

Influence of Chassis Frictions on Vehicle Dynamic Behavior: Vehicle Experimental Investigation

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ABSTRACT

To study the influence of chassis frictions on vehicle dynamic behavior, an experimental investigation is done using a test vehicle with a specially-designed friction control device integrated with the steer-arm ball joints. Extensive vehicle on-road tests were conducted to understand the relationship between the chassis friction level and the following seven performance areas: torque steer, high-speed steering feel, low-speed steering feel, vehicle drift, body roll motion, gross body motion, and brake judder. The research demonstrated that vehicle performance in these areas is highly dependent on the level of friction torque at the steer-arm ball joints in a linear or nonlinear manner. Each performance area can be enhanced by an appropriate level of the friction torque, but different performance areas may require different settings of the friction torque and some settings may contradict each other.

1. Introduction

Frictions exist at multiple locations in an automotive chassis system, including suspensions and steering. With unique nonlinear characteristics, frictions in a chassis system may affect vehicle dynamic behavior.

Passively applying supplemental frictions at a chassis location, such as in the steering gearbox, is a common approach used to tune steering feel or to enhance system toughness for vehicle performance. However, while one friction setting can increase vehicle performance in one area, it may affect performance in other areas. To help design a chassis system that enhances various dynamic and comfort factors, research was done on the influence of chassis frictions.

Related research⁽¹⁾ by the first author reveals that the following seven key vehicle performance areas can be highly affected by chassis frictions: torque steer, high-speed steering feel, low-speed steering feel, vehicle drift, body roll motion, gross body motion, and brake judder. Furthermore, steer-arm ball joint friction torque and lower-arm ball joint friction torque have been identified as the frictions that exert high influence on all of these seven vehicle performance areas.

This paper explains an experimental study on the influence of chassis frictions on vehicle dynamic

behavior. The study involved a test vehicle with a specially-designed on-board friction control device integrated with the steer-arm ball joints. Extensive vehicle on-road tests were conducted to understand the relationship between the friction torque level at the steer-arm ball joints and each of the seven key vehicle performance areas.

2. Experimental Approach

2.1. Test Vehicle

The test vehicle used in the investigation was a sport utility vehicle equipped with a MacPherson front suspension, trailing-arm rear suspension, and rack-and-pinion steering system. In addition, two modifications were made. First, the front lower-arm ball joints, strut bearings, and steering gearbox were replaced with parts of low-limit specifications for friction. Second, at the location of each steer-arm ball joint, a specially-designed friction control device (FCD) was installed as shown in Fig. 1. The design of the FCD consists of a ball joint with movable ball socket and a force actuator that acts on the socket. By the control of the input (in hexadecimal) of the force actuator, the friction torque of the ball joint can be controlled. The design intention of the FCD is to have an on-board device to vary the friction level of the steer-arm ball joint as needed. With the FCD, real-time control of the friction torque can also be possible.

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As demonstrated in other research⁽¹⁾, the steer-arm ball joint friction torque is one common friction that exerts high influence on the seven vehicle performance areas. By changing input to the FCD, the friction torque of the steer-arm ball joints can be varied without physical part change, and the investigation on the relationship between the level of the friction torque and each of the seven vehicle performance areas can be conducted.

2.2. Tool Used to Vary Frictions

The FCD is designed to generate sufficient and smooth friction torques. Friction torques of the FCD can occur in different directions, where the rotational direction is around the axial line of the ball stud and the rocking direction is the direction in which the ball stud swings back and forth relative to the ball socket. Kinetic (or dynamic) friction occurs when the ball stud is rotating or rocking relative to the ball socket, while breakthrough friction is the maximum friction between the ball stud and the ball socket when they are not moving relative to each other (i.e. zero relative velocity). Figure 2 shows an example of the measured FCD friction torques under a given input. As shown,

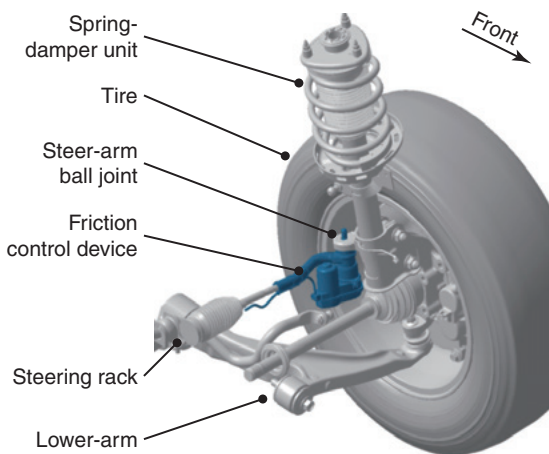


Fig. 1 Friction control device integrated with steer-arm ball joint

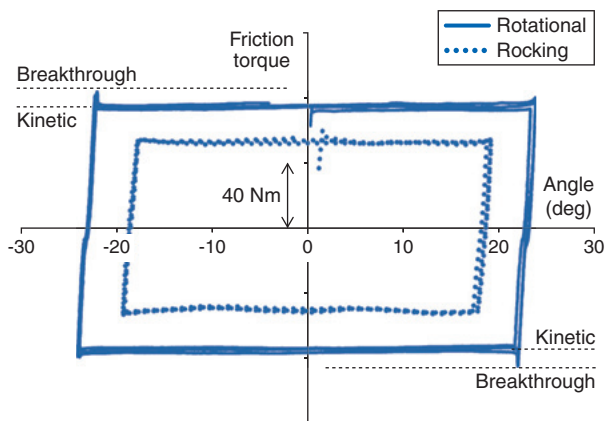


Fig. 2 Rotational and rocking friction torques of FCD at one given input

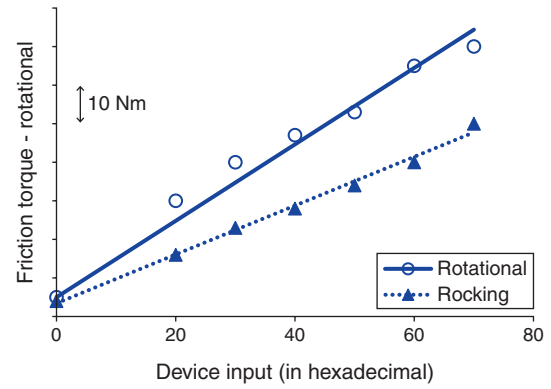


Fig. 3 Friction torque characteristics of FCD with respect to its input

the FCD can create smooth and linear friction torques with little increase from kinetic to breakthrough frictions in both rotational and rocking directions.

Figure 3 shows the measured kinetic FCD friction torques with different device input. It was confirmed that friction torques in both rotational and rocking directions increase linearly with the increase of the device input, the ratio between the friction torques in rotational and rocking directions remains nearly constant regardless of input value, and the variation range of friction torque can achieve 70 Nm maximum in rotational direction and 50 Nm maximum in rocking direction.

3. Performance Dependency on Friction Level

3.1. Torque Steer

Torque steer occurs normally during hard acceleration from zero speed on split- μ surface, which can be quantified by the steering angle change during the hard acceleration event when the driver's hands are free from the steering wheel. Torque steer performance of the test vehicle is investigated against a series of FCD friction torque settings.

Figure 4 illustrates the variation of maximum steering wheel angle with the change of the friction

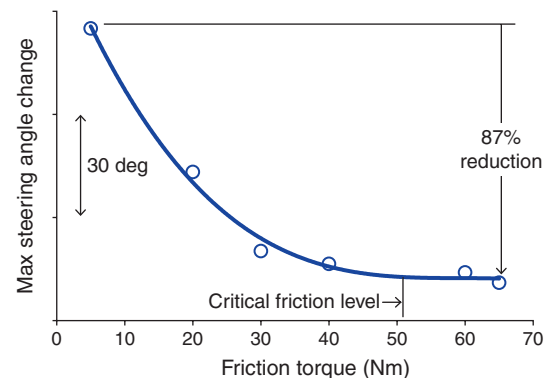


Fig. 4 Variation of maximum steering wheel rotation angle with change of FCD friction setting during torque steer tests

torque during hands-free, hard acceleration events under a given unbalanced vehicle loading condition. As shown, the FCD friction torque has high influence on torque steer performance. Steering wheel rotation and vehicle lateral drift caused by torque steer can be improved by about 87% to an unnoticeable level when the friction torque is increased from the lowest setting to the highest setting.

The data also demonstrate clearly a nonlinear relationship between the torque steer performance and the FCD friction torque. Maximum steering angle change decreases steadily with the initial increase of the friction torque, but beyond a critical level of friction torque, further increase of the friction torque does not further enhance torque steer performance significantly. This implies that the critical level of friction torque can be considered as the sufficient setting for enhancing torque steer performance.

3.2. Steering Feel

Steering feel is evaluated with various FCD friction torques at different vehicle speeds so that the dependency of steering feel on the friction torque can be understood thoroughly. Steering feel for mid to high speeds is focused on an on-center region (small steering input) and characterized by a steering damping factor and a spring coefficient⁽²⁾⁻⁽⁵⁾, while steering feel for low speeds is quantified by the self-centering ability of the steering wheel when the steering wheel is released during a steady-state turning event.

Figure 5 shows on-center steering feel characteristics at a middle speed and a high speed under different FCD friction settings. It is shown that at the middle vehicle speed, the increase of the FCD friction torque from 5 Nm to 30 Nm can increase the steering damping factor while maintaining the level of the spring coefficient for both smaller sinusoid steering input (15 deg) and a relatively larger steering input (30 deg). However, further increasing the friction torque does not considerably increase the damping factor; it actually reduces the effect and raises the spring coefficient for smaller steering inputs. The results indicate that if the goal is to achieve maximum impact on the damping factor for both smaller and larger steering inputs, there exists an optimal friction level for the vehicle speed being discussed.

As shown in Fig. 5(b), the experimental results for high speeds reveal an interesting trend. With a lower level of friction torque, the steering damping factor not only is lower but also has a decreasing trend with the increase of steering input amplitude. This is an undesired situation that causes an insecure steering feel. As evidenced by the figure, this situation can be completely reversed by applying a higher friction torque setting.

On the other hand, Fig. 6 shows that increasing the FCD friction torque quickly decreases the steering wheel's self-centering ability. Since a high level of steering wheel self-centering ability is desired for

achieving a nimble feel, lower FCD friction torque is necessary at lower speeds. This suggests that the vehicle needs a completely different friction setting for enhancing low-speed steering feel from the one required for achieving a good high-speed steering feel.

3.3. Vehicle Drift

Vehicle drift is normally experienced during mid-to high-speed straight-line driving. In order to obtain repeatable results, the test vehicle was set with split camber angles and unbalanced tire conicity forces

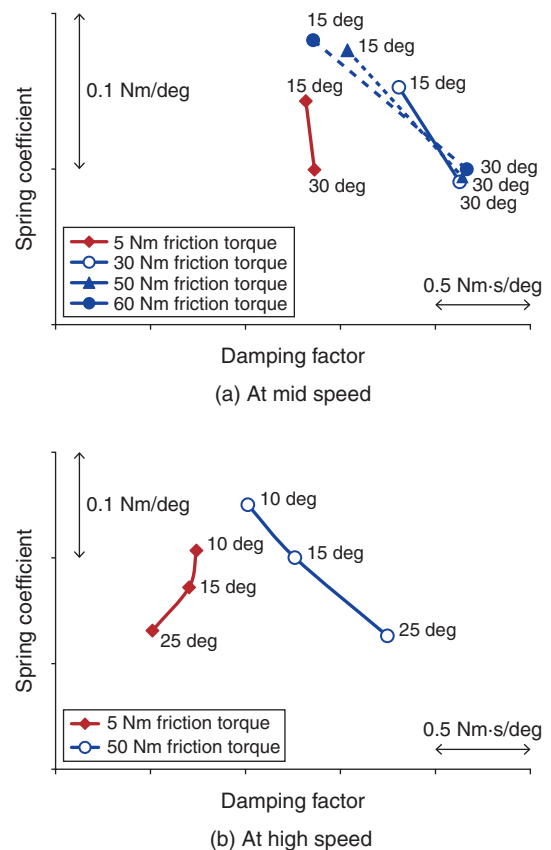


Fig. 5 Variation of on-center steering feel characteristics with changes in FCD friction torque (at mid to high speeds)

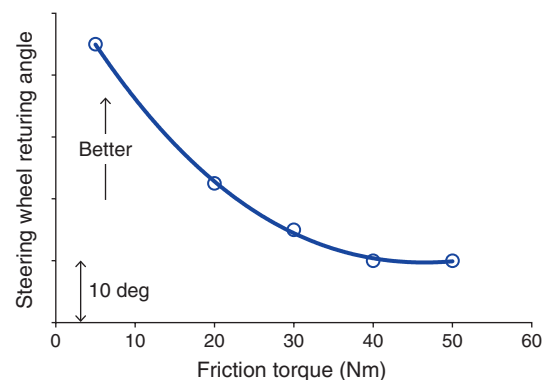


Fig. 6 Variation of steering wheel self-centering characteristics with changes in FCD friction torque (at low vehicle speeds)

between left and right tires. With the driver's hands free from the steering wheel, the vehicle was driven at a constant speed along a straight line on a flat surface. Vehicle drift performance is determined by the lateral displacement of the vehicle within a predefined distance.

As shown in Fig. 7, vehicle lateral displacement during drift tests decreases almost proportionally with the increase of the FCD friction torque, and the lateral displacement can be improved by at least 60% from the lowest to the highest friction torque settings applied in the investigation. The results show that the higher the FCD friction torque, the better the vehicle drift performance.

3.4. Body Roll Motion Control

Body roll motion is evaluated by the combined effect of vehicle roll angle, roll rate, and yaw rate when there is an abrupt change in steering angular input (i.e., the steering wheel is released after a steady-state steering input). Since yaw and roll are coupled during a vehicle roll event, the feeling of body roll motion control is related to both yaw and roll response.

Figure 8 shows the differences in the body roll motion between a lower setting and a higher setting of FCD friction torque. As shown, increasing FCD friction torque lowers the second overshoots in roll angle, roll rate, and yaw rate and reduces maximum roll rate and maximum yaw rate. The trends closely match analytical results⁽¹⁾.

Body roll motion control was evaluated under several FCD friction torque settings. Figure 9 shows the variation of body roll characteristics with changes in friction torque. As shown, the second roll angle overshoot, maximum roll rate, and maximum yaw rate all demonstrate a purely linear relationship with the FCD friction torque. The friction torque has considerable effect on the roll angle and yaw rate and a mild effect on roll rate. The higher the friction torque, the lower the roll angle overshoot, maximum roll rate, and maximum yaw rate. Thus, a high FCD friction torque can create a more-damped and stable roll motion.

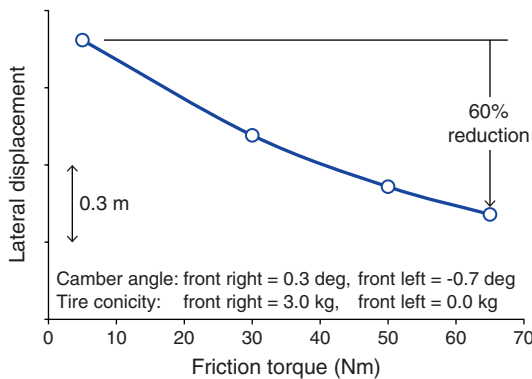
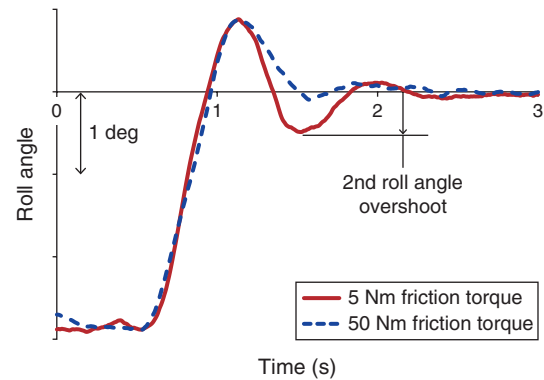


Fig. 7 Variation of vehicle lateral drift with changes in FCD friction torque

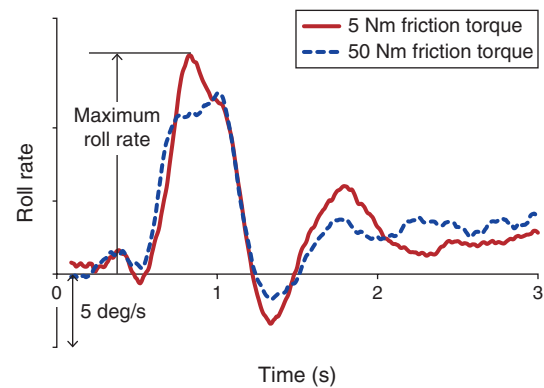
3.5. Gross Body Motion Control

Gross body motion was examined by the vehicle body motion in a vertical direction when the vehicle is tested both on a laboratory four-post tester and on a flat ride road.

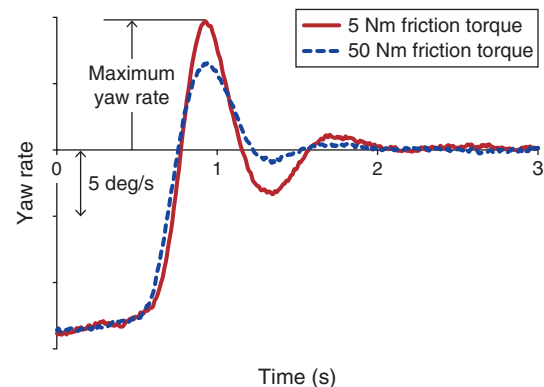
Figure 10 shows the sprung mass (body) response under a larger excitation amplitude and the front unsprung mass (front suspension) response under a smaller excitation amplitude at the tire contact patches, when the FCD friction torque is set to different levels. As shown, with the increase of the FCD friction torque, the peak gain of the frequency



(a) Roll angle



(b) Roll rate



(c) Yaw rate

Fig. 8 Comparison of vehicle roll behaviors between lower and higher settings of FCD friction torque during abrupt change in steering input

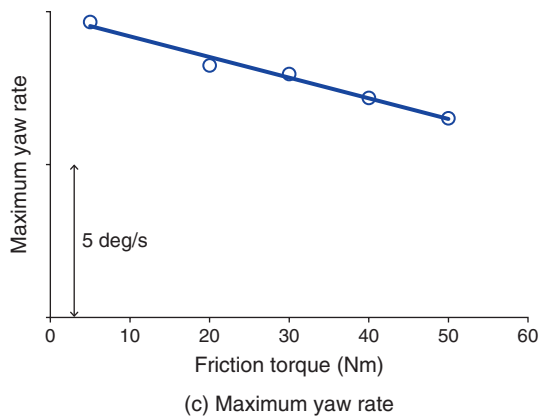
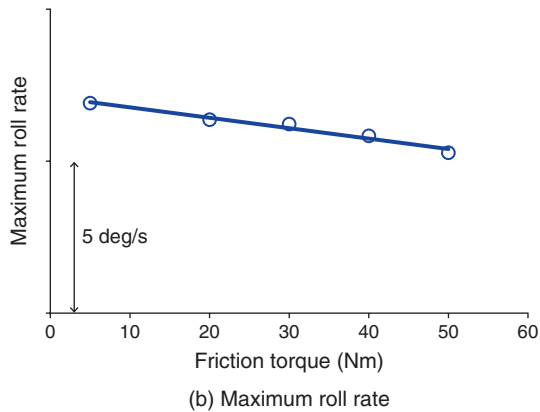
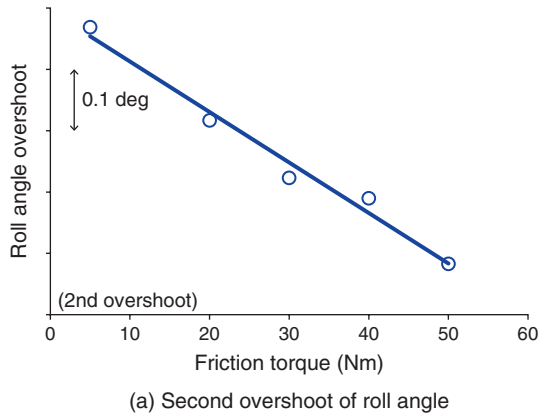


Fig. 9 Variation of body roll characteristics with changes in FCD friction torque

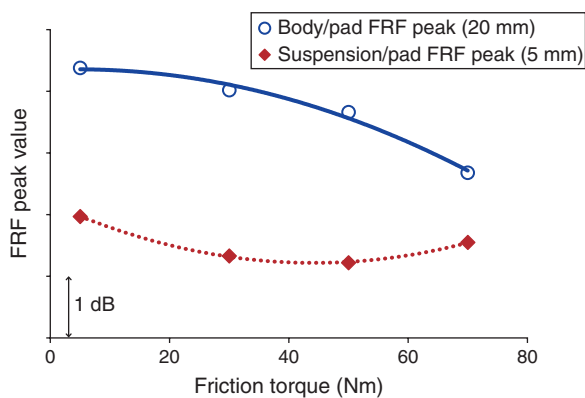


Fig. 10 Variation of FRF peak value with change of FCD friction torque during laboratory four-post excitation tests

response function (FRF) between the sprung mass and the pad of the four-post tester demonstrates a nonlinear decrease trend, while the peak gain of the FRF between the unsprung mass and the pad of the four-post tester exhibits a decrease trend initially and then a subtle increase trend.

Figure 11 shows the nonlinear dependency of seat-rail vibration, body vertical displacement, and steering effort fluctuation on the FCD friction torque when the vehicle is driven on a flat ride road with a sinusoid profile in vertical direction. Similar to the trend of the sprung mass FRF shown in Fig.10, the amplitudes of seat-rail vibration, body vertical displacement, and

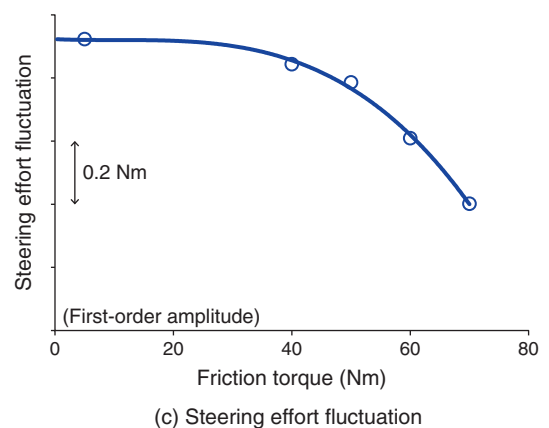
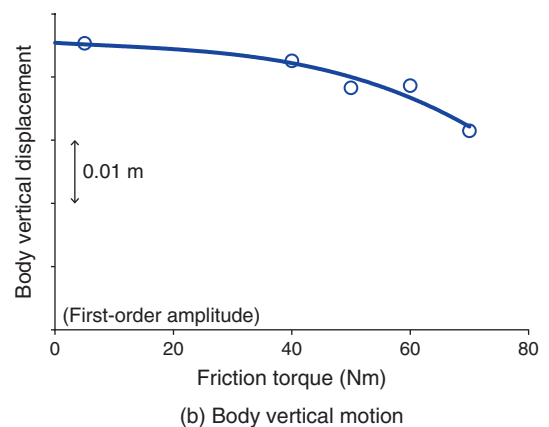
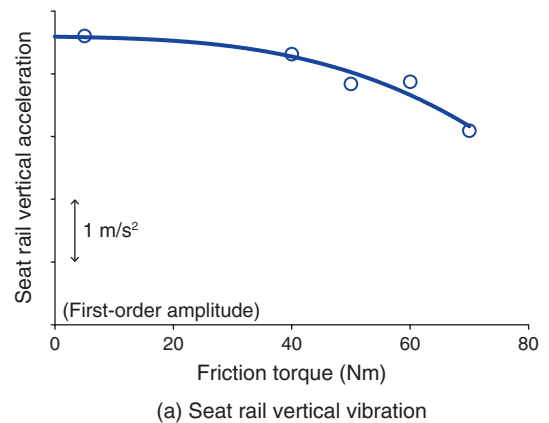


Fig. 11 Variation of flat ride characteristics with changes in FCD friction torque

steering effort fluctuation decrease slightly with initial increase of the friction torque but then decrease with further increase of the friction torque. For best ride comfort under the flat ride road condition, the highest possible FCD friction torque is needed. In addition, the characteristics of steering effort fluctuation shown in Fig. 11(c) suggest that increasing the FCD friction torque can reduce the busyness of the steering wheel and further enhance the driver's comfort.

3.6. Chassis Sensitivity of Brake Judder

Chassis sensitivity of brake judder is quantified as the steering wheel rotational vibration when the front knuckles are excited by a given level of brake torque fluctuation^{(6), (7)}. A brake rotor with known, exaggerated rotor thickness variation is installed in the front right brake system of the test vehicle. During the brake judder tests, the vehicle is decelerated from 140 kph at a deceleration of 2 m/s^2 .

Figure 12 shows examples of brake judder test results when different FCD friction torques are applied. As shown, the FCD friction torque has considerable effect on the peak amplitude of steering wheel vibration during deceleration. Brake judder can be reduced linearly by increasing FCD friction torque and be improved by as much as 6 m/s^2 within the limits of the FCD.

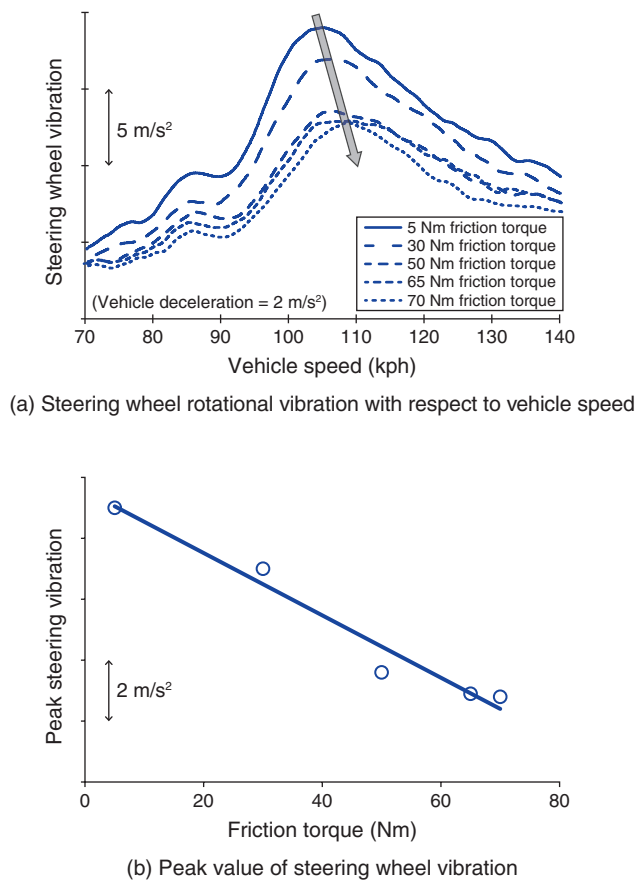


Fig. 12 Variation of brake judder sensitivity with changes in FCD friction torque

4. Conclusion

Building on other research into the influence of chassis frictions on vehicle dynamic behavior⁽¹⁾, an experimental investigation was done using a test vehicle with a specially-designed friction control device integrated with the steer-arm ball joints. Extensive vehicle on-road tests were conducted to understand the relationship between the friction torque level at the steer-arm ball joints and the following seven key performance areas: torque steer, high-speed steering feel, low-speed steering feel, vehicle drift, body roll motion, gross body motion, and brake judder.

It was determined that these vehicle performance areas are considerably affected by the level of friction torque at the steer-arm ball joints in either a linear or nonlinear manner. Each performance area can be enhanced by an appropriate level of friction torque, but different performance areas may require different settings of friction torque and some settings may contradict each other.

This study extends the understanding of chassis frictions' influence on vehicle dynamic behavior. Further investigation is planned to take the advantage of the frictions' effects to simultaneously enhance multiple performance areas.

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