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Parametric Study Using a Braking Distance Simulation of an Anti-locked Braking System Vehicle†

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Over the last century, the braking performance has become the core of vehicle research along with engine performance. The braking distance, which is a very important factor for evaluating the braking performance, is affected by the brake system of vehicles, tires and road friction characteristics. All the vehicles released recently should be equipped with an anti-locked braking system for stability. The anti-locked braking system is quite effective in shortening the braking distance. Therefore, studies in the past focused on the efficiency and method of the control logic for anti-locked braking system. As a result, the brake system was developed but there has been little research on the relationship between a vehicle with anti-locked braking system and the tire characteristics. In this paper, the tire characteristics were studied in terms of the brake distance of a vehicle equipped with an anti-locked braking system. To achieve this, the braking distance simulation method was first developed using a multi-body vehicle dynamic model including brake control logic and tire model and its confidence was verified by an outdoor braking test. The relationship between the tire characteristics and braking distance was analyzed by orthogonal arrays based on the design of experiments. Through tire indoor tests, the relationship between the tire characteristics and its structure design variables, such as tread and side-wall stiffness, were also analyzed. The effect of the tire on the braking performance of a vehicle equipped with anti-locked braking system was assessed.

Key Words: Anti-locked braking system brake, Braking distance, Multi-body vehicle dynamics, Tyre characteristics, Magic formula tyre model.

INTRODUCTION

If the vehicle is decelerated urgently, the wheels of the vehicle are not locked fully due to the anti-locked braking system, which is one of the active devices for preventing tyre slip on the road. The purpose of this system is to prevent accidents and reduce the braking distance with handling during deceleration. An anti-locked braking system itself is not the only component; a combination of the vehicle and tyre also play important roles[1-3]. In particular, because tyres are in direct contact with the road, they affect the braking distance depending on their performance.

To improve the performance of anti-locked braking system, it is important to examine the brake system, as well as the characteristics of the tyre and vehicle. To reduce cost, recent studies used simulation methods instead of outdoor tests. Finally, an outdoor test was performed to validate the simulation method.

Studies in this field can be divided into two types: one area examined the anti-locked braking system controller and control parameters using vehicle dynamics analysis and the other area assessed the vehicle stability during braking using an outdoor test[4-7]. Unfortunately, it is not enough to predict the braking distance and effect of various parameters using multi-body vehicle dynamics model with a tyre and vehicle[8-10].

This paper suggests a vehicle model based on multi-body vehicle dynamics and analysis to predict the braking distance and tyre parameters on the characteristics related to the braking performance.

EXPERIMENTAL

Simulation of braking-distance with anti-locked braking system: An anti-locked braking system equipped vehicle model and a tyre model were developed to analyze the braking distance with a simulation. An objective test was conducted and the results were compared with the simulation to validate the reliability of the simulation method.

Vehicle model: A multi-body dynamics model based on virtual proving ground was generated using commercial S/W, ADAMS and MATLAB to analyze the dynamic characteristics and behaviour of an anti-locked braking system equipped vehicle.

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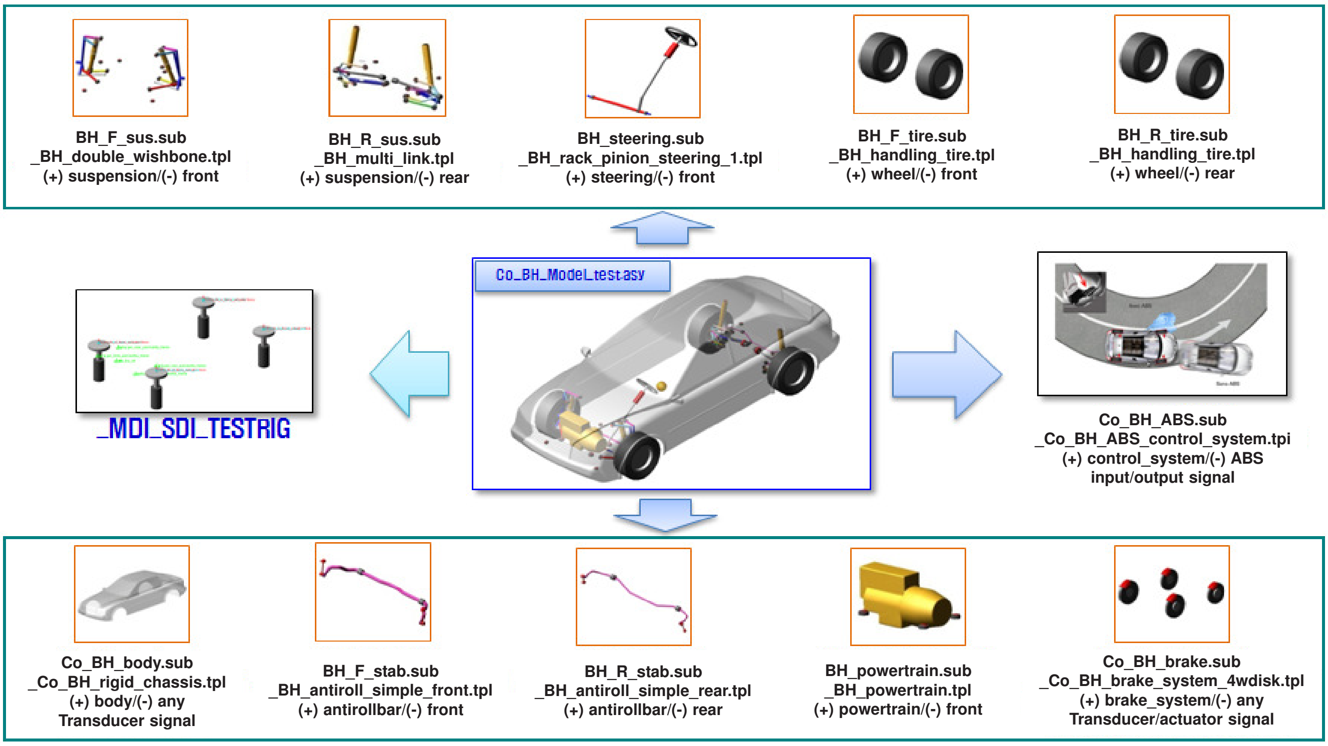

Fig. 1. Multi-body vehicle dynamic model

Nine templates and 10 subsystems were constructed to simulate the braking distance, based on the ADAMS vehicle model, as shown in Fig. 1. Matlab/Simulink S/W were used to generated the anti-locked braking system control logic. Finally, the coupled simulation was performed for the braking distance with an anti-locked braking system using ADAMS/mechatronics.

Tyre model: To analyze the braking distance of a anti-locked braking system equipped vehicle, analytical tyre models were generated using the magic formula tool. The magic formula tool, a specialized commercial fitting S/W focused on the tyre industry, can make an analytical tyre model using the experimental test data. The tyre size used in the simulation was a 225/55R17. Fig. 2 shows the general process to make a tyre model.

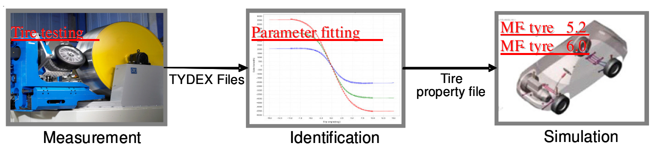

Fig. 2. Tyre model generation process

A foot-print test, static-property test and force and moment test such as pure cornering, pure braking and combined slip, were performed first. The magic formula-tool was used to define the properties or parameters of the tyre model.

Verification of simulation: As mentioned above, the braking distance co-simulation was accomplished with ADAMS/car, ADAMS/Mechatronics and Matlab/simulink.

Moreover, to increase its reliability, this study considered two types of brake pads and 5 types of tyres. As shown in Fig. 3, the results of the simulation and test were similar, as indicated by the R^2 value of 0.9332.

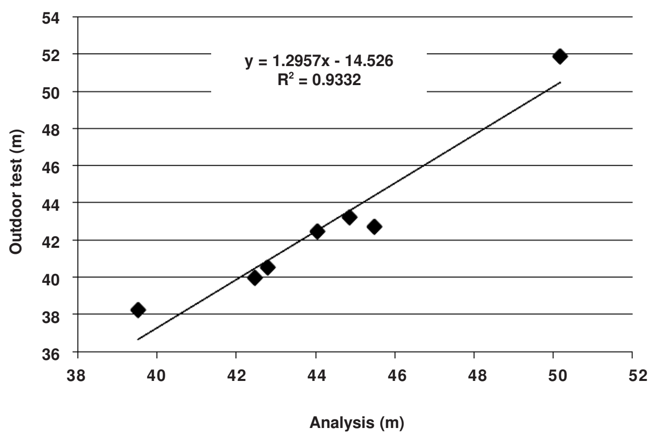

Fig. 3. Comparison on the simulation and outdoor test results

RESULTS AND DISCUSSION

Tyre parametric study: The relationship between the braking-distance and tyre design parameters was analyzed. To achieve this, the analysis was performed using a 2-step process. A comparison of the tyre characteristics with the braking-distance of a vehicle is the first step. This is followed by a comparison of the tyre design parameters with its characteristics.

Tyre parameters: A slip phenomenon can occur if the travel velocity and spin angular velocity of the wheel are different. The variation of it is called the slip ratio, as shown in eqn. (1).

$$\text{Slip Ratio (\%)} = \frac{r\varpi - V}{V} \times 100 \quad (1)$$

where r, ω and V is the effective rolling radius, spin angular velocity of the tyre and travel velocity of the vehicle, respectively. When slip occurs during traveling, a longitudinal force is generally represented as curve shape, as shown in Fig. 4. The longitudinal force per load is represented as the friction coefficient; the peak value is located in the slip ratio between 10 and 20 %.

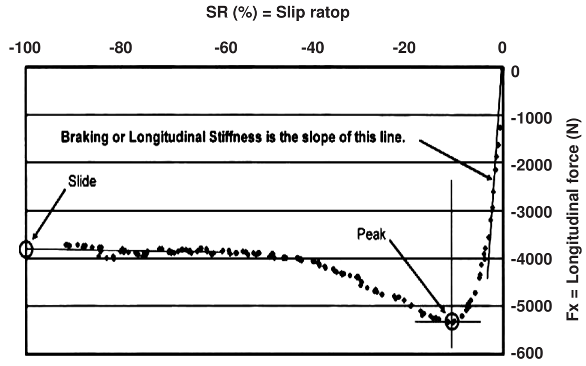

Fig. 4. Longitudinal force characteristic of the tyre

In this paper, the maximum friction coefficient and slip ratio of the time were named the 'Mu-peak' and 'peak slip ratio', respectively. In addition, when the slip ratio was 100 %, *i.e.* spin velocity of tyre was zero, the friction coefficient was called the 'Mu-slide'.

The design of experiment was used to analyze the effects of the tyre parameters on the braking distance. As shown in Table-1, an orthogonal array table is composed of 3 factors and 2 levels. The level of each parameter is based on the min-max values that could occur from the effect of only the pattern of tyres.

Tyre models with the parameter results shown in Table-1 were generated. To achieve this, the scaling factors of the magic formula model generated earlier were modified for our products (225/55R17 size). Fig. 5 shows the longitudinal force curve shape for 8 tyre models using an ADAMS tyre test rig.

TABLE-1
ORTHOGONAL ARRAY FOR DOE ANALYSIS

Version	Braking characteristic factor		
	μ-peak	Peak slip ratio	μ-slide
A	1.14	22.8	0.57
B	1.14	22.8	0.65
C	1.14	14.7	0.57
D	1.14	14.7	0.65
E	1.30	22.8	0.57
F	1.30	22.8	0.65
G	1.30	14.7	0.57
H	1.30	14.7	0.65

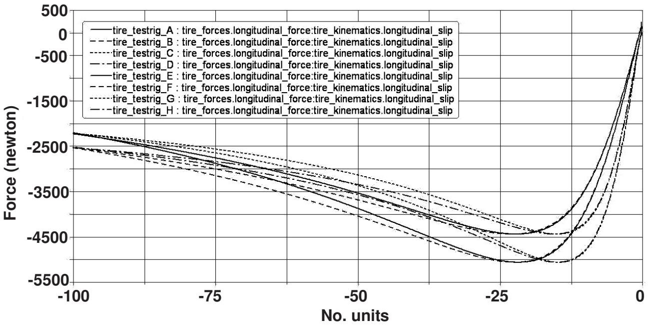

Fig. 5. Simulation results for an 8-version tyre

The braking distance simulation was performed with or without anti-locked braking system to analyze the effect of the tyre parameters. The results are shown in Fig. 6.

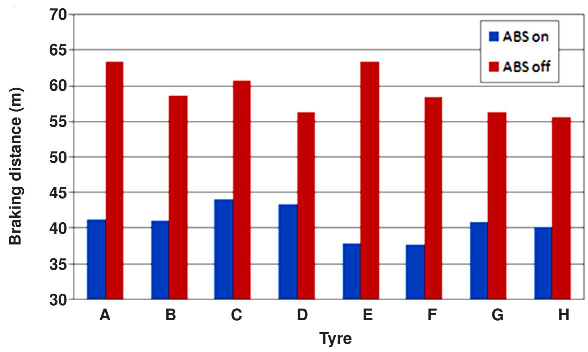

Fig. 6 Simulation results for the anti-locked braking system braking distance

The results of the braking distance simulation with anti-locked braking system were analyzed. As a result, the braking distance decreased with increasing Mu-peak or peak slip ratio, as shown in Fig. 7. In particular, the result for peak slip ratio was suitable because the target slip ratio of the control logic was set to 20 %. In addition, the effect of Mu-slide was quite small.

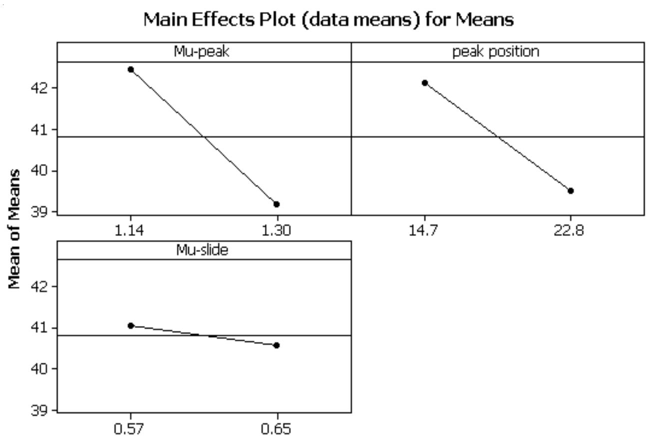

Fig. 7. Main effect of the braking distance with ABS

A study on tyre design parameters: The tyre design parameters can be classified into compound, pattern and structure. In this study, the structural design factors that affect the Mu-peak and peak slip ratio were considered (Fig. 8).

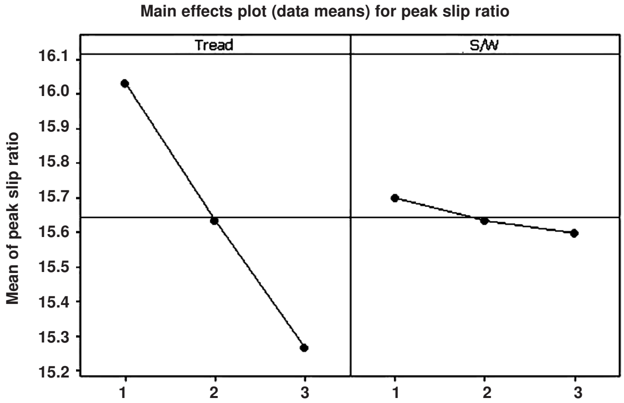

Fig. 8. Main effect of the peak slip ratio

To validate the influence of the tyre design factors, this study considered 2 factors and adjusted its range by 3 levels. In the case of the tread stiffness, the steel belt width, steel belt angle and code type were considered. In addition, in case of the sidewall's stiffness, the bead filler's height, presence or absence of a side wall insert was considered.

As mentioned above, each case of tyres was made to obtain a Mu-peak and peak slip ratio. The braking test was conducted using drum type ZF force and moment test machine. The results are listed in Table-2.

TABLE-2
RESULTS OF INDOOR BRAKING TEST

Tire	TR stiffness	SW stiffness	Mu-Peak	Peak slip ratio
A	H	H	1.23	16.0
B	H	M	1.21	16.1
C	H	L	1.23	16.0
D	M	H	1.21	15.6
E	M	M	1.20	15.7
F	M	L	1.24	15.6
G	L	H	1.20	15.5
H	L	M	1.23	15.1
I	L	L	1.22	15.2

Using these results, the mean and variance of the Mu-peak and peak slip ratio were analyzed.

Conclusion

The tyre characteristics and tyre design parameters were analyzed using a braking distance simulation of a vehicle equipped with anti-locked braking system.

The following results were obtained:

(1) The Mu-Peak and peak slip ratio affected the braking distance of a vehicle with anti-locked braking system. The braking distance decreased with increasing Mu-peak. The closer the peak slip ratio was to the target slip ratio of the control logic, the more the braking distance was reduced.

(2) The structural design factors of a tyre do not effect to the Mu-peak. On the other hand, the structural design factors related to the tread stiffness affect the peak slip ratio.

(3) The range to control the slip ratio through structural design factors was as small as 1 %.

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