

Prediction of Braking Distance Temperature Dependence through Bench Test

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ABSTRACT

The temperature of the road surface is known to affect vehicle braking distance. This study demonstrated that the variation in wet braking distance with road temperature is affected by the viscoelastic properties of the tread rubber of the tires. Consequently, a study was carried out focusing on the friction and viscoelasticity of the tire tread rubber. Based on the results of this study, a method of predicting the braking distance over a wide range of road surface temperatures was established from the results of a viscoelastic characteristics bench testing of the tire tread rubber and also the results of a braking distance test performed using an actual vehicle at arbitrary road surface temperatures.

1. Introduction

Braking distance performance is an important measure of active safety performance. The results of braking distance performance have been publicized in Japan New Car Assessment, and preparations for testing are being carried out in the U.S. and Europe as well.

Also, braking distance is evaluated independently in automobile magazines throughout the world, and the results of these evaluations are of interest to consumers.

The factors shown in Fig. 1 are considered to have a major effect on the braking distance⁽¹⁾.

Some of these impacting factors, including the method of human operation, the measuring system, the vehicle specifications and the road profile can be maintained constant to some extent by controlling the test method. However, in order to understand the effect of the road surface temperature condition on the braking

distance, it is necessary to perform an actual vehicle test from a low temperature range to a high temperature range.

In order to understand the effect of the road surface temperature on the braking distance, it is necessary to perform multiple tests using an actual vehicle over a long period of time, so it is difficult to make an evaluation within a limited period.

In this research, attention was focused on the viscoelastic characteristics of the tire tread rubber under bench test conditions, and a method of predicting the braking distance which varies with the road surface temperature from the minimum test results obtained using an actual vehicle was developed in order to provide a method of more readily evaluating the performance of the tires.

2. Dependence of Braking Distance on Road Surface Temperature for Different Tires

Figure 2 shows the change in the braking distance with change in temperature of a dry road and a wet road. As shown here, with some tires the braking distance varies with the road surface temperature, so it is not possible to cover all conditions of use in the market by simply evaluating the tires in a certain temperature region.

The tests were carried out on the Multipurpose Track of the Honda R & D Tochigi Proving Ground, and the test method used was based on Japan New Car Assessment Program (J-NCAP: an automobile assessment published by the automobile accident countermeasure organization of an independent administrative corporation). Regarding the road surface temperature, however, tests were also performed at temperatures that exceeded the J-NCAP

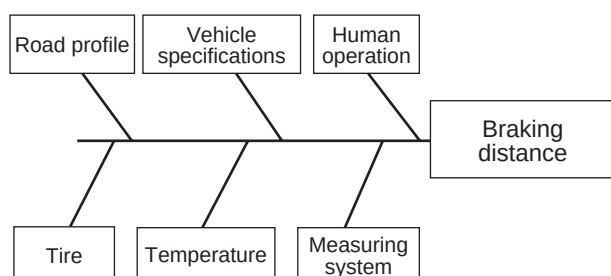


Fig. 1 Cause and effect diagram for braking distance

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upper and lower limit values. The test vehicle used was an FF (front engine, front wheel drive) 2.0 L minivan.

Figure 3 shows the braking distance results obtained for a wide range of road surface temperatures using the same vehicle, in order to confirm the dependence of braking distance on road surface temperature for different tires on a wet road surface. Also, the tires used in the test are shown in Table 1.

The tests shown in Fig. 3 were carried out on the Multipurpose Straight Track of the Japan Automobile Research Institute, and the test method used was based on J-NCAP. Regarding the road surface temperature, however, tests were also performed at temperatures that exceeded the J-NCAP upper and lower limit values. The test vehicle used was an FF 1.5 L passenger vehicle.

From these results, it was confirmed that the dependence of braking distance on road surface temperature tends to vary from one tire to another.

The braking distance with respect to road surface temperature for tire A is short at low temperature, and increases in the high temperature region. On the other hand, the variation in the braking distance with respect to road surface temperature for tire B is less than that of tire A, but the braking distance increases in both the low temperature region and the high temperature region. Tire C is ranked mid-way between tires A and B. Like tire A, the braking

Table 1 Tire characteristics

	Tire A	Tire B	Tire C	Tire D	Tire E
Tread compound	1	2	3	4	5
Construction	a	b	c	d	d
Tread pattern	I	II	III	IV	IV
Tire size	185/70 R14	185/70 R14	185/70 R14	185/70 R14	185/70 R14

distance increases in the high temperature range, however this tendency is less than that of tire A.

The three types of tires shown in Fig. 3 differ from each other in tread rubber, construction and pattern. In order to determine which of these elements has an effect on the dependence of braking distance on road surface temperature, braking distance tests were performed using tires of different tread rubber, tires of different construction, and tires of different patterns.

As a result of performing braking distance tests on an actual vehicle, it was found that differences in tread rubber had the effect on the dependence of braking distance on road surface temperature.

Figure 4 shows the braking distance results for tires D and E, which were of the same pattern and size but differed only by tread rubber.

Tires D and E, which differed only in tread rubber, exhibited different dependence of braking distance on road surface temperature, and it was found that the temperature dependence of braking distance varied with the type of tread rubber used.

Consequently, it was confirmed that the tread rubber had an effect on the temperature dependence of braking distance.

Test track: Honda R&D, Ltd. Tochigi Proving Ground
Test method: J-NCAP (with change to specified road surface temperature)
Test vehicle: FF 2.0L Minivan

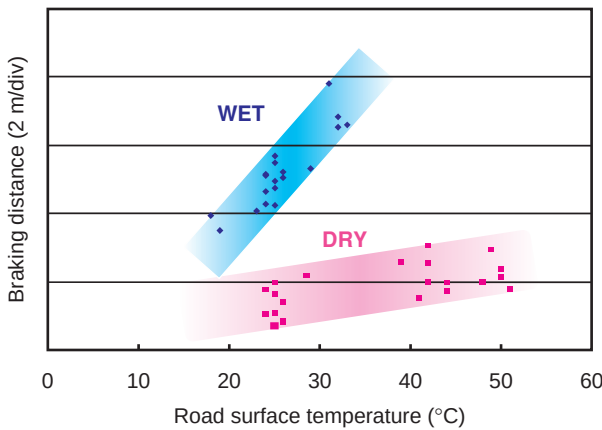


Fig. 2 Wet and dry braking distance vs road surface temperature

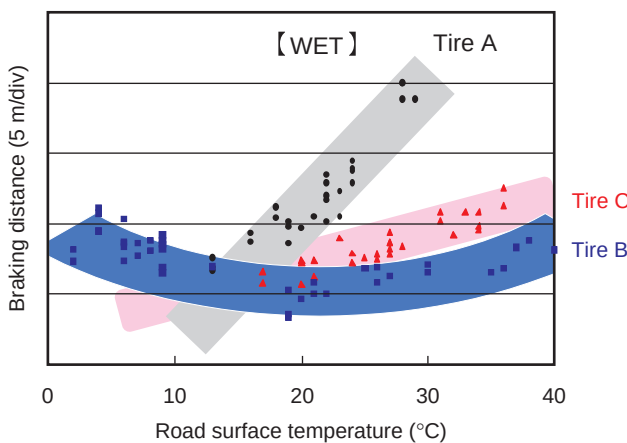


Fig. 3 Road temperature dependence of braking distance by tire

3. Examination of Mechanism

3.1. Friction and Viscoelasticity of Tread Rubber

The friction force of the tire is expressed as the sum of the friction force by hysteresis of the tread rubber F_H and the friction force by adhesion F_A (Fig. 5).

The hysteresis friction force F_H is the friction force due to the energy loss generated when the rubber undergoes relatively large deviation due to irregularities in the road surface. The larger the phase delay (hysteresis loss: $\tan \delta$) due to deformation of the rubber, the greater is the hysteresis friction force F_H .

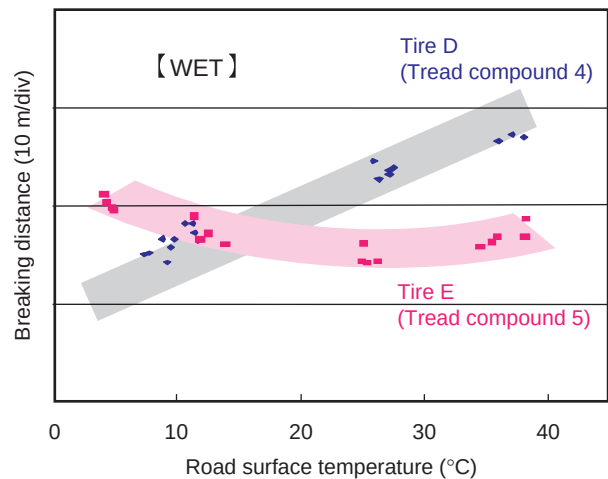


Fig. 4 Road temperature dependence of braking distance by tread compound

Because the braking distance is inversely proportional to the braking force, it is possible to assume that following equation holds, where the braking distance due to the friction force by hysteresis F_H is defined as X_H .

$$X_H \propto 1/F_H \propto 1/\tan \delta \quad (1)$$

The adhesion friction force F_A is generated by energy loss resulting from adhesion between the tread rubber and the road surface aggregate (intermolecular force).

Consequently, the adhesion friction force F_A increases in proportion to the actual area of contact of the tire⁽²⁾.

Adhesion friction force $F_A = M$ (Contact area) $\cdot S$ (Tread rigidity per unit area)

From a microscopic viewpoint, the contact area M is considered to be related to the modulus of elasticity E^* of the rubber material in a micro-deformed state that follows the surface irregularities of the road surface aggregate (Fig. 5), and in the low temperature region the actual contact area changes in inverse proportion to the increase of E^* . Therefore, if the braking distance due to the adhesion friction force F_A is defined as X_A , it can be assumed that the following equation holds in the low temperature region.

$$X_A \propto 1/F_A \propto 1/M \propto E^* \quad (2)$$

3.2. Prediction Equation

As a result of studying the relationship between braking distance and tread rubber friction, an equation for predicting the dependence of braking distance on road surface temperature was determined.

It is possible to express the change of braking distance with road surface temperature ΔX as the sum of the change of braking distance ΔX_H due to the change in the hysteresis friction force F_H with road surface temperature and the change of braking distance ΔX_A due to the change in the adhesion friction force F_A with road surface temperature.

$$\Delta X = \Delta X_H + \Delta X_A$$

In addition, from previous investigation⁽³⁾ it is known that the braking distance on a wet road is related to $\tan \delta$ in the vicinity of 0 °C from the tire tread rubber viscoelasticity characteristics test.

This means that the greater the value of $\tan \delta$ in the vicinity of 0 °C in the viscoelasticity test, the larger is the hysteresis friction force F_H , and the shorter is the braking distance on a wet road.

Concerning the road surface temperature dependence of the braking distance, it was considered that the increase in the braking

distance in the high temperature region was due to the effect of the temperature gradient of $\tan \delta$ in the vicinity of 0 °C in the viscoelasticity test, and thus the following equation was assumed.

$$\Delta X_H = f(t) \times a \quad (3)$$

Where,

a: Gradient of $\tan \delta$ in the vicinity of 0 °C

f(t): Linear expression of road surface temperature t

f(t) was assumed to be a linear expression with respect to road surface temperature t because the braking distance showed a tendency to increase in proportion to the increase of road surface temperature.

Next, it was considered that the magnitude of the modulus of elasticity E^* in the vicinity of 0 °C was a factor that caused the braking distance to increase in the region of low road surface temperature, and the following equation was assumed.

$$\Delta X_A = g(t) \times b \quad (4)$$

Where,

b: E^* in the vicinity of 0 °C

g(t): Expression of 1/t

Also, g(t) was assumed to be the function 1/t with respect to road surface temperature t because of the fact that the braking distance increases in inverse proportion to the road surface temperature in the low temperature region.

Consequently, if the braking distance to be predicted at road surface temperature ta is defined as X_a , it can be expressed by the following equation in which the change in the braking distance due to the road surface temperature is added to the reference braking distance X_c at road surface temperature t_c .

$$X_a = \Delta X_H + \Delta X_A + X_c \quad (5)$$

Here, it was assumed that the reference braking distance X_c was measured using an actual vehicle because it varies depending upon the vehicle specifications and tire size. In other words, it can be expressed using the following equation.

$$X_a = f(t) \times a + g(t) \times b + X_c \quad (6)$$

3.3. Relationship between Road Surface Temperature Dependence and Viscoelasticity Characteristics

In order to verify the trend of $\tan \delta$ and E^* of tire D and tire E used in Fig. 4, test pieces were cut from the tread rubber, and the viscoelasticity characteristics were measured using a spectrometer (Fig. 6).

The results of the viscoelasticity test are shown in Fig. 7 and Fig. 8.

In the case of tire D shown in Fig. 4, the braking distance increases more or less in proportion to the increase in the road surface temperature. It is thought that this is because, as shown in Fig. 7, $\tan \delta$ in the vicinity of 0 °C which has a correlation relationship with the hysteresis friction force F_H of tread rubber (4) falls as the temperature rises from the vicinity of 0 °C.

The braking distance of tire D increases more than that of tire E when the road surface temperature is between 20 °C and 30 °C. This is considered to be due to the fact that the slope of $\tan \delta$ in the vicinity of 0 °C in the case of tread rubber (4) is greater than that of tread rubber (5).

On the other hand, the braking distance of tire E shown in Fig. 4 increases in inverse proportion to road surface temperature, particularly in the low temperature region.

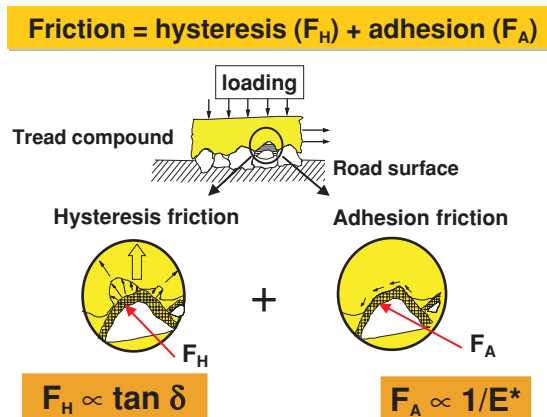


Fig. 5 Friction of tread compound

It is thought that this is because although the tread rubber maintains a stable contact area in the region where the road surface temperature is at least a certain value, the E^* of the tread rubber rises as the temperature falls, decreasing the contact area and causing the adhesion friction force to decrease, as shown in Fig. 8.

It is also considered that the tendency for the braking distance of tire E to increase in the low temperature region is greater than that of tire D because of the fact that E^* in the low temperature region in the case of the tread rubber (5) is greater than that of tread rubber (4).

Using the braking distance results obtained for tires D and E and also $\tan \delta$ and E^* of tread rubbers (4) and (5) obtained using

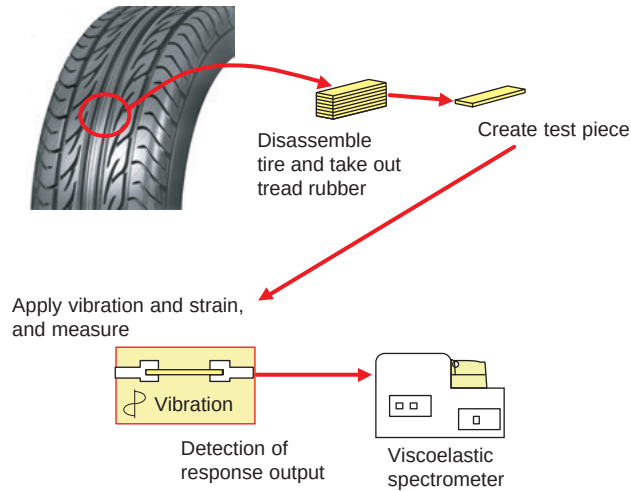


Fig. 6 Measurement method for viscoelasticity of rubber

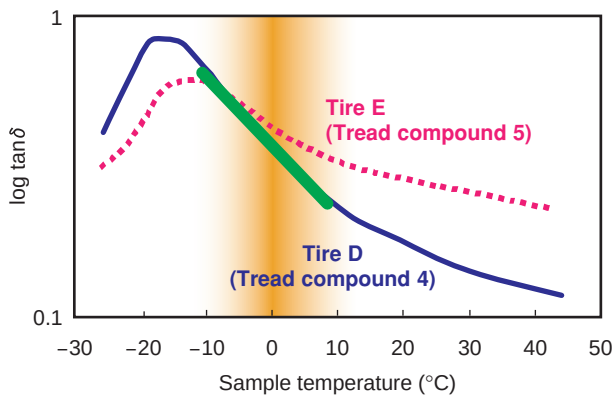


Fig. 7 Viscoelasticity measurements for Tires D and E

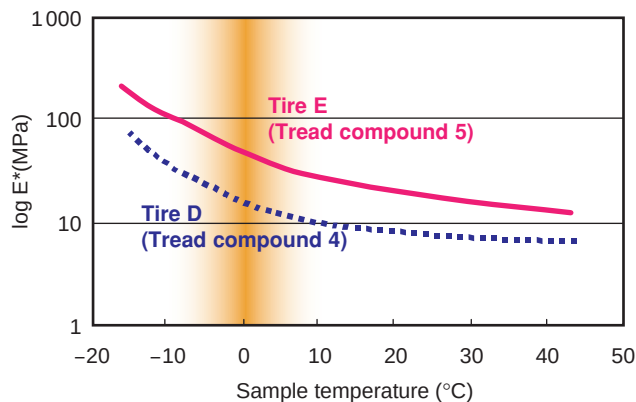


Fig. 8 Viscoelasticity measurements for Tires D and E

the bench viscoelasticity spectrometer, multiple correlation analysis using the method of least squares was performed. From these results, the coefficients for the prediction equation were set, and the prediction equation was determined.

By using the resulting prediction equation, the correlation between results of predicting the braking distance on road surface temperature for other roads based on the braking distance obtained using an actual vehicle at a road surface temperature of 10 °C for tire D and tire E, and the actual braking distance, was confirmed (Fig. 9 and Fig. 10). From these results, the proposed equation for predicting the temperature dependence of braking distance based on tread rubber viscoelasticity characteristics was verified.

4. Results of Application of the Prediction Method

In the development of the prediction equation, two kinds of tread rubbers were used. A verification concerning the prediction for a different rubber compound was carried out.

A verification concerning prediction with regard to the tread pattern, vehicle, and tires (size and construction) was also performed.

The test conditions are shown in Table 2.

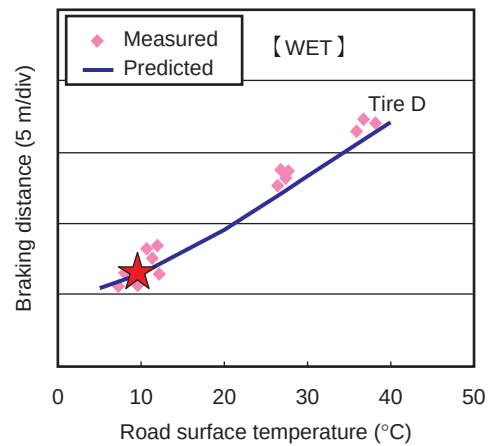


Fig. 9 Road surface temperature dependence of Tire D Prediction based on results of measurement at 10°C

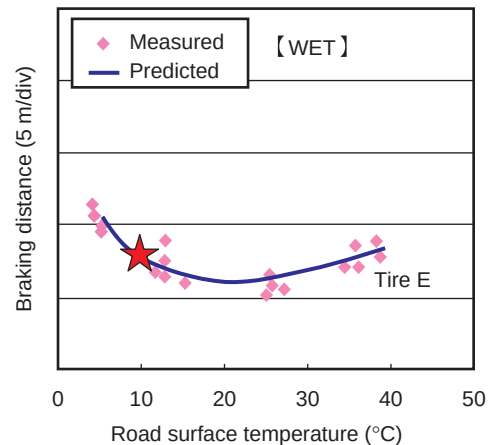


Fig. 10 Road surface temperature dependence of Tire E Prediction based on results of measurement at 10°C

Table 2 Tire characteristic

	1	2		3	
	FF 1.5 L Passenger Tire F	FF 1.5 L Passenger Tire G	FF 1.5 L Passenger Tire H	FF 0.66 L Passenger Tire I	FF 2.4 L Minivan Tire J
Tread Compound	6	4	5	7	8
Construction	d	d	d	e	f
Tread pattern	IV	V	V	VI	VII
Tire size	185/70R14	185/70R14	185/70R14	155/65R13	215/60R16

4.1. Verification According to Differences between the Tread Rubbers

Tire F, which consists of tire D with the tread rubber alone changed to (6), was fabricated.

Figure 11 shows the results predicted from the actual vehicle test with Tire F for a road surface temperature of 10 °C and the results of testing the temperature dependence on an actual vehicle.

Thus, there is good agreement with the results obtained using an actual vehicle, even when the tread rubber is changed.

4.2. Verification According to Difference in Tread Pattern

Tires G and H, which consist of tires D and E with the tread pattern alone changed, were fabricated.

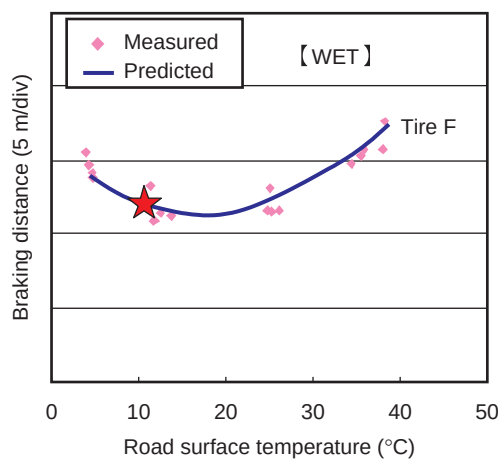


Fig. 11 Road surface temperature dependence of Tire F Prediction based on results of measurement at 10°C

Figure 12 shows results predicted from the results of the actual vehicle test with Tire G and H for a road surface temperature of 10 °C and the results of testing the temperature dependence on an actual vehicle.

Thus, there is good agreement with the results obtained using an actual vehicle, even when the tread pattern is changed.

4.3. Verification According to Differences between Vehicles and Tires

Finally, a vehicle verification was performed using an FF minivan and an FF light passenger vehicle.

Figures 13 and 14 show the results predicted from the results of the actual vehicle test for a road surface temperature of 10 °C and the results of testing the temperature dependence on an actual vehicle.

Thus, there is good agreement with the results obtained using an actual vehicle, even for different tires (tread rubber, construction, pattern and size).

In the above way, in the verification of the differences between tread rubbers, tread patterns, vehicles and tires (size and construction) as well, it was found that the results of the braking distance test performance using an actual vehicle agreed with the predicted results from the viscoelasticity characteristics of tread rubbers, thus verifying the versatility of the prediction equation.

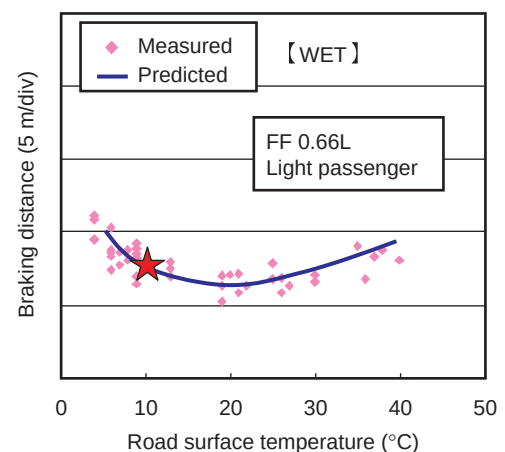


Fig. 13 Verification of by varying tires and vehicles Prediction based on results of measurement at 10°C

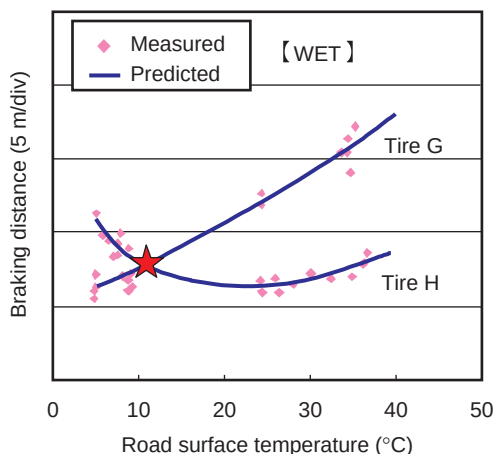


Fig. 12 Verification of accuracy by varying tread pattern Prediction based on results of measurement at 10°C

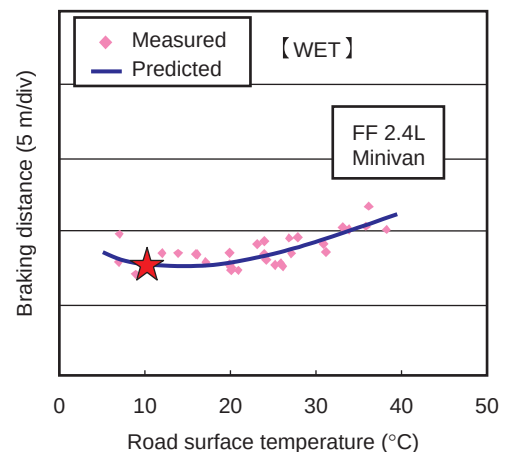


Fig. 14 Verification of by varying tires and vehicles Prediction based on results of measurement at 10°C

5. Conclusion

The following facts were established as a result of the foregoing research.

- 1) As a result of measuring the braking distance according to tire difference over a wide range of road surface temperatures using the same vehicle, it was possible to prove that the dependency of the braking distance on road surface temperature differed from one tire to another. In addition, it was found that the tire tread rubber was the dominant factor that determined the road surface temperature dependence of the braking distance.
- 2) A method of predicting the braking distance over a wide range of road surface temperatures was established from the results of a viscoelastic characteristics bench testing of the tire tread rubber and also the results of a braking distance test performed using an actual vehicle at arbitrary road surface temperatures.

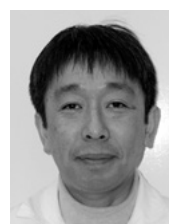
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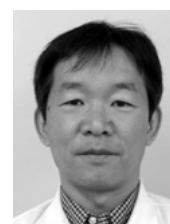
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