

Influence of Chassis Frictions on Vehicle Dynamic Behavior: Analytical Study

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ABSTRACT

An extensive analytical study was performed to analyze the influence of chassis frictions on vehicle dynamic behavior and identify the relative importance of frictions in different locations of a chassis system. First, a multi-body simulation model of a full vehicle was developed that integrates customized friction functions in all major chassis joints. The model was correlated with measurement in chassis kinematics, compliance, system-level frictions, and vehicle dynamic performance. Using the simulation, along with the confirmation of two test vehicles, seven key vehicle performance areas affected by chassis frictions were identified. This was followed by a thorough sensitivity analysis to identify frictions that have high influence on each of those performance areas. Common influential frictions that have a considerable influence on multiple performance areas were identified.

1. Introduction

Vehicle dynamics and comfort have become two principal vehicle attributes that customers judge when deciding on a vehicle purchase. However, simultaneously achieving these attributes has been a challenging task for automotive engineers. It is even more challenging to achieve in passenger cars with high-power front-wheel drive and in vehicles with a high center of gravity, such as sport utility vehicles.

Friction exists in any mechanical joint in an automotive chassis system, and many frictions can have considerable effect on vehicle performance. Passively applying supplemental frictions at a chassis location, such as in the steering gearbox, is a common approach used to enhance system toughness and performance. Nevertheless, while one friction setting can enhance vehicle performance in one area, it may affect performance in other areas.

The influence of chassis frictions has not been studied thoroughly to determine the influence of a specific friction at a given location to a performance area; what level of friction is best for a given performance area; how a required friction level can be realized; and more importantly, how to appropriately control chassis frictions to enhance multiple performance areas without compromising others areas.

To answer these questions, systematic research was conducted. As the initial step in this research, an extensive analytical study was performed to quantify the influence of chassis frictions on various

vehicle performance areas and to identify the relative importance of those frictions. A broad spectrum of performance in dynamics and comfort was analyzed, including torque steering, vehicle drift and pull, brake judder, vehicle gross body motion control, vehicle body roll control, steering feel at both low and high speeds, steering kickback, impact harshness, driving vibration, and self-steer. This paper explains first the development of a full vehicle multi-body simulation model that integrates customized friction functions in all major chassis joints. The model was correlated with the measurement of chassis kinematics, compliance, system-level frictions, and vehicle dynamic performance. Using the simulation and a confirmation with two test vehicles, key vehicle performance areas affected by chassis frictions were then identified. Next, a virtual sensitivity analysis was done to find influential frictions for each of the affected performance areas. From this research, common influential frictions that have influence on multiple performance areas were identified.

2. System Modeling

2.1. Modeling Approach

A multi-body simulation model was developed for a sport utility vehicle equipped with a MacPherson front suspension, trailing-arm rear suspension, and a rack-and-pinion steering system. To build the model, an Adams/Car environment was used due to its ability to assemble different sub-systems.

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In order to capture critical effect of chassis frictions on vehicle performance, custom templates and sub-systems were created to include frictions at major chassis joints in translational, rotational, and rocking directions. Figure 1 shows the frictions that were considered in the study, which included strut bearing friction torque, front damper friction force, front damper friction torque, and lower-arm ball joint friction torque for the front suspension, steer-arm ball joint friction torque and steering gearbox friction force for the steering system, and upper-arm ball joint friction torque and rear damper friction force for the rear suspension.

In order to help achieve numerical simulation stability and replicate a realistic friction profile, velocity-dependent friction functions (Fig. 2) are used to describe the chassis frictions. The velocity-dependent friction profile allows the breakthrough friction to exponentially decay to the kinetic one while guarantying continuity at zero relative velocity. The breakthrough friction and the ratio of kinetic friction to breakthrough friction are measured by using related components for each defined chassis friction.

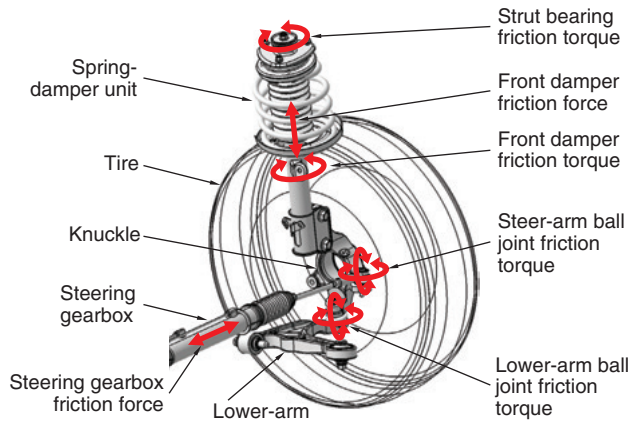
Figure 3 shows the full vehicle simulation model, which includes the front chassis, rear chassis, power train system, tires and wheels, rigid body, front and rear stabilizer bars, front and rear sub-frames, and chassis frictions. Displacement-dependent stiffness and damping characteristics were considered for all

mount bushings. A Pacejka tire model with relaxation consideration was used for the tires in order to capture both low-speed and high-speed behavior. The complete vehicle model functions as a single tool to analyze multiple dynamic phenomena.

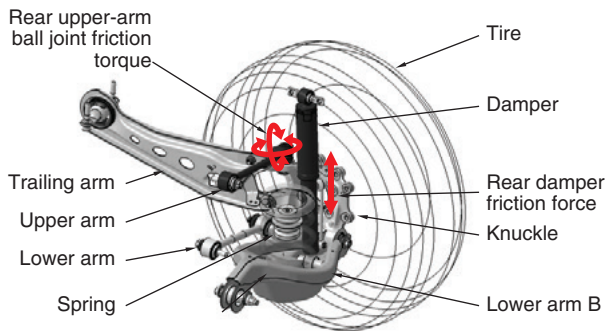
2.2. Vehicle Model Validation

In order to systematically validate the vehicle simulation model, the simulation results of chassis kinematic, compliance, and friction characteristics were compared in sequence with the measurement data of the vehicle. The simulation model was then compared with the test vehicle in multiple performance areas.

The measured kinematic and compliance characteristics are captured on a suspension parameter measurement machine (SPMM). During the measurement of vertical friction of suspension systems, a quasi-static loading cycle in vertical direction on the SPMM was carried out, and the vertical friction was then determined as half of the hysteresis bandwidth of the suspension displacement-loading force curve. During the measurement of steering friction torque of the front suspension and steering system, the vehicle was supported at the front tire contact patches by a pair of friction-free bearings, and a quasi-static steering lock-to-lock cycle was performed. Half of the hysteresis bandwidth of the steering angle-torque curve was used as the steering friction torque of the chassis system.



(a) MacPherson front suspension and steering system



(b) Trailing-arm rear suspension

Fig. 1 Frictions in vehicle chassis system

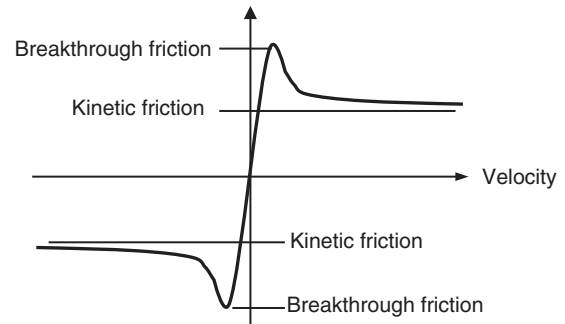


Fig. 2 Velocity-dependent friction profile used to define chassis frictions

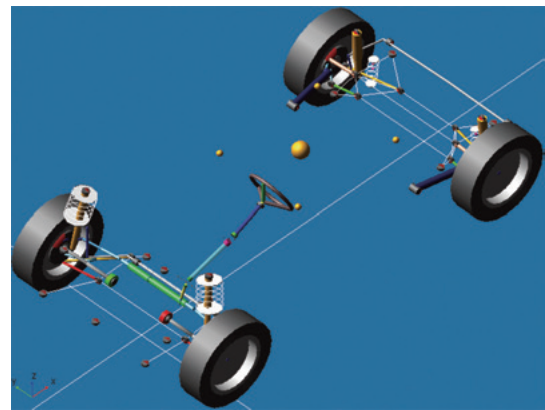


Fig. 3 Multi-body simulation model for complete vehicle

Table 1 Friction specifications of the Low-Friction and High-Friction vehicles

Friction name	Low-Friction	High-Friction
Lower-arm ball joint friction torque (Nm)	7	21
Steer-arm ball joint friction torque (Nm)	0.5	11
Strut bearing friction torque (Nm)	1.7	8
Steering gearbox friction force (N)	100	175
Rear upper-arm ball joint friction torque (Nm)	1	17.5

During the validation of compliance characteristics, a common stiffness scaling factor was included for all suspension bushings, sub-frame bushings, and steering gearbox mounting bushings, while during the friction correlation of the simulation model, a common friction scaling factor was used for all frictions in the chassis system.

Three vehicles (High-Friction vehicle, Low-Friction vehicle, and Production vehicle) were specially built to validate the model. The vehicles all had the same specifications except for different friction levels in the following chassis parts: strut bearing, lower-arm ball joint, steer-arm ball joint, steering gearbox, and the upper-arm ball joint of the rear suspension. These parts were chosen based on the production line capability for manufacturing parts with varying friction specifications. The differences in friction specifications between the Low-Friction and the High-Friction Vehicles are listed in Table 1. The ratio of system-level frictions between the High-Friction and Low-Friction vehicles achieved 1.3 in vertical direction of the front suspension and 1.6 in the steering rotational direction.

Whereas the kinematic and compliance correlation was mainly based on the Production vehicle, the friction correlation was performed on all three vehicles. Figure 4 illustrates an exemplary comparison between simulated and measured suspension kinematic and compliance characteristics. As shown, the simulated bump toe, bump camber, lateral compliance, and longitudinal compliance have fairly good agreement with the measurement. Similarly, good correlation results are obtained for other kinematic and compliance parameters, such as steering ratio, roll stiffness, wheel rate, and toe compliance.

Figure 5(a) demonstrates the measured and simulated suspension vertical frictions. As shown, the simulated system-level friction results closely match those from measuring all three vehicles and for both front and rear suspension systems. Figure 5(b) shows close correlation between simulated and measured steering friction torques of the chassis system in all three vehicles.

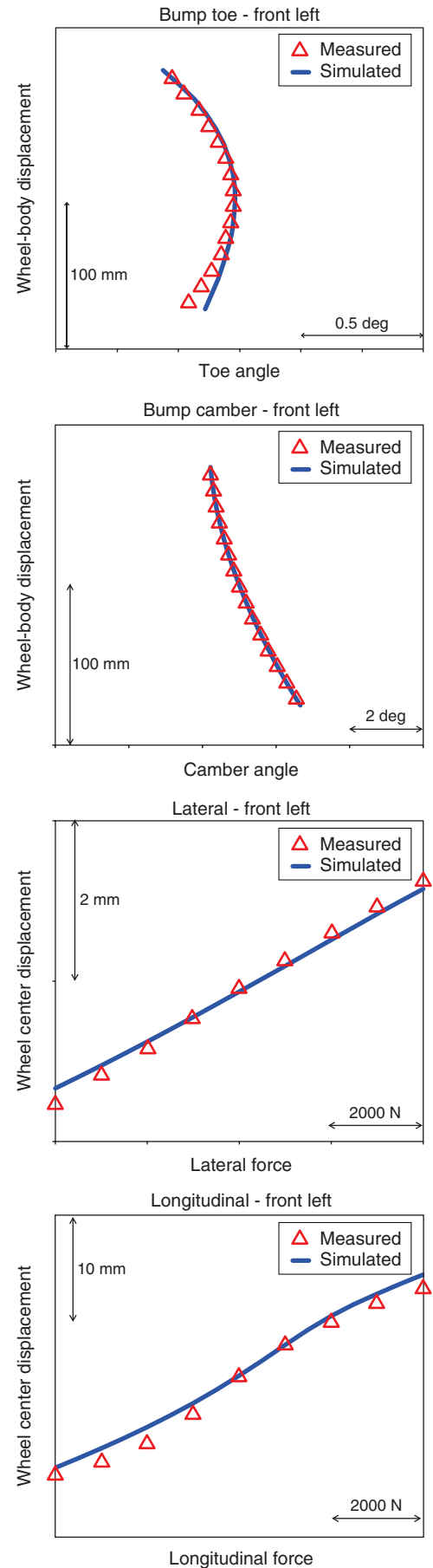


Fig. 4 Comparison of simulated and measured chassis kinematic and compliance characteristics

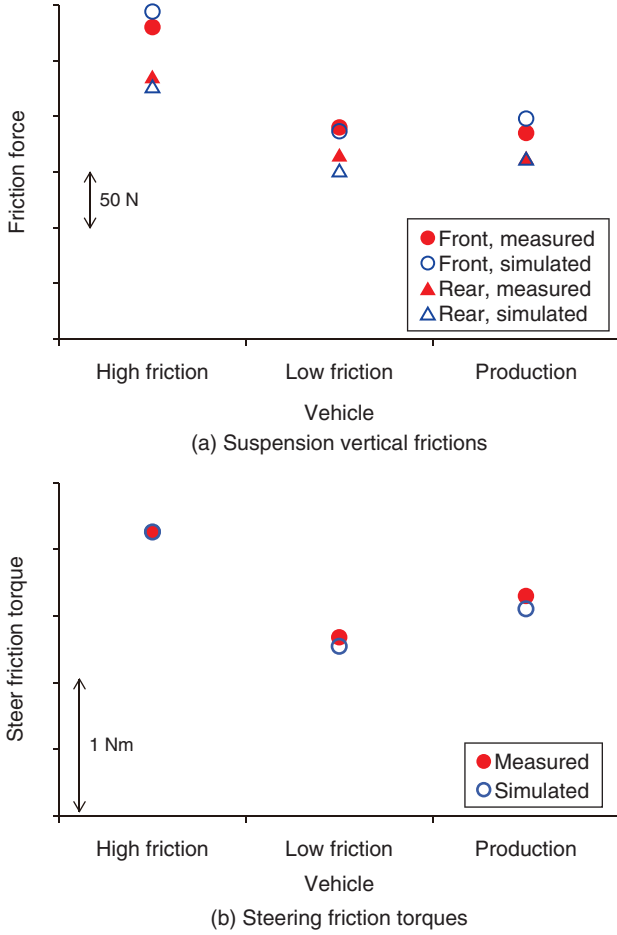


Fig. 5 Comparison of simulated and measured system-level friction characteristics

3. Performance Areas Affected by Frictions

3.1. Quantifying the Influence of Frictions

The High-Friction and Low-Friction vehicles were used to evaluate the relative performance change in each area and the evaluation results were used to further validate the simulation model.

The performance areas covered in the investigation include high-speed steering feel, low-speed steering feel, torque steer, vehicle drift and pull, brake judder sensitivity, gross body motion, body roll motion, steering shimmy, steering kickback, impact harshness, driving vibration caused by the tire-wheel's second order imbalance, and self-steer. High-speed steering feel is focused on the on-center steering angle-torque characteristics that can be presented by a steering damping factor and a spring coefficient⁽¹⁾⁻⁽⁴⁾, while low-speed steering feel is evaluated by the nimble feeling and maneuverability at low speeds. One of the key low-speed steering feel attributes is the self-centering ability of the steering wheel when it is released during a steady-state turning event. It is quantified by the steering wheel returning angle from a given angle in a certain period of time after the steering wheel is released.

Torque steer is when a vehicle drifts to one side during hard acceleration from zero speed on a split- μ

surface, which can be judged by the steering angle change during a hands-free acceleration event. Self-steer is the extent of steering effort degradation with the increase of steering input during cornering. Vehicle drift (and pull) is normally experienced during middle-to high-speed straight-line driving.

On the other hand, chassis sensitivity of brake judder and steering shimmy can be quantified as the transmitted vibration at the steering wheel when the front knuckles are excited by a given level of brake torque fluctuation or tire-wheel imbalance^{(5), (6)}. Whereas gross body motion is judged by the vehicle body motion in vertical direction, body roll motion is evaluated by the combined effect of the first and second overshoots of roll angle, roll rate, and yaw rate when there is an abrupt change in steering angular input. Steering kickback is measured as the steering effort fluctuation while impact harshness is quantified by a specially-designed index for the impact to vehicle seats, floor, and steering wheel, when the vehicle runs over an obstacle on a road.

Extensive simulation and measurement have been performed for the performance areas described above. Figure 6 shows the simulated and measured results of the high-speed steering feel characteristics under a sinusoid steering input (at 0.5 Hz). It suggests that chassis frictions can affect the steering damping factor but maintain steering spring coefficient for various

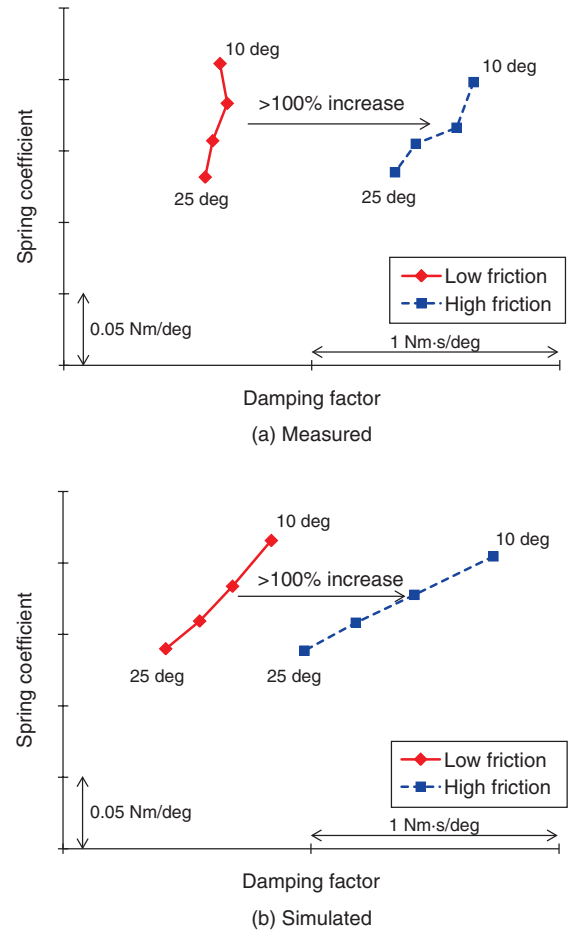


Fig. 6 Measured and simulated on-center steering feel characteristics (at high speed)

amplitudes of steering input. It was also confirmed that the simulation can accurately predict the trend.

Figure 7 compares the torque steer performance between the High-Friction and Low-Friction vehicles during hard acceleration from zero speed. As shown, the steering wheel angle change is reduced about 80% from the Low-Friction to High-Friction vehicle, and the simulation model accurately predicts the maximum steering angular rotation.

Figure 8 shows how body roll behavior changes between the Low-Friction and High-Friction vehicles when the steering wheel is released after a steady-state steering input of 60 degrees. As shown, increasing chassis frictions results in a reduction in the second overshoots and a mild decrease in the first overshoots of roll angle, roll rate, and yaw rate. It is further shown that the friction change from the Low-Friction vehicle to the High-Friction vehicle is able to reduce the number of roll rate and yaw rate overshoots from four to two. This can enhance a stable performance feel during abrupt maneuvers, such as making an emergency lane change or avoiding an obstacle.

These examples suggest that the higher the chassis frictions, the better the vehicle performance in torque steer, body roll control, and high-speed steering

damping. However, this trend does not hold true for low-speed steering feel. During low-speed maneuvers, such as in city driving or parking, lower levels of chassis frictions are desired to achieve a nimble and clear steering feel. Figure 9 shows the effect of frictions on low-speed steering feel by comparing the steering wheel self-centering ability of the High-Friction vehicle versus Low-Friction vehicle. Due to the increase in frictions, the self-centering ability of the High-Friction vehicle is reduced by almost 50%.

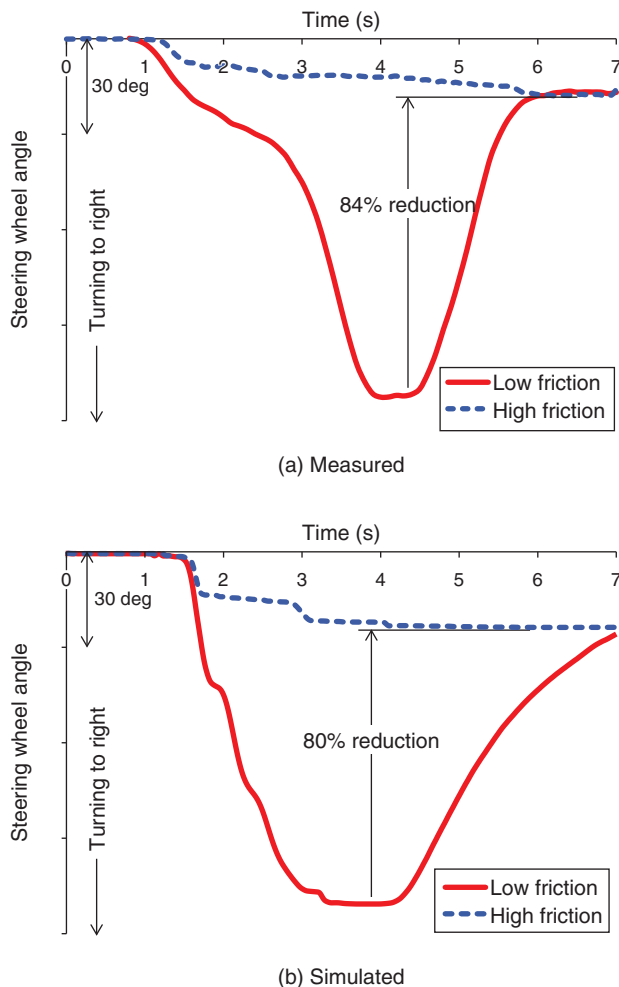


Fig. 7 Torque steer during hard acceleration from zero speed

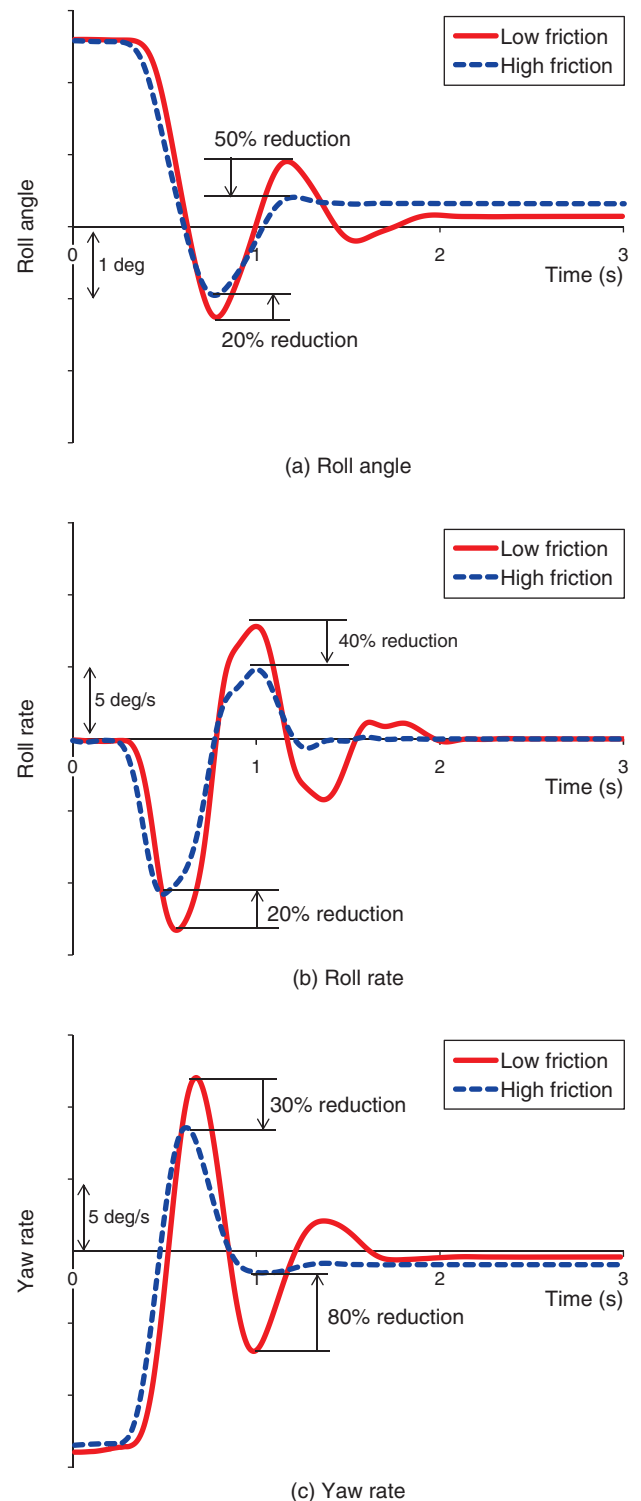


Fig. 8 Simulated vehicle roll motion control

3.2. Performance Areas Influenced by Frictions

In order to compare the impact of chassis frictions on different vehicle performance areas, the percentage of performance change from the Low-Friction vehicle to the High-Friction vehicle is calculated for each performance area. The absolute values of the percentage results are then summarized as relative changes in performance in Fig. 10.

In general, one quarter (or 25%) change in performance can be considered as significant enough for normal drivers to feel the difference. Thus, as shown in Fig. 10, chassis frictions can considerably affect the following performance areas: high-speed steering feel, torque steer, vehicle drift, low-speed steering feel, body roll motion, brake judder, and gross body motion.

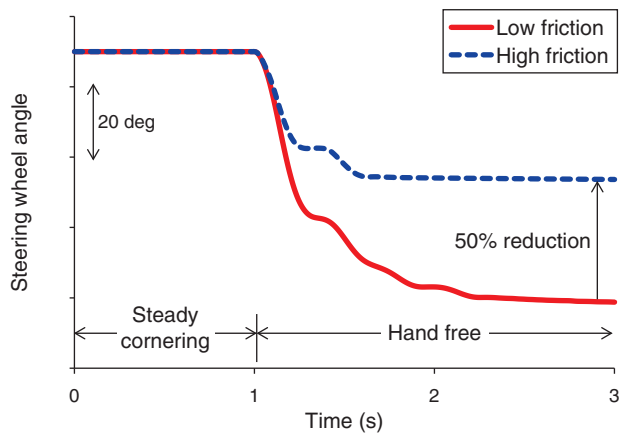


Fig. 9 Simulated steering wheel self-centering ability

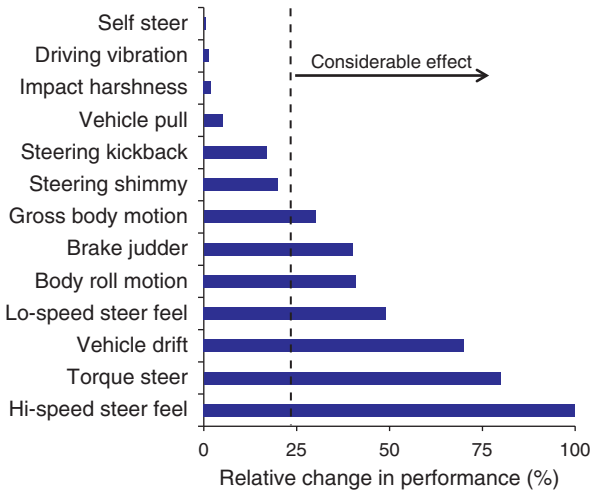


Fig. 10 Influence of chassis frictions on vehicle performance areas

4. Sensitivity of Performance to Frictions

4.1. Most Influential Frictions

A virtual sensitivity analysis was conducted to identify which frictions have more influence. During the sensitivity analysis, the vehicle model with half of production specification levels of chassis frictions

was used as a baseline model. Next, one derivative model was created for each chassis friction in such a way that the breakthrough and kinetic values of that specific chassis friction in the baseline model was increased up to five times as much as the corresponding production specification, while other chassis frictions remained unchanged. Because there are eight chassis frictions included in the baseline model, there are eight derivative models in total. The baseline model and the derivative models were used to predict individual performance areas; the relative sensitivity of each performance area to the changes of chassis frictions was analyzed, and most influential frictions for each performance area were determined.

Figure 11 shows that for torque steer, steer-arm ball joint friction torque, steering gearbox friction force, and lower-arm ball joint friction torque have high influence; strut bearing friction torque has some influence; while front damper friction force, front damper friction torque, rear damper friction force, and rear upper-arm ball joint friction torque have no influence. Conversely, for gross body motion, Figure 12 suggests that front damper friction force has high influence; lower-arm ball joint friction torque and steer-arm ball joint friction torque have some influence; rear damper friction force has low influence;

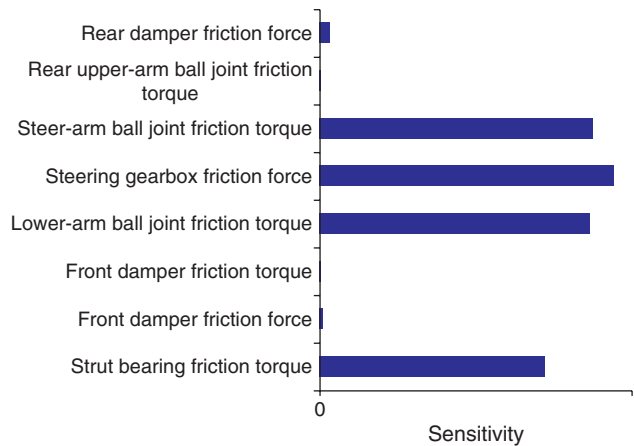


Fig. 11 Sensitivity of torque steer to chassis frictions

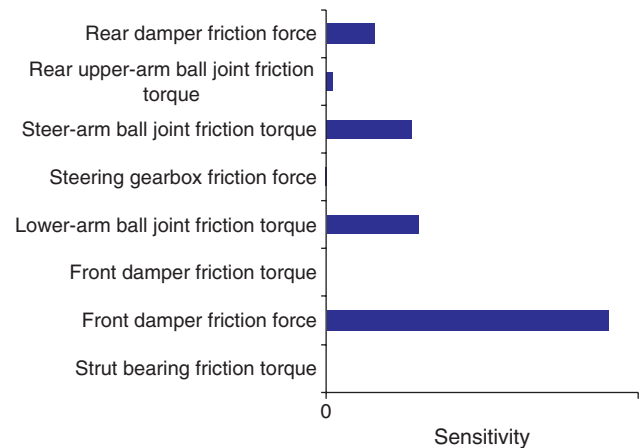


Fig. 12 Sensitivity of gross body motion to chassis frictions

and strut bearing friction torque, front damper friction torque, steering gearbox friction force, and rear upper-arm ball joint friction torque have no influence.

Similarly, Figs. 13 and 14 show that with respect to low-speed and high-speed steering feel, steer-arm ball joint friction torque and steering gearbox friction force have high or some influence, lower-arm ball joint friction torque and strut bearing friction torque have low influence, and all other frictions have no influence.

4.2. Common Influential Frictions

Table 2 summarizes the findings of the high-influence chassis frictions for each performance area. As shown, steer-arm ball joint friction torque and lower-arm ball joint friction torque are the only chassis frictions that affect all seven performance areas, while steering gearbox friction force is influential on most, but not all, performance areas. The data also imply that steer-arm ball joint friction torque, lower-arm ball joint friction torque, and steering gearbox friction force are principal chassis friction elements that need close attention during vehicle development.

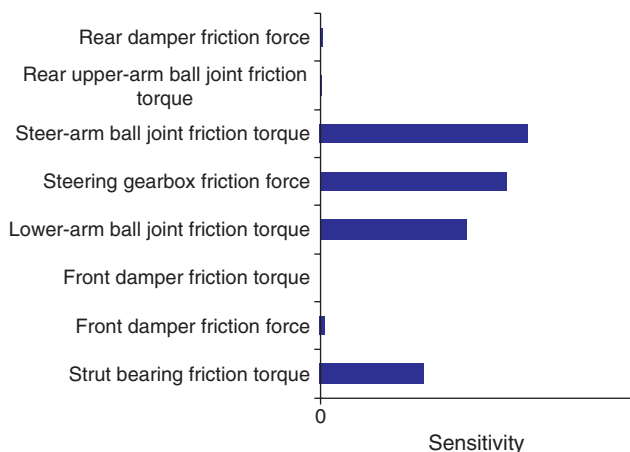


Fig. 13 Sensitivity of low-speed steering feel to chassis frictions

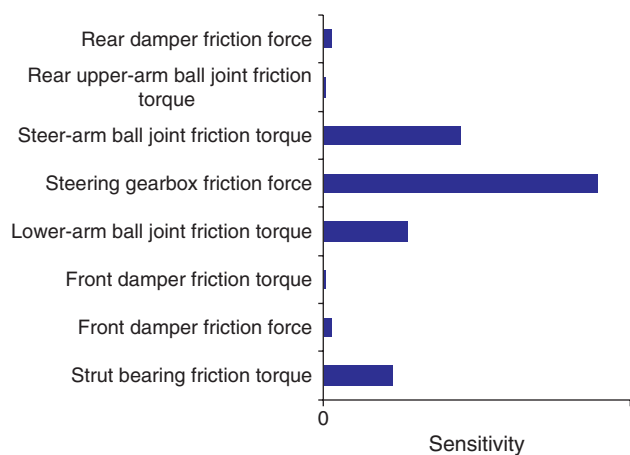


Fig. 14 Sensitivity of high-speed steering feel to chassis frictions

Table 2 Summary of the sensitivity of vehicle performance to chassis frictions

⊙ Most influential ○ Influential △ Less influential × Not influential

Friction \ Performance	Strut bearing friction torque	Front damper friction force	Front damper friction torque	Lower-arm ball joint friction torque	Steer-arm ball joint friction torque	Steering gearbox friction force	Rear upper-arm ball joint friction torque	Rear damper friction force
Hi-speed steer feel	△	×	×	△	○	⊙	×	×
Torque steer	○	×	×	⊙	⊙	⊙	×	×
Vehicle drift	⊙	×	×	⊙	○	○	×	×
Lo-speed steer feel	△	×	×	○	⊙	⊙	×	×
Body roll motion	○	○	×	○	○	⊙	×	△
Brake judder	⊙	×	×	○	○	⊙	×	×
Gross body motion	×	⊙	×	○	○	×	×	△

5. Conclusion

An extensive analytical study was conducted to quantify the influence of chassis frictions on vehicle dynamic performance areas and to identify the relative importance of frictions in different locations in a chassis system. A multi-body simulation model of a full vehicle was developed with the integration of customized friction functions in all major chassis joints and the correlation with measurement in chassis kinematics, compliance, system-level frictions, and vehicle dynamic behavior. Using vehicle simulation and actual measurement, it was determined that chassis frictions can affect seven key vehicle performance areas, which include high-speed steering feel, torque steer, vehicle drift, low-speed steering feel, body roll motion, brake judder, and gross body motion. This was followed by a thorough sensitivity analysis to identify the high-influence frictions for each of those performance areas. As a result, steer-arm ball joint friction torque, lower-arm ball joint friction torque, and steering gearbox friction force were identified as the common influential chassis frictions that exert considerable effect on almost all of the seven vehicle performance areas.

The study provides valuable information for understanding the influence of chassis frictions on vehicle dynamic behavior and for developing an effective friction control strategy for vehicle development. Further experimental investigation is conducted⁽⁷⁾ to understand how each of the seven key performance areas can be affected by the different friction levels at a selected location.

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