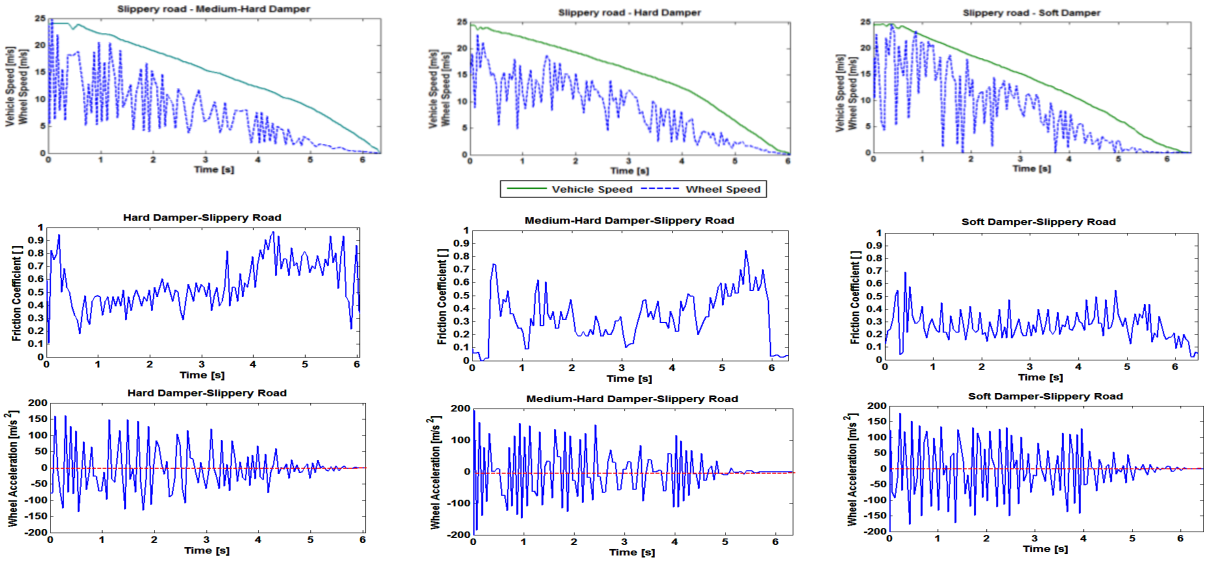
6.4.1. ABS performance parameter results for wet rough road

As shown in Fig.9a, when medium-hard damper results are observed, at the beginning of braking maneuver, the high brake pressure level causes the accordance between the wheel speed and vehicle speed to decrease in high velocity area of the piston. However, hard damper applies more damping force than that needed by wheel at high piston velocity. This causes the wheel to accelerate upward or downward. Nevertheless, for this reason, the brake pressure build-up and reductions become more oscillatory, regardless of the changes in piston velocity. Thereby, the slippery road results show that when the surface of road becomes slippery during ABS-braking, the wheel load effect with medium-hard damper becomes insufficient for keeping the tire-road contact at high level for all piston velocities.

When the wheel load effect decreases due to reductions in piston velocity, the damping force to increase the brake pressure level is obtained. This performance increasingly continues as the piston velocity decreases. In here, it should be noticed that the wheel load effect at high piston velocity is compensated by keeping the brake pressure changes at low level. However; the wheel load effect of soft damper remains insufficient and it leads the wheel to severely accelerate and decelerate in upward and downward direction in both piston velocity areas.

This provides the wheel to accelerate and decelerate at same rates. Thus, at low piston velocity area, the damping force of medium-hard damper gradually reduces the acceleration and deceleration of the wheel, as the vehicle speed decreases. In this way, the braking is completed without locking of the wheel.

Hard damper results indicate that in high piston velocity area, hard damper leads the sudden reductions in wheel speed, and therefore the oscillatory wheel speeds occur as shown in Fig.9b. This causes the friction coefficient and the wheel acceleration or deceleration to become more oscillatory due to high brake pressure change speeds. Also, the sudden reduction in brake pressure level causes the friction coefficient to decrease in low piston velocity area. For this reason, at the end of braking maneuver, the wheel speed changes could not be sensed within short time and the ABS-braking maneuver is completed with blocked wheel. As for soft damper results, soft damper causes more oscillatory wheel speeds in high piston velocity area as shown in Fig. 9c.



(a) (b) (c)

Figure 10. ABS braking performance parameters for hard, medium-hard and soft dampers on slippery road

6.4.2. ABS performance parameter results for slippery rough road

Medium hard damper results show that the wheel speed becomes extreme oscillatory in high piston velocity area as shown in Fig.10b. This causes the friction coefficient to be oscillatory at low level. For this reason, the high piston velocity leads severe changes in wheel deceleration and accelerations. With the decreasing of piston velocity, the difference between wheel speed and vehicle speed is increased due to brake pressure at low level and brake pressure build-ups at low speeds. This causes wheel to suddenly accelerate and decelerate with oscillatory friction coefficient changes as shown in Fig.10b.

These changes at wheel speed cause the friction coefficient to decrease. Thus, the acceleration and deceleration of wheel become unstable. In addition, when the piston velocity decreases at the end of braking, the brake pressure becomes also unstable. This leads the friction coefficient to drastically drop as shown in Fig. 9c. Therefore, the wheel is decelerated much more severely than that of the vehicle body as shown in Fig.10. After all, ABS-braking maneuver is completed with blocked wheel in longer time period than that of hard damper. In here, it is a remarkable point that soft damper leads the inconsistency between level of brake pressure and brake pressure change rates for same piston velocity.

Therefore, medium-hard damper greatly increases the tendency of wheel to locking.

Hard damper results show that the damping force causes the wheel speed to suddenly reduce in high piston velocity area at some times as shown in Fig.10a. However, the accordance between the wheel speed and vehicle speed is kept by maintaining at low level of brake pressure and holding brake pressure build-ups at low level within long time period.

This provides sufficient friction coefficient and wheel deceleration to be obtained by accelerating the wheel at low level. When the piston velocity is decreased, the accordance between wheel speed and vehicle speed is recovered by enhancing level of brake pressure and holding brake pressure build-ups at high level. These brake pressure changes enable the friction coefficient to increase and the wheel to be gradually decelerated. In this way, the wheel speed and vehicle speed are reduced at same rates without locking wheel as shown in Fig.10a.

Soft damper results show that in all piston velocities, the unstable brake pressure build-ups and reductions cause the sudden reductions in wheel speed as shown in Fig.10c.

7. Conclusions

Nowadays, the integration of damping control systems into ABS gradually increases. In order to establish this integration, self-tuning damper is used. Also, many automotive companies use these integrations for safer ABS braking system and shorter braking distance. This requires the test methodology of this integration to be developed. For this, in this study, it is aimed to occur the effects of changes in damping capacity of damper on ABS braking performance. Therefore, the test methodology is developed for testing the effects of damping stages on ABS braking performance. For this aim, ABS braking tests are conducted on wet and slippery surfaces of rough road using hard, medium-hard and soft dampers representing all damping stages of a self-tuning damper, when the damper stage changes during braking with ABS.

The test results show that the changes in damping capacity cause different brake pressure levels to be applied by ABS. Therefore, the build-ups and reductions in brake pressure determine the changes in braking distance with ABS. In here, it is considerable point that the effects of dampers on brake pressure changes strongly depend on the direction and velocity of piston motion of the damper.

For this reason, the friction coefficient is reduced to low level within long time period of ABS-braking maneuver. These friction coefficient changes lead severe acceleration and decelerations of wheel as shown in Fig.10c. Therefore, the ABS-braking maneuver is completed with blocked wheel.

Therefore, all results show that this test methodology can determine full and accurate characterization of the effects of the changes in damping force of damper on ABS braking performance. This is confirmed with the changes in braking distance.

The test methodology in this study will be beneficial for testing the effects of changes in damping capacity during braking with ABS. Also, the companies combining self-tuning damper into ABS braking control cyle can employ the developed test methodology.

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