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A Study on the Development Direction of a Tire Using Objective Evaluation and Analysis Techniques

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Abstract This study examines the characteristics of the steering stability performance of a vehicle with varying tire cornering stiffness. The vehicle and its front and rear tire models, which are the basis of simulation, were fabricated using SPMM and Flat Trac, respectively. Tire cornering stiffness of the front and rear wheels was modulated by changing the LKY, one of the scaling coefficients in the tire model. Steering stability performance evaluation is based on frequency response (ISO7401)[1] which can analyze the dynamic characteristics of the vehicle with varying steering input cycle and Steady State Speed (ISO4138)[2] which enables dynamic analysis of the vehicle with varying transient inputs. The results were analyzed by using measurement assessment factors with high correlation with actual stiffness evaluation. As a result of the evaluation, it was confirmed that the steering and stability performance of the vehicle increase when the cornering stiffness of the front wheel is increased and the cornering stiffness of the rear wheel is decreased, which has enabled us to identify the direction of development of real tires. It is expected that this study will be a starting point to improve the efficiency of the research and development to identify the cause of the decline of the running performance of the tires and the way to enhance it.

Keywords Objective Handling, Tire Model, Frequency Response, Steady State Circle, Steering Performance, Stability Performance

1. Introduction

It is no exaggeration to say that the steering stability of the vehicle is the largest part of the performance that ordinary drivers can feel. In addition, since the steering stability performance is closely related to safety issues, automakers, tire companies are constantly investing time in R & D to satisfy the performance. Steering stability is determined by the dynamic behavior of the vehicle and varies greatly with tire performance changes of tires. Generally, it is difficult to predict the performance before the actual test, so various simulations and indoor evaluations are used to predict the results and researches on the relationship with actual vehicles are also under way. In this study, the cornering stiffness of the front tires and the rear tires were set as design variables to improve the steering stability performance while the steering input cycle change test and the transient input test were conducted through simulations. The analysis of the dynamic characteristics of the vehicle utilized some key parameters of the "4 parameter methods" [3], [4], [5] as well as key factors of the "target setting evaluation method", which was studied internally in the past. [6]

2. Tire Model Configuration of Vehicle

2.1. Test Vehicle

The vehicle required for this study is a small SUV model, the main specifications of which are as shown in the Table 1. Kinematic parameters (alignment, roll center, wheel center displacement) and compliance characteristics (lateral, alignment torque, longitudinal, etc.) required for vehicle model configurations were applied to the modeling of multi-body dynamics simulator using SPMM equipment. Engine, power train and external parameters that are not required for vehicle dynamic characterization were excluded from this model configuration.

2.2. Test Tire

Table 2 shows the tire specifications used in this study. Other numerical values required to manufacture tire models were measured by using Flat Trac equipment that are capable of measuring Force & Moment of a single tire.

Table 1. Vehicle information

Overall Length	4697mm
Overall Width	1923mm
Overall Height	1624mm
Wheel Base	2807mm
Tread (Front)	1550mm
Tread (Rear)	1550mm
Weight	1770kg

Table 2. Tire information

Category	Front Tire	Rear Tire
Width	235mm	255mm
Aspect Ratio	55	50
Diameter	18inch	18inch

3. Performance Evaluation

In this paper, the performance evaluation is carried out by using “Frequency Response” test and “Steady State Speed” test, which are mainly used for steering stability evaluation while the change of steering stability performance is compared through comparison of major factors.

3.1. Evaluation Condition: Frequency Response

In order to analyze the dynamic characteristics of the vehicle while varying the steering input cycle, ISO7401 was used and the analysis was divided into time domain and frequency domain. The detailed evaluation conditions such as vehicle speed, lateral acceleration (steering angle), steering cycle and the like can be changed and evaluated within the scope of the specification under the regulations depending on the judgment of that who conduct the test. In this study, the same test conditions as in Table 3 were used. Figure 1 shows the input values as a graph.

In this test mode, the response of the vehicle was divided into three sections to analyze the dynamic characteristics of the vehicle. Table 4 shows the analysis items. Each item consists largely of Gain and Delay, and 1Hz interval value is calculated and used. The 1 Hz interval assumes normal operating conditions, and in some cases, 0.2 Hz or 1.5 Hz interval is analyzed.

Table 3. Test Condition

Vehicle Speed	100 km/h
Steering Angle	27 deg
Steering Frequency	0.2 Hz ~ 3.5 Hz
Duration	18 s

Table 4. Analysis Metrics

Metrics		Unit
Steering Wheel Angle to Lateral Acceleration	1Hz Gain	m/s2 / deg
	1 Hz Delay	ms
Steering Wheel Angle to Yaw Velocity	1 Hz Gain	deg/sec / deg
	1 Hz Delay	ms
Yaw Velocity to Lateral Acceleration	1 Hz Delay	ms

3.2. Evaluation Condition: Steady State Speed

ISO4138 is used to analyze the dynamic characteristics of the vehicle with varying transient input, and the Steady State Speed is basically included in the steady state circle. Steady state circle is classified into a steady state angle that increases the speed with the steering wheel angle fixed and a steady state radius, which increases the speed and steering wheel angle with fixed turning radius, and a steady state speed which increases the steering wheel angle with fixed speed. This study utilized the same test conditions as shown in Table 5. The input values are shown in Fig. 2 as a graph.

Table 5. Test Condition

Vehicle Speed	100 km/h
Steering Angle	0 deg to 180 deg
Steering Input Speed	30 deg/sec
Duration	8 s

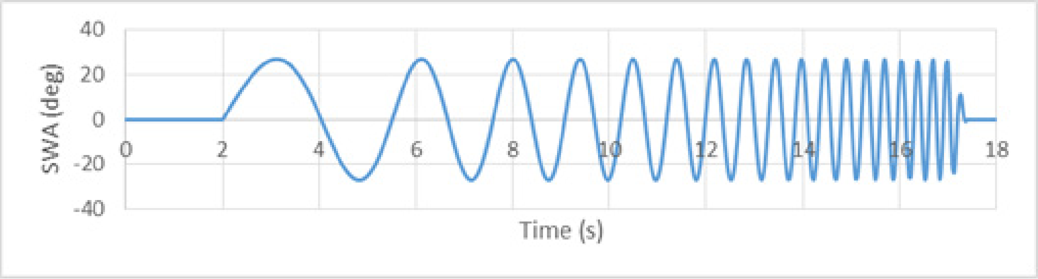

Figure 1. Steering Input

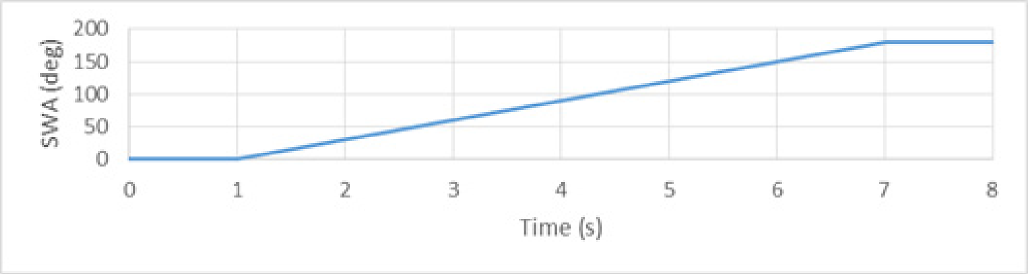

Figure 2. Steering Input

In this test mode, items related to stability can be mainly analyzed among the dynamic characteristics of the vehicle. Table 6 shows the analysis items. The maximum grip and steer characteristics of the vehicle and the performance harmonies of the front and rear wheels can be identified.

Table 6. Analysis Metrics

Metrics	Unit
Steering Wheel Gradient	deg / m/s2
Side Slip Gradient	deg / m/s2
Maximum Lateral Acceleration	m/s2
Front Axle Slip Angle(4 m/s2)	deg
Front Axle Slip Angle(7 m/s2)	deg
Rear Axle Slip Angle(4 m/s2)	deg
Rear Axle Slip Angle(7 m/s2)	deg

3.3. Evaluation Condition: Tire characteristics

Prior to this study, three design conditions were selected first for semi-finished tires (steel belt angle, cap ply step number, bead filler height), and the trend of performance change in a single tire under varying conditions was identified through Force & Moment evaluation. Tire design conditions and F&M results were analyzed through analysis of variance. Cornering stiffness, which showed the most significant difference, was set as a design factor. Cornering stiffness is the lateral force that occurs when the tire slip angle is 1 degree. The cornering stiffness is proportional to the lateral force. Larger cornering stiffness values indicate that the lateral force is performing better. The cornering stiffness, which is set as the design factor, is increased or decreased as shown in Table 7 to create total 9 conditions, on the basis of which simulations were carried out. Performance changes were analyzed based on 100% of front wheel and 100% of rear wheel, and other parameters were not changed.

Table 7. Tire Condition

Cornering Stiffness (F)	Cornering Stiffness (R)
115%	115%
	100%
	85%
100%	115%
	100%
	85%
85%	115%
	100%
	85%

Figure 3 and Figure 4 show changes in lateral force with the slip angle changes of the front and rear tires.

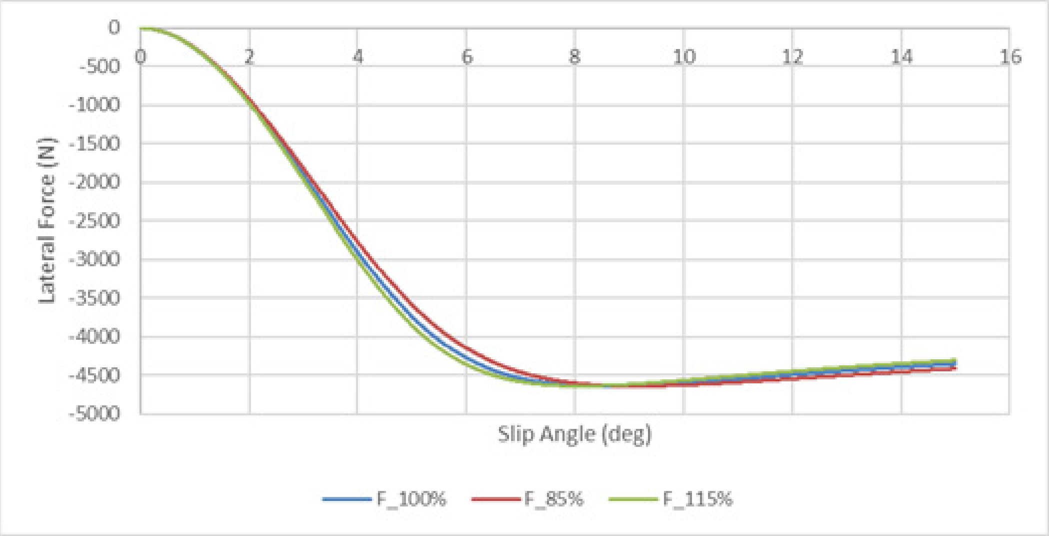

Figure 3. Front Tire Cornering Stiffness

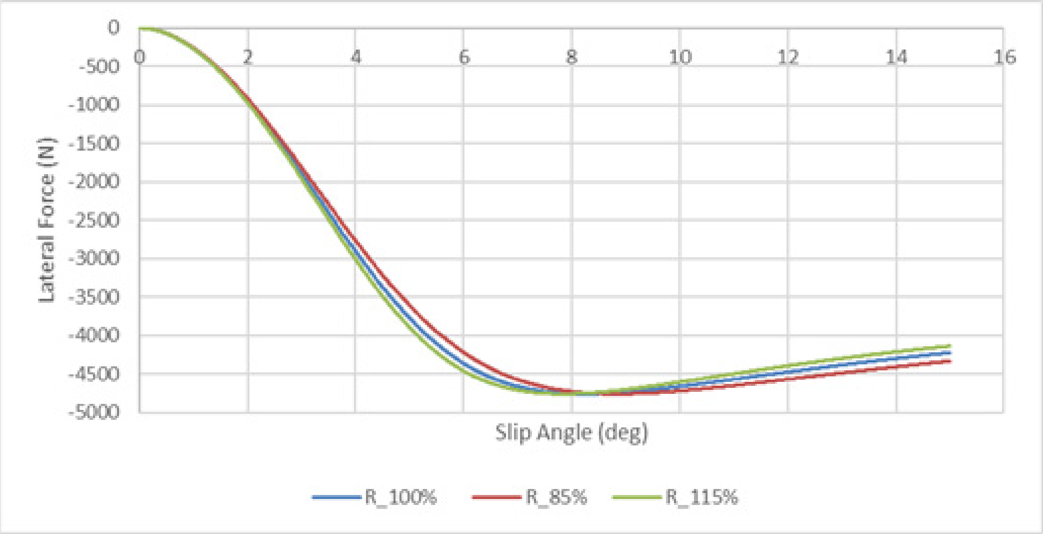

Figure 4. Rear Tire Cornering Stiffness

4. Performance Analysis

4.1. Frequency Response

The frequency response is used to quantitatively measure and analyze the response of the vehicle to the frequency change input. It is easy to understand that when steering is inputted into the vehicle at various frequency of sinusoidal wave, each characteristic of the vehicle responds at the same frequency with a certain size and specific phase angle with respect to the input. The frequency response is used mainly for the phase (represented by Gain or Amplitude) and the response time (represented by seconds or dB). The basic response characteristics of vehicle can be simply expressed as follows.

Steering Wheel Torque → Steering Wheel Angle → Front Axle Slip Angle → Yaw Velocity → Rear Axle Slip Angle → Lateral Acceleration → Roll Motion

Based on the conclusions obtained from existing correlation studies, the response characteristics of the front wheel including the rear wheel performance can be derived in the section from the input of the steering wheel angle to the generation of the yaw model while the response characteristic of the rear wheel including the front wheel performance can be derived in the section from the generation of the yaw motion to the generation of the lateral acceleration model. Figure 5, 6, and 7 show the performance when the cornering stiffness of the front wheel is fixed to the original state and the rear wheel is changed. Basically, we use FFT to analyze the results.

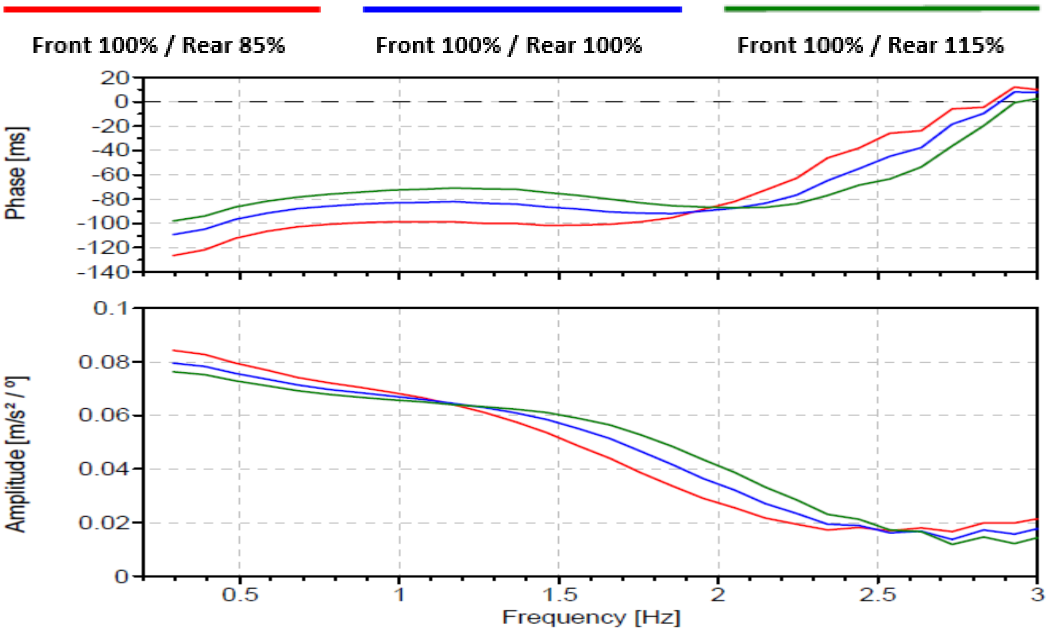

Figure 5. Steering Wheel Angle to Lateral Acceleration Section

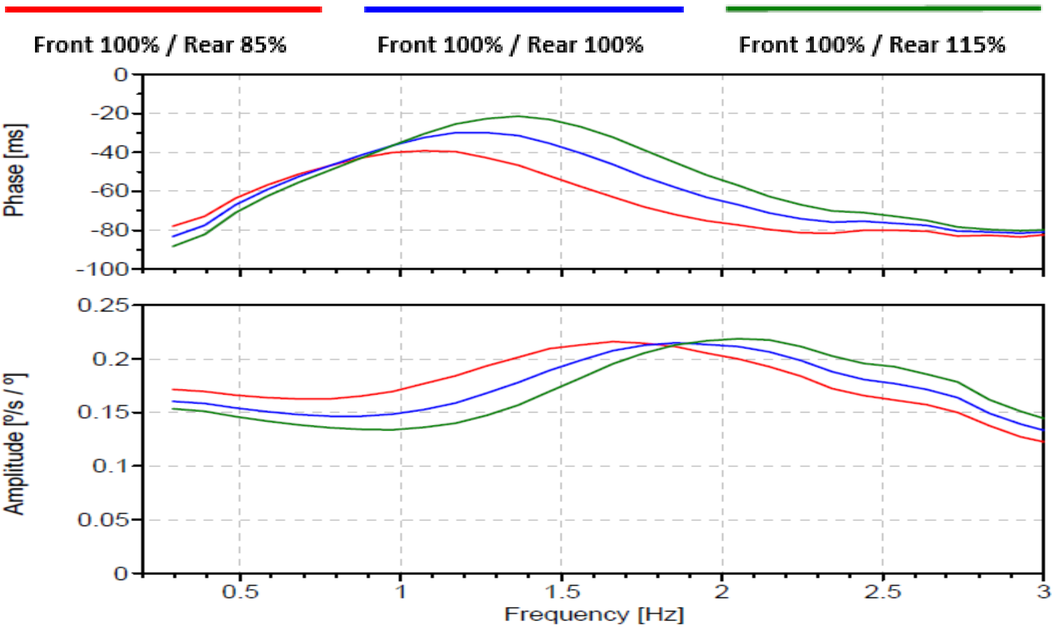

Figure 6. Steering Wheel Angle to Yaw Velocity Section

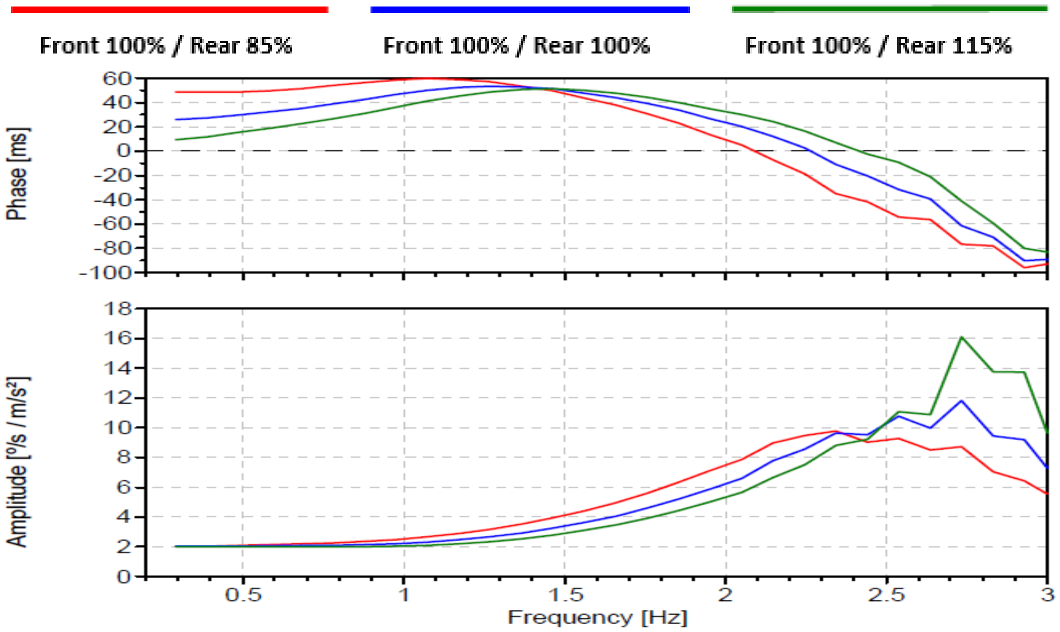

Figure 7. Yaw Velocity to Lateral Acceleration Section

As in the above analysis, the cornering stiffness combination of the rear wheels was evaluated while increasing or decreasing the cornering stiffness of the front wheels. Table 8 summarizes the results.

The results show that the response performance of the front and rear wheels is the best when the cornering stiffness of the front wheel is reduced and the cornering stiffness of the rear wheel is increased. The SWA-Latac section showed 120%, the SWA-YawR section showed 117%, and the YAWR-Latac section showed 123% in a performance improvement, respectively. Although the gain values of SWA-Latac and SWA-YawR are small, it is negligible considering that the delay performance weight is high. As a result, we can identify that the performance matching or balance between the current vehicle and the original tire is not correct. In addition, it was found that the tires of the front wheels should be reduced in stiffness and the tires of the rear wheels should be increased in stiffness by changing the tire structure and compound in order to improve the performance.

Table 8. Frequency Response Test Result

F (%)	R (%)	SWA To LATAC		SWA To YAWR		YAWR to LATAC
		1 Hz Gain	1 Hz Delay	1 Hz Gain	1 Hz Delay	1 Hz Delay
115	115	0.068	74.69	0.143	33.18	41.52
	100	0.069	86.01	0.161	35.58	50.47
	85	0.07	102.8	0.186	42.84	60.05
100	115	0.065	71.76	0.136	30.64	41.13
	100	0.066	82.59	0.153	32.57	50.06
	85	0.067	98.74	0.177	39.17	59.66
85	115	0.061	68.36	0.128	27.7	40.67
	100	0.062	78.62	0.143	29.07	49.59
	85	0.063	93.97	0.166	34.86	59.21

4.2. Steady State Speed

The Steady State Speed test is used to quantitatively analyze the steering characteristics, maximum grip and stability performance of the vehicle according to the transient input. When the cornering stiffness of the front wheel is fixed to the original state and the rear wheel is changed, based on the conclusions obtained from existing correlation studies, the performance is shown in Figure 8, Figure 9 and Figure 10.

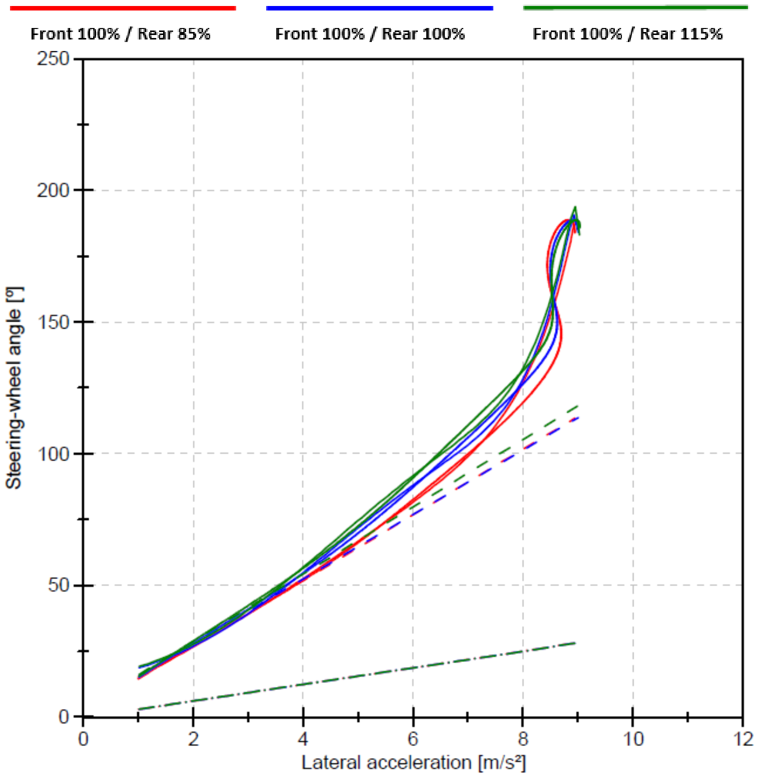

Figure 8. XY Plot : Steering Wheel Angle – Lateral Acceleration

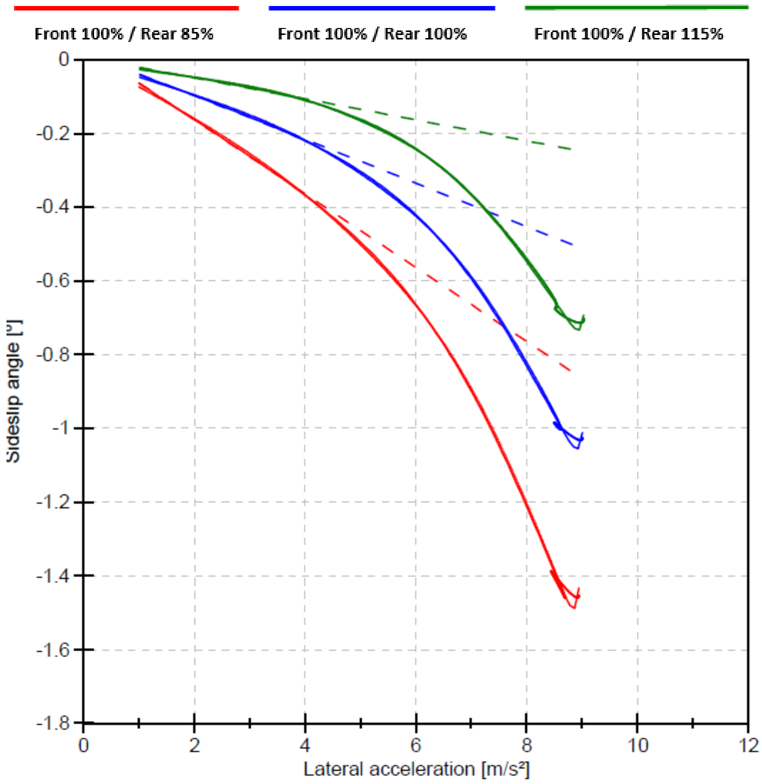

Figure 9. XY Plot : Side Slip Angle – Lateral Acceleration

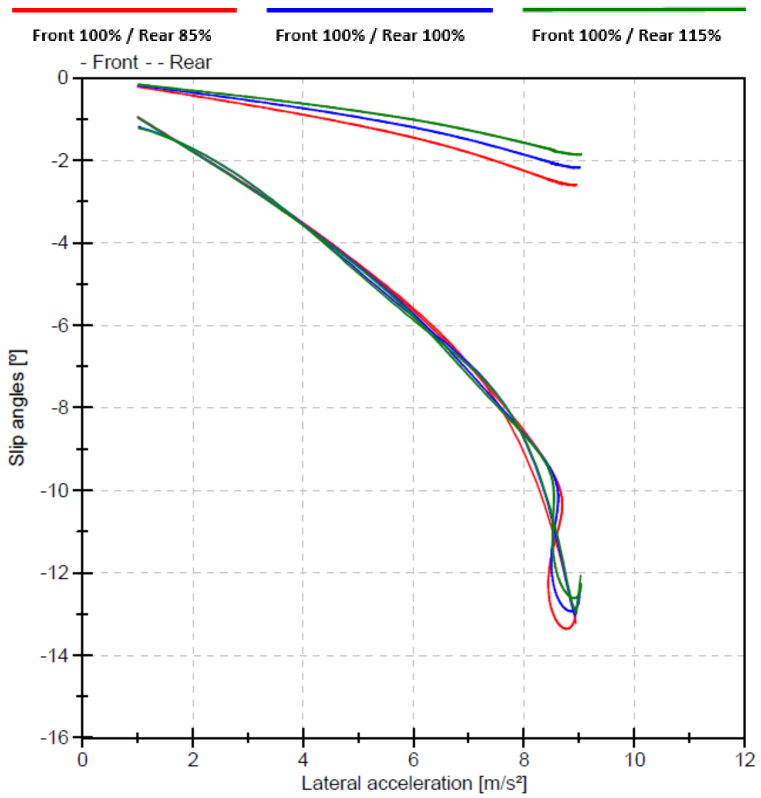

Figure 10. XY Plot : Front, Rear Axle Slip Angle – Lateral Acceleration

Table 9. Steady State Speed Test Result

F (%)	R (%)	SWA Grad	Side Slip Grad	Max LAT
115	115	12.7	0.03	9.03
	100	13.38	0.06	8.99
	85	14.04	0.1	8.92
100	115	12.76	0.03	9.03
	100	12.24	0.06	9.01
	85	12.46	0.1	8.94
85	115	14.57	0.03	8.93
	100	13.79	0.06	8.94
	85	12.74	0.1	8.95

F (%)	R (%)	Linear		Non Linear	
		F/A Slip A.	R/A Slip A.	F/A Slip A.	R/A Slip A.
115	115	3.38	0.63	6.57	1.28
	100	3.43	0.75	6.74	1.53
	85	3.4	0.9	6.72	1.82
100	115	3.58	0.62	6.98	1.27
	100	3.55	0.74	7	1.52
	85	3.59	0.9	6.96	1.82
85	115	3.93	0.63	7.78	1.23
	100	3.91	0.74	7.68	1.49
	85	3.88	0.9	7.53	1.81

As in the above analysis, the cornering stiffness combinations of the rear wheels were evaluated while increasing or decreasing the cornering stiffness of the front wheels. Table 9 summarizes the results. For the axle side slips of the front wheels and the rear wheels, the analysis was conducted on two split sections, which are the linear section (4m / s2) and the non-linear section (7m / s2).

As a result of the analysis, it is identified that decreasing the cornering stiffness of the front tire and increasing the cornering stiffness of the rear tire exhibit the understeer characteristics as compared with the original tire. The maximum grip generally follows the compound characteristics, and the simulation results are shown to be reasonable because the evaluation only changed the simple cornering stiffness. Also, it is generally considered that the neutral steering characteristic is better because it follows the driver's input, but the neutral steering characteristic is not absolutely safe at high speed in terms of the vehicle and the tire. This is because the higher the speed, the greater the force to be handled at the rear tires. In order to improve the stability of the vehicle, it is desirable to have understeer characteristics. Of course, it should be assumed that there is no trade-off for other performance of the vehicle. This test allows you to set the development direction as in the Frequency Response Test results.

5. Conclusions

In this paper, we discuss the performance characteristics of steering stability of a vehicle varying to changes in tire cornering stiffness. The Frequency Response and the Steady State Speed simulation evaluation were performed to quantitatively confirm the steering, response, and safety performance of the vehicle. It is confirmed that all the performance is improved when the cornering stiffness of the front wheel is lowered and the cornering stiffness of the rear wheel is increased. It is possible to set the development direction of the tire through this, and it is expected that the improvement of steering stability performance will be achieved if it is reflected in the business. This study is focused on improvement of steering stability performance and development direction setting according to changed tire design parameters. In the future, it is planned to reflect the simulation results in actual tire development and to conduct correlation studies with actual vehicle results.

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