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Study of Suspension Effects on Braking Performance for Improving Driving Safety and Comfort

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***Abstract* - Suspension systems are vital in determining the vehicle's response to various driving conditions, including braking maneuvers. This paper aims to investigate the impact of suspension characteristics on braking performance, to improve overall driving safety and comfort. This study used a sedan car model that drives on a straight track and cornering. Modeling was carried out using the Altair Motion view 2021 with two test cases: braking tests on a straight track and brake-in-turn tests with speeds of 30 km/h and 60 km/h. The results showed that in braking tests on a straight track, increasing suspension stiffness reduces longitudinal slip on the rear wheels and suspension travel on both the front and rear wheels. This reduction in longitudinal slip results in the actual wheel speed value getting closer to the wheel rotational speed. While in the brake-in-turn test, increasing stiffness affects the lateral slip of the rear wheels. This improves driving safety because it reduces the potential for the car to skid.**

Keywords: brake-in-turn test, braking system, longitudinal slip, lateral slip, straight line brake, suspension system.

I. INTRODUCTION

Cars are one of the most common modes of transportation, which can be used as personal, public, or for transporting goods [1][2][3]. Passenger cars are vehicles whose main function is to transport passengers which prioritize comfort, with a closed roof, and the ability to transport at least 4 passengers and luggage. Meanwhile, driving comfort is influenced by various factors, including ease of control, fuel efficiency, cabin space, and vibration and shock absorption capabilities [4][5][6][7].

The suspension system plays an important role in improving the controllability and stability of the vehicle [8][9]. In addition, the suspension also functions to absorb shocks received from the road, so the suspension also affects driving comfort [10]. However, the controllability and comfort of a suspension system can be in conflict because the controllability is not comparable to driving comfort.

In addition to comfort, a vehicle's safety also should be considered. For this purpose, a moving system must have a system that can provide deceleration that is the braking system functions which provide friction so that the vehicle's movement can be slowed down. However, too much braking force is undesirable because it can interfere with driving control capabilities. Therefore, the braking system on today's cars is generally equipped with an anti-lock braking system (ABS) [11].

For passenger cars, a suspension system is expected to provide good shock absorption capabilities but does not result in poor vehicle control performance. Likewise, a good braking system must be able to prevent locking conditions on the wheels to minimize the potential for accidents caused by excessive braking force. In this research, the impact of suspension characteristics on braking performance to improve overall driving safety and comfort is investigated. A sedan car model that drives on a straight track and cornering is applied with two test cases: braking tests on a straight track and brake-in-turn tests with speeds of 30 km/h and 60 km/h.

II. BASIC THEORY AND METHODOLOGY

2.1 Vehicle Model

In this study, 14 DoF (Degree of Freedom) are used to analyze the braking performance of the vehicle. These 14 DoF consist of longitudinal, lateral, vertical, roll, pitch, and yaw motions at the center of gravity sprung mass, as well as rotational and vertical motions at each wheel of the vehicle. Figure 1 and Figure 2 show the vehicle model with 14 DoF and the free body diagram of the vehicle, respectively.

2.2 Braking Forces on a Straight Track

In the braking process, there are various forces acting on the wheels, namely the contact force between the wheels and the road, the force due to braking, and the force due to vehicle speed (longitudinal force) [11][12]. The equilibrium force of this condition is illustrated by free body diagram on Figure 3.

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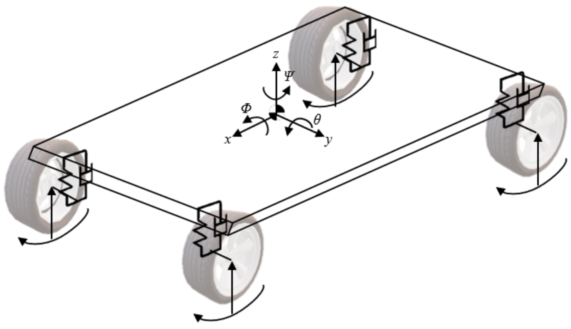

Figure 1: Vehicle Model with 14 DoF

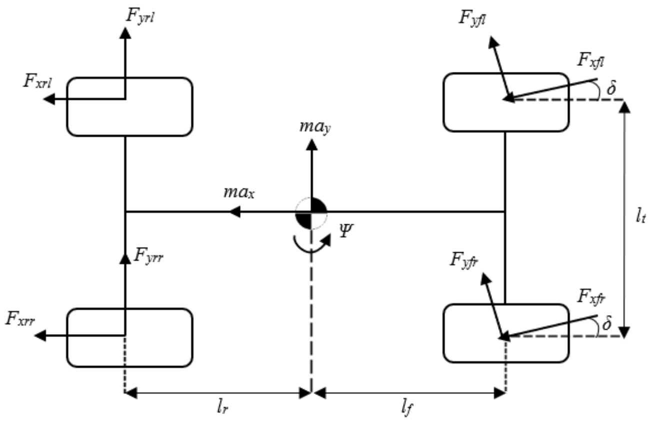

Figure 2: Free Body Diagram of Vehicle

The equilibrium moment about the rear wheels in braking conditions before the wheels lock is

$$F_{zf}(l_1 + l_2) - Pl_2 - P_z h = 0 \quad (1)$$

At rest (J = 0):

$$P_f = \frac{Pl_2}{l_1+l_2} \quad (2)$$

The deceleration with J m/s^2 on the front wheel is as follows:

$$F_{zf} = \frac{Pl_2}{l_1+l_2} + \frac{Pzh}{l_1+l_2} \quad (3)$$

$$F_{zf} = P_f + \frac{Pzh}{E} \quad (4)$$

and on the rear wheel is

$$F_{zr} = \frac{Pl_1}{l_1+l_2} - \frac{Pzh}{l_1+l_2} \quad (5)$$

$$F_{zr} = P_r - \frac{Pzh}{E} \quad (6)$$

For a car with locked wheels, its free body diagram is shown in Figure 4 and the equilibrium of force is expressed as

$$P = F_{zf} + F_{zr} = mg \quad (7)$$

Meanwhile, the longitudinal force equilibrium is given by the following equation

$$ma_x = F_{xf}{}' + F_{xr}{}' \quad (8)$$

Furthermore, the friction on the wheel is

$$\left(F_{xf}{}' + F_{xr}{}'\right) = \mu_t\left(F_{zf} + F_{zr}\right) \quad (9)$$

and

$$\mu_t = \frac{\left(F_{xf}{}' + F_{xr}{}'\right)}{\left(F_{zf} + F_{zr}\right)} = \frac{a_x}{g} = z \quad (10)$$

Where is μ_t is the coefficient of friction between the tire and the road. In a skidding condition, load transfer can still occur. However, the magnitude of the braking force is due to the coefficient of friction between the tire and the road, not due to the friction that occurs on the brake.

Wheel slip can be interpreted as the ratio between the rotational speed of the wheel, ω, and the translational speed at the wheel center, V, thus [13]

$$Wheel\ slip = \frac{V - \omega r_r}{V} \quad (11)$$

In Equation 11, r_r represents the radius of the wheel. When the wheel stops on a straight road, the slip will increase as the deceleration increases and the wheel will skid when the slip reaches 100%.

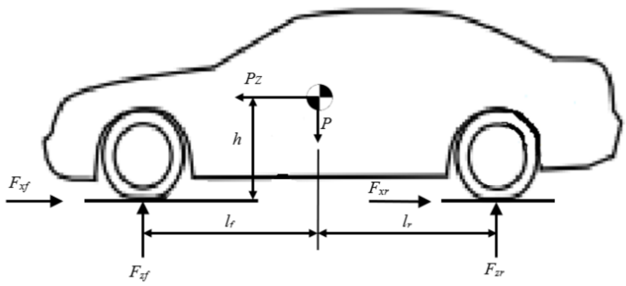

Figure 3: Free Body Diagram of Braking Force with Unlocked Wheel Condition

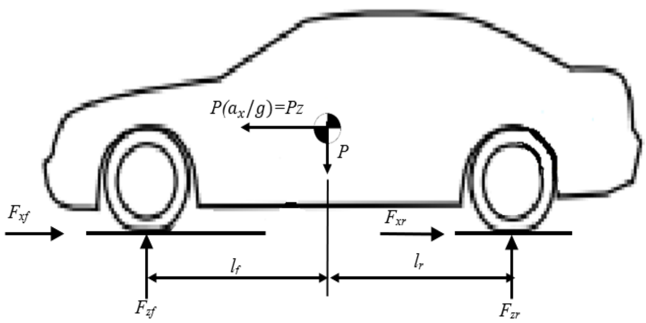

Figure 4: Free Body Diagram of Braking Force on a Car When the Wheels Are Locked

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2.3 Brake in Turn Braking

Figure 5 shows a car cornering on a horizontal road on stationery and cornering condition. The lateral force then can be formulated as follow:

$$F_c = \frac{(mv^2)}{R} \quad (12)$$

Where *v* is the speed of the car (m/s) and *R*is the radius of the corner (m). Taking moments about the outside tyre contact patch:

$$F_{zi} l_t - P\frac{l_t}{2} + hF = 0 \quad (13)$$

The normal force acting on the inside tyre is

$$F_{zi} = \frac{P}{2} - \frac{hF}{t} \quad (14)$$

and the normal force acting on the outside tyre is

$$F_{zo} = \frac{P}{2} + \frac{hF}{t} \quad (15)$$

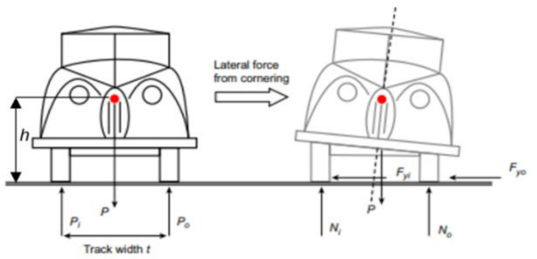

Figure 5: Free Body Diagram of Braking Forces During Cornering [12]

On the above equations, *P*/2 is the static load on the wheel, and *hF*/*t* is the lateral load transfer. In the cornering process, the vertical load will be distributed from the inside wheel to the outside wheel. If the vehicle is not cornering, then the lateral load transfer value is zero.

2.4 Specifications of Vehicle and Suspension Model

Modeling of the vehicle that is used in this study was carried out using Altair Motion view 2021. The Altair Motion view application provides a sedan car model that can be accessed through the assembly wizard. The designed model consists of a car chassis, car body, front and rear suspension systems, car drive train systems, wheels, and various other complementary systems. Car specifications can be adjusted according to the available data. Table 1 shows the specifications of the car used in this study [14].

In this study, three suspensions are applied to the tested car. It is assumed that all those suspension models use a spring damper value of 2 Ns/mm [15]. Table 2 shows the specifications of the three suspension models to be tested.

2.5 Testing Methodology

ISO 7975:2006 specifies an open-loop test procedure for testing the handling characteristics of a vehicle and how it stays on track under braking [16]. This method tests the steady-state circular response of a vehicle that changes only due to the braking action. This test standard applies only to passenger cars and light trucks. The initial condition of the ISO 7975:2006 test is that the vehicle is traveling at a constant longitudinal speed on a circle with a certain radius. At the start of the brake-in-turn test, the vehicle is traveling at an initial speed of 30km/h and 60km/h on a track with a radius of 100m. Then, the car will brake with a deceleration of 5m/s^2.

Table 1: Specification of Vehicle and Suspension Model

Specification	
Mass	1369 kg
Engine volume	2.0L
Drive type	Front Wheel Drive (FWD)
Wheelbase	2634 mm
CoG location from rear wheel	1311 mm
High of Center of Gravity	450 mm
Track width	1760 mm
Ground clearance	139 mm
Front suspension	MacPherson Strut
Rear suspension	*Multi-Link*
Tyre size	P205/60HR16
Mass of wheel and tyre	36 kg
Number of seat	5

Table 2: Suspension Model Configurations

Suspension Specification			
Suspension model	Spring rate of front suspension (N/mm)	Spring rate of rear suspension (N/mm)	Spring damper (Ns/mm)
Model 1	73.6	58.8	2
Model 2	100	80	2
Model 3	137	137	2

Braking tests on straight tracks were conducted with initial speed configurations of 30 km/h and 60 km/h. Braking was performed until the vehicle stopped. The choice of the speed is based on the minimum speed rate on city and toll road conditions. The amount of deceleration for braking tests on straight tracks was 5 m/s^2.

On the other hand, the brake in-turn-braking test was conducted with an initial speed configuration of 30 km/h and 60 km/h. Braking was done until the vehicle stopped. The amount of deceleration for the braking test on a straight track was 5m/s^2. The length of the straight track was determined to be 10 m, and the radius of the track was 100 m[17].

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III. RESULTS AND DISCUSSIONS

Figure 6 shows longitudinal slip versus time in braking tests on a straight track with an initial 30km/h speed. Longitudinal slip is influenced by longitudinal force and indicates the difference between wheel rotation and sliding speeds. From Figure 6, the longitudinal slip on the rear wheels is higher than the longitudinal slip on the front wheels. The value of the left front wheel slip peaked at 3.1% in model 1. On the rear wheels, the slip value reached 10% in model 1 and the slip reached 4.75% in model 3.

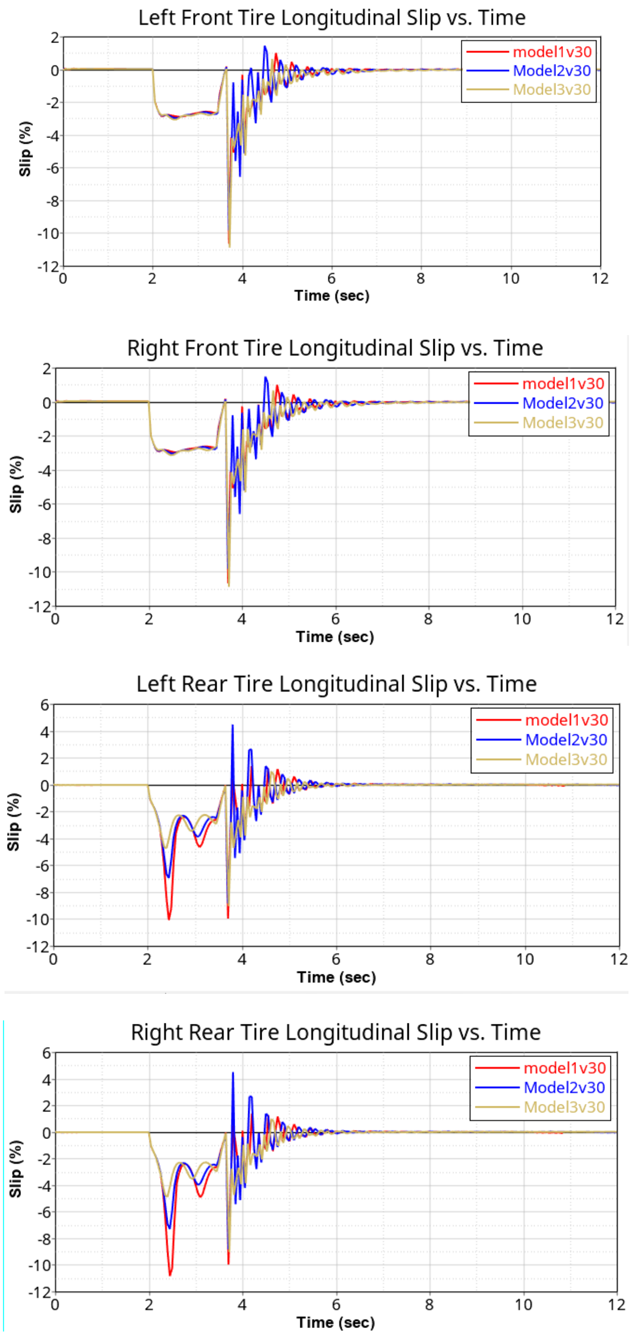

Figure 6: Longitudinal Slip versus Time in Braking Tests on a Straight Track with an Initial 30 km/h Speed

Figure 7 shows suspension travel versus time in braking testing on a straight track with an initial speed of 30 km/h. Suspension travel shows the amount of suspension movement during braking. From Figure 7, it can be seen that the suspension travel on the front wheels decreases when braking occurs. This is due to the front of the car experiencing a dive. On the other hand, the suspension travel on the rear wheels increases because the rear of the car experiences a squat. It can also be seen that the front left suspension is compressed by 10 mm in model 1 and the model 3 suspension is compressed by 5.5 mm. The rear left suspension extends 83 mm in model 1, and the model 3 suspension extends by 46 mm.

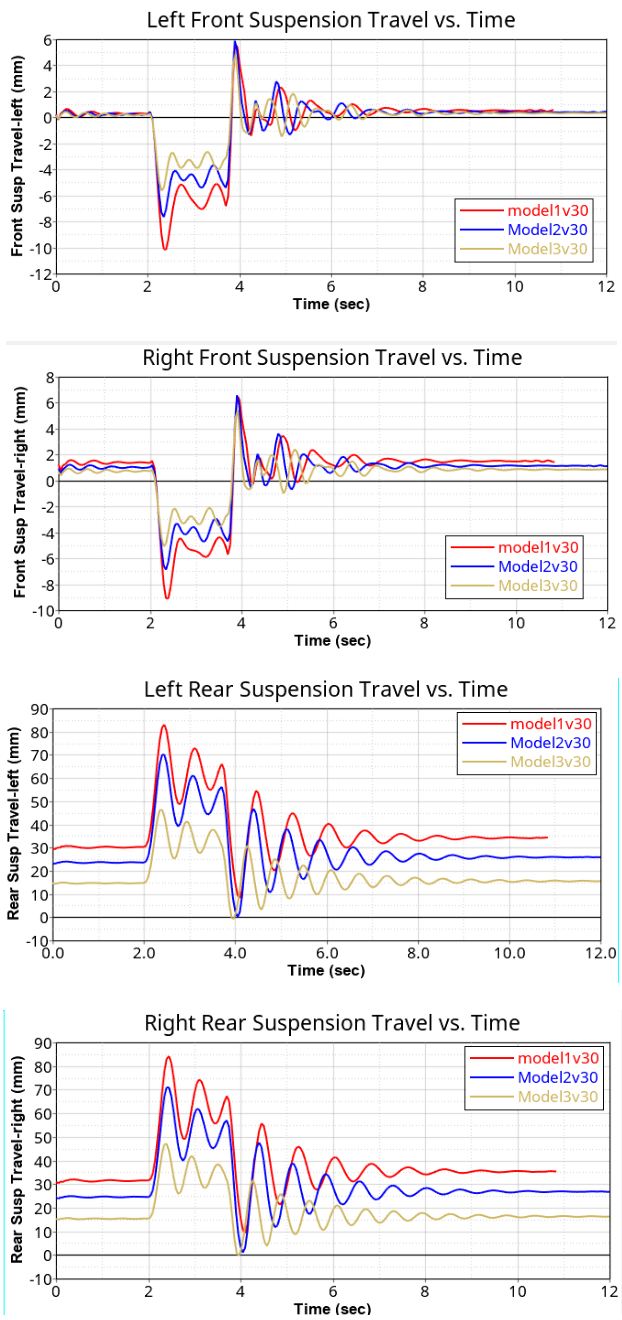

Figure 7: Suspension Travel versus Time in Braking Testing on a Straight Track with an Initial Speed of 30 km/h

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Longitudinal slip and suspension travel for braking tests on a straight track with an initial speed of 60 km/h are shown in Figures 8 and 9, respectively. It can be seen from Figure 8, that the slip value of the left front wheel peaked at 2.9% in model 1. On the rear wheels, the slip value reached 9.5% in model 1 and 4.75% in model 3.

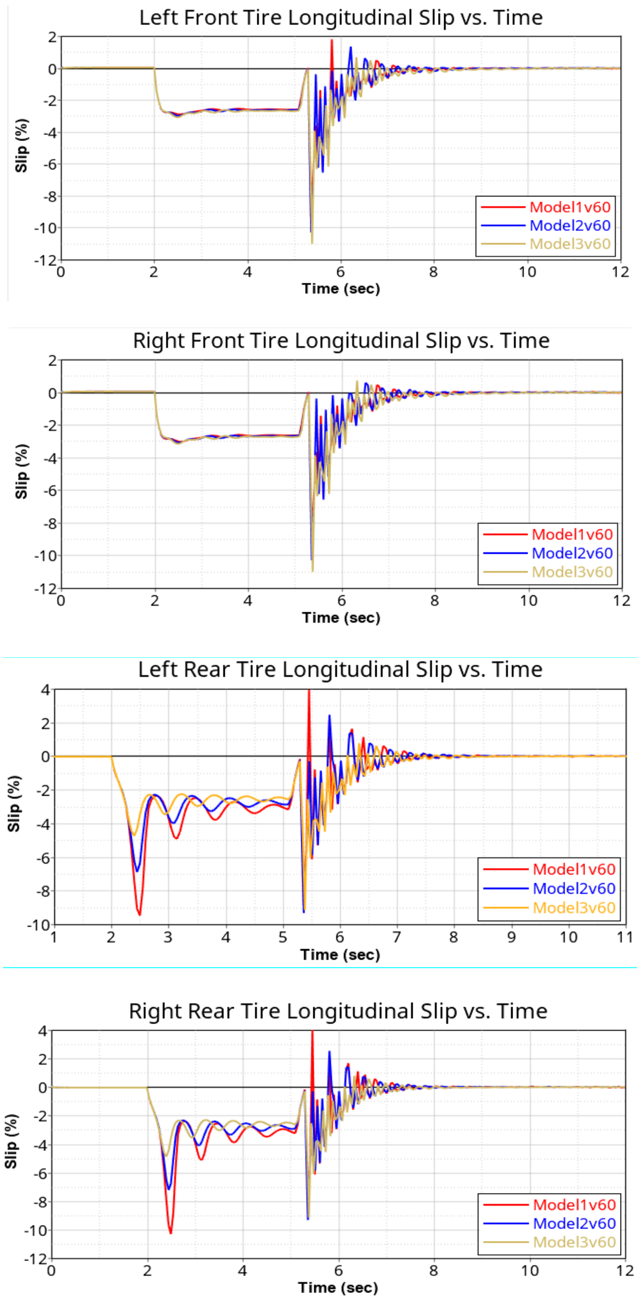

Figure 8: Longitudinal Slip versus Time in Braking Tests on a Straight Track with an Initial 60 km/h Speed

As for the braking test on a straight track with an initial speed of 60 km/h, the suspension travel that occurs on the front wheels decreases during braking because the front of the car experiences a dive. Meanwhile, the suspension travel on the rear wheels increases because the rear of the car experiences a squat. This is shown in Figure 9. It can also be seen if the front left suspension is compressed up to 10.5 mm on model 1 and the model 3 suspension is compressed up to 5.5 mm. Meanwhile, the rear left suspension extends 86 mm on model 1, and the model 3 suspension extends up to 47 mm.

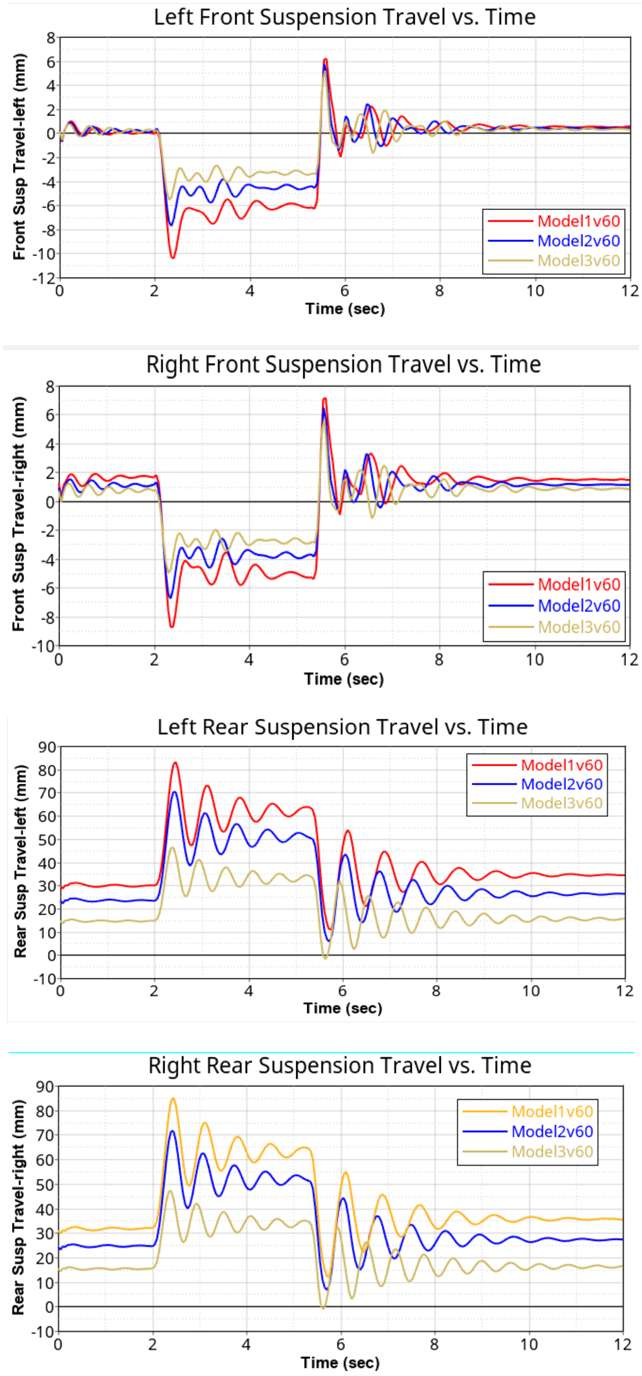

Figure 9: Suspension Travel versus Time in Braking Testing on a Straight Track with an Initial Speed of 60 km/h

Driving stability when turning can be indicated by tire lateral slip. The lateral slip value indicates the magnitude of the side slip angle of each wheel on the car. Tire lateral slip versus time in the brake-in-turn test for initial speeds of 30 km/h and 60 km/h in this study are shown in Figures 10 and 11, respectively.

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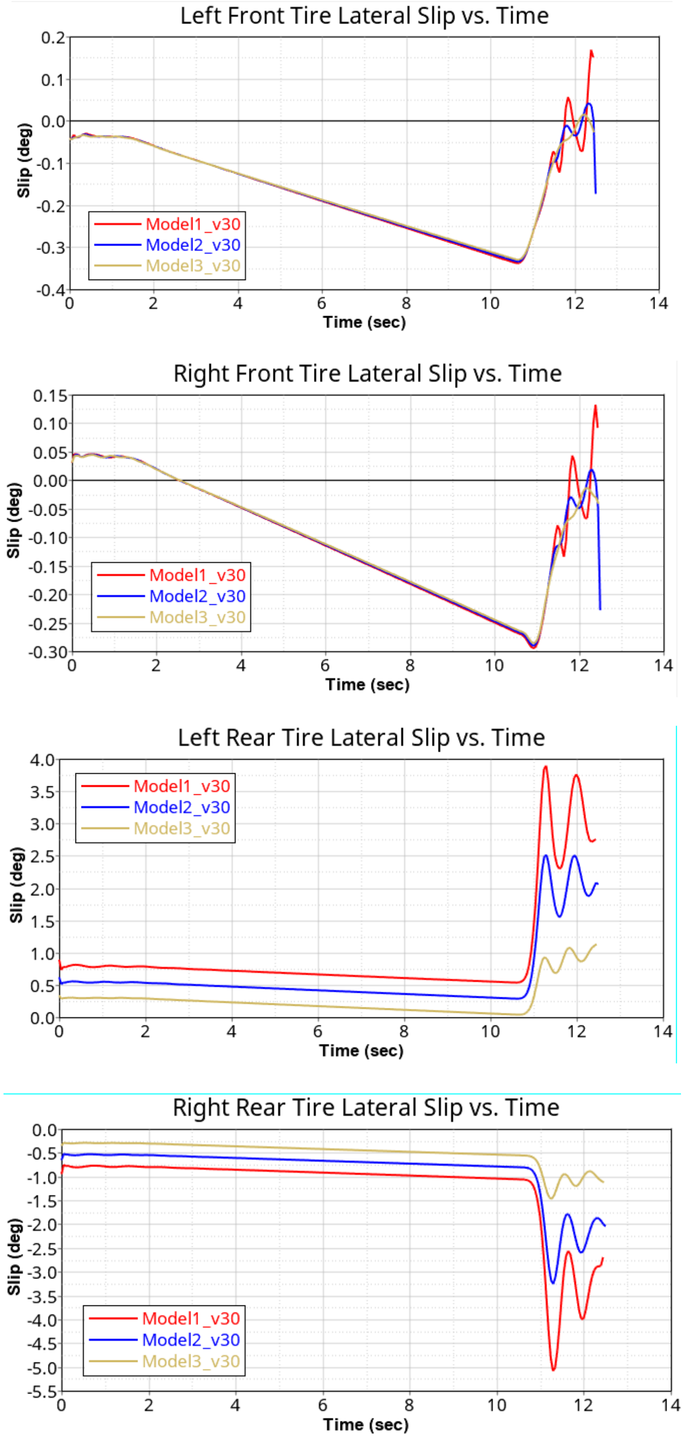

Figure 10: Tire Lateral Slip versus Time in Brake-in -Turn Test with Initial Speed of 30km/h

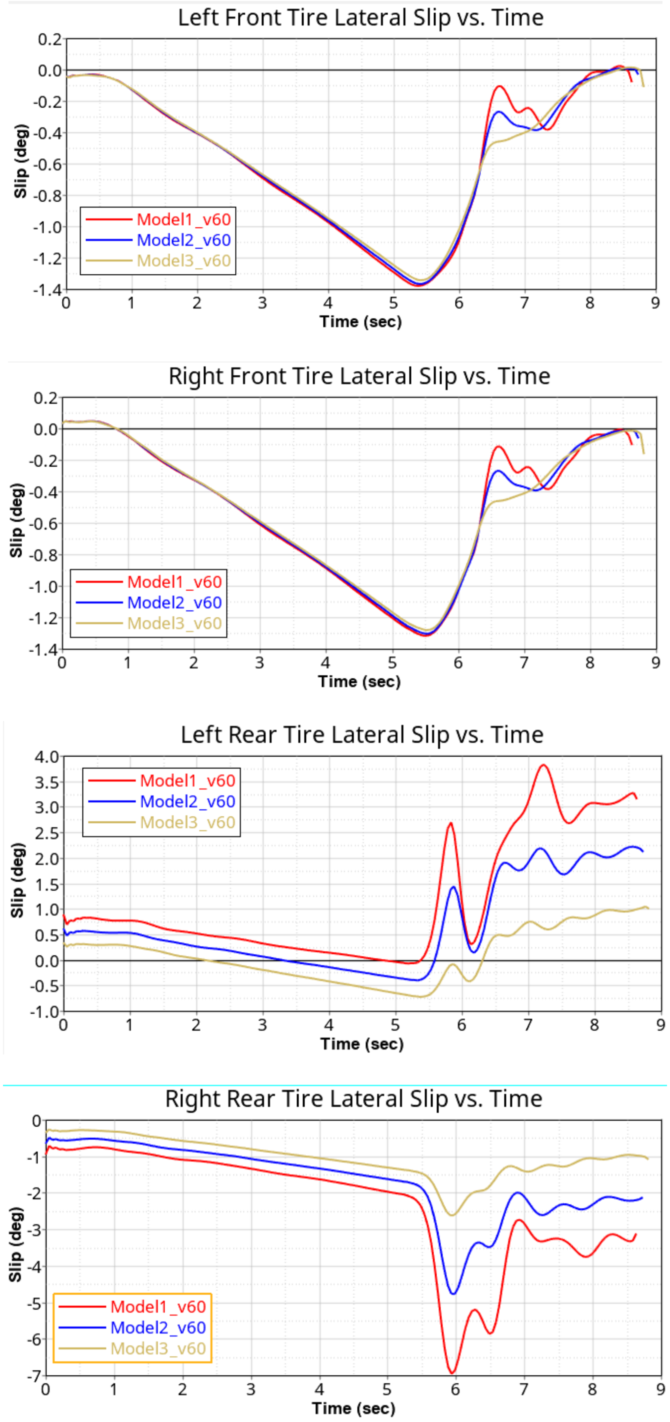

Figure 11: Tire Lateral Slip versus Time in Brake-in -Turn Test with Initial Speed of 60km/h

From Figure 10, it can be seen that in the brake-in-turn test with an initial speed of 30 km/h, the lateral slip on the front and rear wheels is very small so skidding is not possible when braking on a curved track. On the rear wheels when braking begins, the lateral slip value can reach 5° on the right rear wheel of the model 1 suspension. Meanwhile, the lateral slip of model 3 is lower with a value of 1.5° on the right rear wheel. Reducing the lateral slip value can increase driving stability.

For an initial speed of 60 km/h, the lateral slip on the front and rear wheels is also relatively small, as shown in Figure 11, so skidding is not possible when braking on a curved track. On the rear wheels when braking begins, the lateral slip value can reach 7° counterclockwise on the right rear wheel of model 1 suspension. Meanwhile, the lateral slip of model 3 is lower with a value of 2.625° on the right rear wheel. Furthermore, the reduction in the lateral slip value can increase driving stability.

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IV. CONCLUSION

Suspension modeling and test cars were carried out using the Altair Motionview 2021 application. The car model used was based on the assembly wizard feature in the application. Furthermore, the configuration that had been built was tested using the task wizard feature. From the braking test on a straight track, it can be concluded that increasing suspension stiffness reduces longitudinal slip on the rear wheels and suspension travel on both the front and rear wheels. The reduction in longitudinal slip resulted in the actual wheel speed value getting closer to the wheel rotational speed. Meanwhile, in the brake-in-turn test, increasing stiffness affects the lateral slip of the rear wheels. This increases driving safety because it reduces the potential for the car to skid.

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