

# Research on Optimization of Viscoelastic Properties of Tire Tread Rubber to Reduce Rolling Resistance and Decrease Braking Distance

Emiko MOGI\*      Tetsuya MIZONE\*  
Hiroyuki HASE\*      Koji NISHITANI\*

## ABSTRACT

The achievement of reduced rolling resistance and lower braking distances is important in terms of automotive fuel efficiency and safety. These goals are strongly dependent on the performance of the tread rubber used in the tire, but are contradictory in terms of viscoelastic properties, an issue which needs to be addressed if these goals are to be satisfied simultaneously.

The research discussed in this paper involved analyses of the behavior of the contact patch of a vehicle's tires when the vehicle is cruising and braking. The results show that the two edge sections of a tire in the direction of width make the greatest contribution during braking, and the center section of a tire makes the greatest contribution during cruising. This discovery led to the proposal of a segmented tread configuration. Tires were developed on this basis, using different rubber compounds with optimized viscoelastic properties in the different segments. The distribution of contact pressure on the contact patch was also equalized. The newly developed tires displayed a 5-m reduction in wet braking distance when compared to other tires with identical rolling resistance characteristics.

## 1. Introduction

Ongoing efforts to increase fuel efficiency and enhance safety performance have highlighted the goals for tires to display reduced rolling resistance and decrease braking distance.

Figure 1 shows the relationship between the rolling resistance coefficient (RRC) of tires and their wet braking distance, as determined in tests based on the Japan New Car Assessment Program (JNCAP) of the National Agency for Automotive Safety and Victims' Aid (NASVA). As Figure 1 indicates, RRC and wet braking distance are contradictory parameters, and it is therefore difficult for both parameters to simultaneously enhance performance.

The research discussed in this paper focused on the behavior of the contact patch of a vehicle's tires while cruising and braking. The placement of the tread rubber

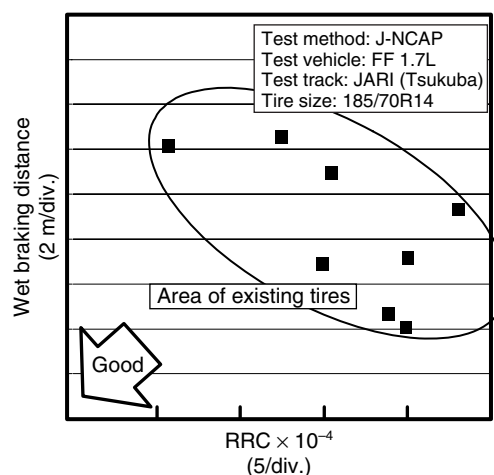


Fig. 1 Relationship between wet braking distance and RRC

\* Automobile R&D Center

was optimized and the contact pressure on the contact patch was equalized to develop a tire that displayed a low RRC and reduced braking distance.

## 2. Viscoelastic Properties of Tire Tread Rubber

### 2.1. Contradictory Performance Goals and Relationship with Viscoelasticity

The RRC of tires has an effect on fuel efficiency: a 10% reduction in the RRC is known to result in a 1-2% increase in fuel efficiency<sup>(1)</sup>. The RRC is generated by the loss of energy caused by repeated deformation of the rubber and high-molecular fibers that make up the greater part of a tire when a tire is turning. Rubber is a viscoelastic material, having both elastic and viscous properties. Because it has viscous properties, it loses some energy as heat when it is deformed, and cannot recover all the energy it had prior to deformation. Hysteresis loss therefore occurs. Hysteresis loss is proportional to the  $\tan\delta$  of the material (loss tangent = loss elastic modulus/storage elastic modulus), and is therefore generally expressed using  $\tan\delta$ <sup>(2)</sup>. Figure 2 shows a simple schematic of hysteresis loss.

The contribution of the tire tread rubber to the RRC is approximately 50%<sup>(3)</sup>. The RRC can be reduced by reducing the  $\tan\delta$  of the tread rubber.

However, the tread rubber is the only part of a tire that makes contact with the road surface, and therefore wet braking performance must be considered in addition to the RRC. Braking force is determined by the friction force of the tread rubber, which is expressed as the sum of the friction force due to hysteresis loss and the adhesion friction force. It has been demonstrated that the temperature-dependence of the braking distance of an actual vehicle can be accurately predicted from the viscoelastic properties of the tire tread rubber<sup>(4)</sup>. On a wet road, the water film reduces the area of contact between the road surface and the tread rubber, which reduces

adhesion friction force and thus increases the contribution of the friction force that is generated due to hysteresis loss. This means that increasing the  $\tan\delta$  of the tread rubber would be an effective means of enhancing wet braking performance.

The preceding discussion indicates that different  $\tan\delta$  characteristics are required for reduction of the RRC and enhancement of the braking performance. Conventionally, however,  $\tan\delta$  control method has focused on the difference in the input frequency to the rubber when the vehicle is being driven and when it is braking, based on the relationship between tire behavior and the deformation frequency-dependence of  $\tan\delta$  shown in Fig. 3.

The RRC of a tire is generated by the deformation of the tire by the road surface that occurs once every revolution of the tire. By contrast, braking force is generated by minute deformation of the tread rubber against the tiny (0.1-mm pitch) concavities and convexities of the road surface aggregates. If these deformations are considered in terms of frequency, the RRC corresponds to a deformation input frequency of  $10^1$ - $10^2$  Hz, and braking force corresponds to a deformation input frequency of  $10^4$ - $10^6$  Hz. Frequencies of higher than 1000 Hz are difficult to reproduce in the laboratory. Given this, time-temperature conversion using the WLF equation, which is often used in studies of viscoelastic substances, can be applied to convert these frequencies into temperatures. When this is done for measurement of  $\tan\delta$  at around 10 Hz, the RRC corresponds to 50-60 °C, and the braking force during wet braking corresponds to a figure of close to 0 °C<sup>(5)-(7)</sup>. Therefore, a rubber with a low  $\tan\delta$  at around 60 °C and a high  $\tan\delta$  at around 0 °C would enable simultaneous reduction of the RRC and braking distance. Table 1 summarizes the requirements for a tire tread rubber to fulfill these two performance goals, as viewed from the perspective of hysteresis loss.

However, it would be difficult to achieve a simultaneous increase in  $\tan\delta$  at 60 °C and 0 °C using conventional methods of controlling  $\tan\delta$ , which have aimed to decrease  $\tan\delta$  at 60 °C and increase it at 0 °C.

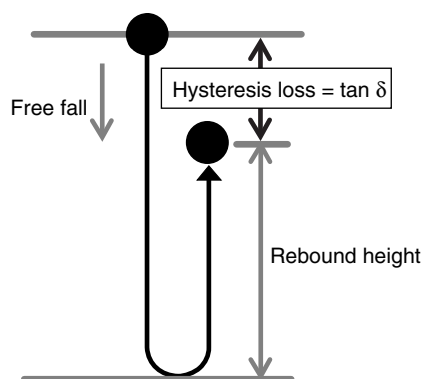


Fig. 2 Image of hysteresis loss of viscoelastic compound

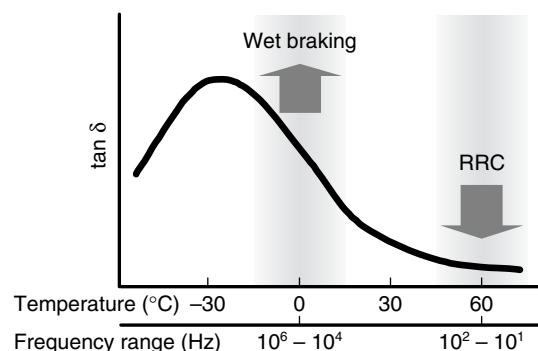
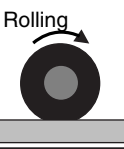
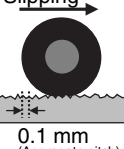


Fig. 3 Temperature dependence and frequency dependence of  $\tan\delta$

Table 1 Comparison of direction of enhanced tread compound

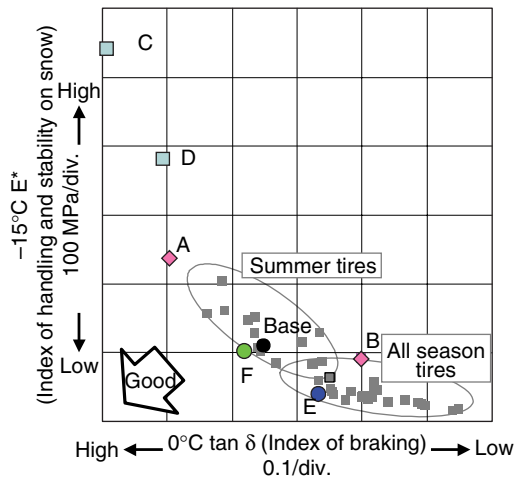
|             | Phenomenon                                                                                                                | Frequency                | Index Direction                          |
|-------------|---------------------------------------------------------------------------------------------------------------------------|--------------------------|------------------------------------------|
| RRC         | Rolling<br>                              | $10^1 - 10^2 \text{ Hz}$ | $60^\circ\text{C } \tan \delta$<br>Small |
| Wet braking | Slipping<br><br>0.1 mm (Aggregate pitch) | $10^4 - 10^6 \text{ Hz}$ | $0^\circ\text{C } \tan \delta$<br>Large  |

Moreover, in addition to the RRC and the braking performance of the tires, their performance on snow, which is affected by the properties of the tread rubber, must also be considered. Figure 4 shows the relationship between the low-temperature ( $-15^\circ\text{C}$ ) elastic modulus,  $E^*$ , and  $\tan \delta$  at  $0^\circ\text{C}$  for various rubbers. As Figure 4 shows, the range of distribution of  $\tan \delta$  at  $0^\circ\text{C}$  differs for all season tires (M+S tires), which are required to perform well at low temperatures, and standard summer tires. In other words, the viscoelastic properties of all season tires and standard summer tires have been controlled to fall within different ranges of low-temperature  $E^*$ .

## 2.2. Study of the Relationship between Changes in Viscoelastic Properties and Tire Performance

Using the tread rubber of mass-production tires as a base, a variety of different test rubbers were formulated to clarify the relationship between the viscoelastic properties of the tread rubber and tire performance, as follows:

- A:  $\tan \delta$  at  $0^\circ\text{C}$  was increased
- B:  $\tan \delta$  at  $60^\circ\text{C}$  was reduced

Fig. 4 Relationship between  $0^\circ\text{C } \tan \delta$  and  $-15^\circ\text{C } E^*$ 

- C:  $\tan \delta$  at  $0^\circ\text{C}$  was increased (an increase in  $E^*$  at  $-15^\circ\text{C}$  was allowed)
- D:  $\tan \delta$  at  $60^\circ\text{C}$  was reduced (an increase in  $E^*$  at  $-15^\circ\text{C}$  was allowed)
- E:  $\tan \delta$  at  $-15^\circ\text{C}$  was maintained within the allowable range for all season tires,  $\tan \delta$  at  $0^\circ\text{C}$  was increased, and  $\tan \delta$  at  $60^\circ\text{C}$  was decreased
- F:  $E^*$  at  $-15^\circ\text{C}$  was maintained within the allowable range for summer tires,  $\tan \delta$  at  $0^\circ\text{C}$  was increased and  $\tan \delta$  at  $60^\circ\text{C}$  was reduced

The following reasoning was used with regard to the chemical composition required to realize these properties. The type of polymer and the type and quantity of inorganic filler (carbon black or Silica) used has an effect on the viscoelastic properties of rubber. To reduce  $\tan \delta$  at  $60^\circ\text{C}$ , it would be necessary to increase the dispersability and reactivity of the filler. A peripherally functionalized solution polymerized styrene butadiene rubber was therefore selected as the main polymer, and its reinforcement efficiency was increased.  $\tan \delta$  at  $0^\circ\text{C}$  was increased by using a high filler content.

$E^*$  at  $-15^\circ\text{C}$  was adjusted by optimizing the amount of butadiene rubber and the type of added oil.

Figures 4 and 5 show the relative positioning of the tread rubber of mass-production tires and rubbers A-F in terms of viscoelastic properties.

Figure 6 shows the results of evaluation of the

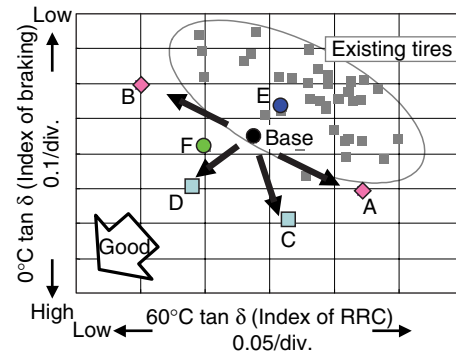
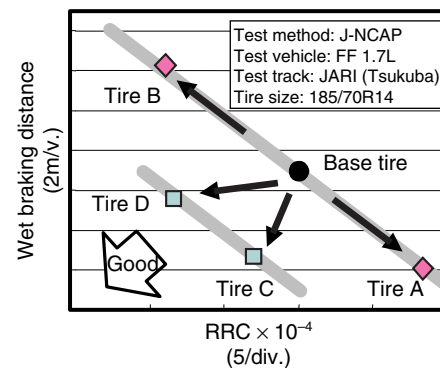
Fig. 5 Relationship between  $60^\circ\text{C } \tan \delta$  and  $0^\circ\text{C } \tan \delta$ 

Fig. 6 Relationship between wet braking distance and RRC

performance of Tires A-D, formed using rubbers A-D, against the performance of a base mass-production tire. The performance of tires A and B is situated on a line determined by the incompatibility between achieving enhancements in both the RRC and braking performance. By contrast, the performance of tires C and D, in which snow performance was not considered and  $E^*$  at  $-15^\circ\text{C}$  was allowed to increase, shows enhancements in both the RRC and braking performance. This demonstrated that there was a limit to the enhancement in the RRC and braking performance that could be obtained by controlling viscoelastic properties if performance on snow was maintained. A new approach that could be used in combination with control of viscoelastic properties was therefore required.

The project therefore began to focus on the exchange of forces between the tire contact patch and the road surface, and conducted analyses of the contact patch behavior of tires during braking, cruising, and driving on snow.

### 3. Analysis of Contact Patch Behavior for Each Performance Parameter

The contact patch is the part of the tire that makes contact with the road surface. The form and pressure distribution of the contact patch of any individual tire will vary depending on the air pressure and the load on the tire. In addition, the state of the contact patch varies depending on whether the vehicle is being driven, braking, or being driven on snow. The team conducting the research conjectured that different areas of the contact patch contributed to different aspects of performance. Conventionally, the tread section has been formed from a single type of rubber, but optimizing the placement of different types of rubber in different parts of the tread section might generate performance enhancements. Tire behavior was analyzed on this basis.

In this paper, the length of the contact patch in the direction of the circumference is termed the contact length, and the length of the contact patch in the direction of width is termed the contact width. The central section in the direction of width is termed the center, and the two edge sections are termed the shoulders. Figure 7 shows these sections.

#### 3.1. Analysis of Contact Patch Behavior during Braking

The JNCAP assessment includes full braking at 100 km/h. Figure 8 shows the changes in load on the front tire of a 1.7L FF vehicle in a wet braking test based on the JNCAP test. The load on the front wheel goes from a steady state to maximum load in 0.2 seconds, i.e. the change in the load on the tire occurs in an extremely short time period.

The test set-up shown in Fig. 9 was used to analyze the behavior of the contact patch under these conditions.

An electromagnetic shaker was used to impart a 5 Hz dynamic vibration to the tire, and a sensor (75 mm x 75 mm; resolution: 2 mm) with a responsiveness of 120 Hz was used to measure the pressure distribution on the contact patch. Measurements were also taken when a static

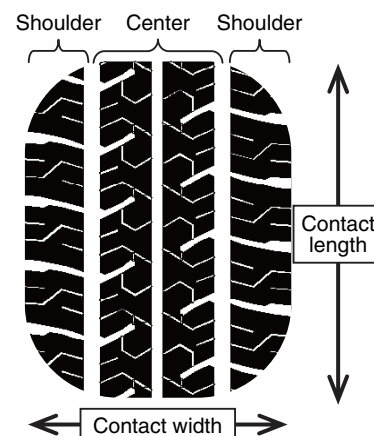


Fig. 7 Definition of footprint (Contact patch)

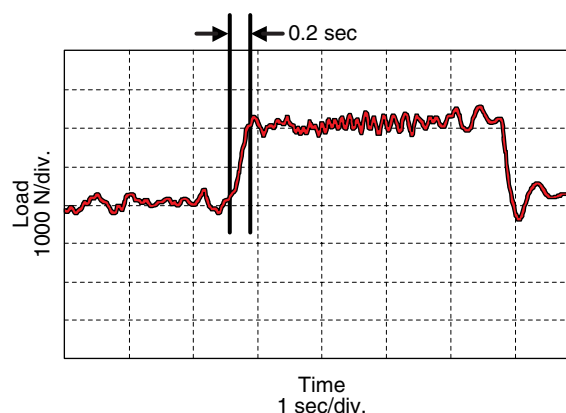


Fig. 8 Front wheel load variation in wet braking

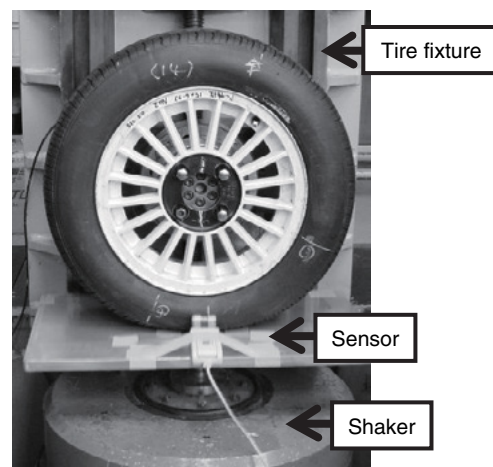


Fig. 9 Dynamic contact patch measuring equipment

braking load was applied (i.e. when the braking load causes saturation of the contact pressure), for comparison. The area in which measurements were taken is shown in Fig. 10, and the results of the measurements are shown in Fig. 11.

A comparison of the results of measurements of contact patch pressure under a normal load and maximum braking load in the dynamic braking tests (Fig. 11) shows no change in the contact pressure in the center, but a significant change in the shoulders. This indicates that the shoulders are the sections of the contact patch that are subject to the highest pressure load during braking. A

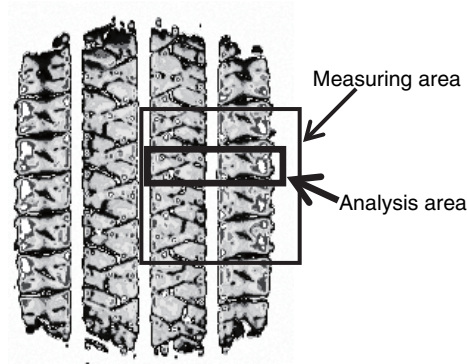


Fig. 10 Measuring and analysis areas of contact patch

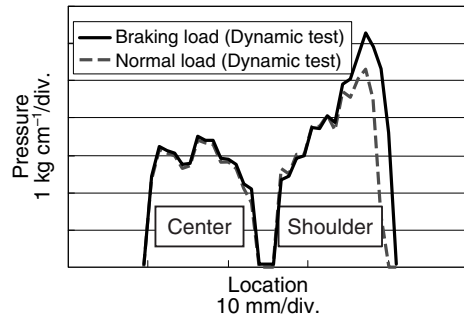


Fig. 11 Comparison of contact patch pressure distribution in normal load and braking load

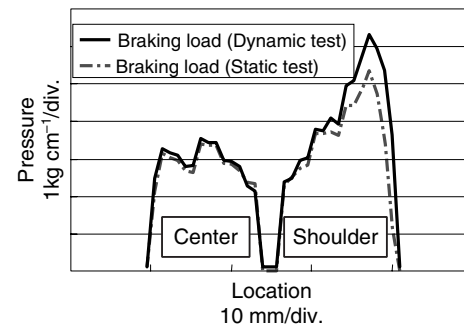


Fig. 12 Comparison of contact patch pressure distribution in dynamic and static tests

comparison of the contact pressure results from static and dynamic tests (Fig. 12) indicates that the contact pressure on the shoulders is higher when the load is applied dynamically.

In general, the lower the contact pressure of rubber the higher its friction coefficient ( $\mu$ ), therefore, it was conjectured that preventing the phenomenon of imbalance in the contact pressure of a tire could result in a reduced braking distance. Using the same rubber, two prototypes of tires were produced in which the high contact pressure on the shoulder section and the uniform contact pressure, as shown in Fig. 13. According to the comparison of these tires in the actual vehicle test regarding a wet braking distance, the braking distance of the tire with the uniform contact pressure was shorter than the tire with the high contact pressure on the shoulder section by 3 m or more. It was confirmed that equalization of the contact pressure enhanced the reduction of the braking distance.

### 3.2. Analysis of Contact Patch Behavior when Vehicle is Cruising

An FEM simulation input, with the properties of the various sections of the tire and conducted under conditions of usual driving, was done to analyze the behavior of the contact patch when the vehicle is cruising. The results, as shown in Fig. 14, indicated that energy loss was greatest in the rubber at the center of the tire, and that the rubber at the center therefore makes the greatest contribution in terms of the RRC.

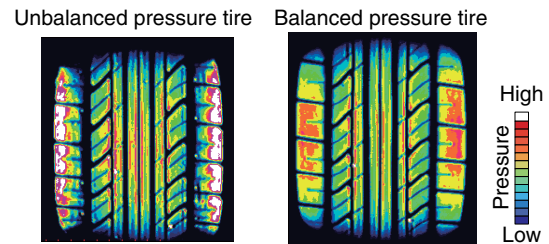


Fig. 13 Comparison of contact patch pressure under braking load

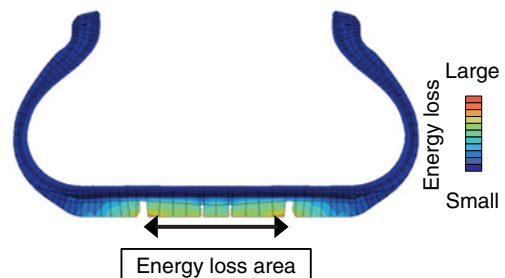


Fig. 14 Hysteresis loss distribution by finite element method analysis

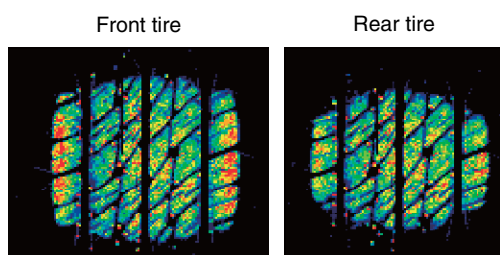


Fig. 15 Comparison of contact pressure

### 3.3. Analysis of Contact Patch Behavior when the Vehicle is Driven on Snow

On snow, compression resistance, shearing force of snow in void, adhesion friction force, and shearing friction force (edge effect) are the main mechanisms by which friction force is generated<sup>(8)</sup>. The design of the tread pattern and the elastic modulus of the rubber at low temperatures therefore determine the performance of the tire on snow. The contact state of the rear tires, i.e. the contact patch behavior under low loads, is important in ensuring the stability of a FF vehicle on snow. Figure 15 compares the contact patches of front and rear tires on snow for a FF 2.0L vehicle. The ratio of the surface area of the tire occupied by the rubber at the center is greater in the rear tire, and it is therefore important for handling on snow to help ensure that the rubber at the center is flexible at low temperatures.

## 4. Technology to Enhance Tire Performance and Results Achieved

Table 2 shows performance goals, the section of the tire that contributes to each performance goal, and the rubber property required for each section, as determined in the analyses of contact behavior. To realize these properties in a tire, a segmented tread structure was developed, as shown in Fig. 16. In this configuration, a rubber compound that is effective in reducing the RRC and helping ensure effective handling in snow is used in the center, and a rubber compound that is effective in terms of wet braking performance is used for the shoulders. The pressure distribution over the entire contact patch was also equalized to ensure that these properties of the rubber compounds could be displayed effectively.

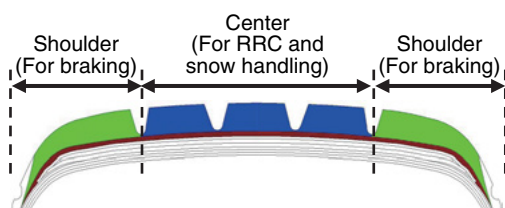


Fig. 16 Segmentation of tread construction

Table 2 Target tire characteristics

| Performance goal | Part of contact patch | Index of tread compound property | Direction |
|------------------|-----------------------|----------------------------------|-----------|
| Braking          | Shoulder              | 0°C tan $\delta$                 | Up        |
| RRC              | Center                | 60°C tan $\delta$                | Down      |
| Snow handling    | Center                | -15 °C E*                        | Down      |

### 4.1. Rubber Compounds Used

In order to satisfy the requirements shown in Table 2, rubber E, as described in Section 2.2., was used for the center, and rubber F was used for the shoulders.

### 4.2. Equalization of Distribution of Contact Pressure

The following method was used to equalize the distribution of contact pressure on the tire. Figure 17 shows a cross-section of a tire. The distribution of contact pressure can be equalized by optimizing the crown shape<sup>(9)</sup>. The target function was therefore established as a minimum deviation in contact pressure and the design parameter was set as the crown R shape, and FEM analysis was used to determine the optimum cross-sectional shape. The results are reflected in the shape of the vulcanizing die.

### 4.3. Verification of Performance Enhancements

Tires were produced with optimized crown R shapes and optimized positioning of the developed rubbers in the three-segment structure, and were subjected to performance tests. The new tires displayed a uniform contact patch pressure at maximum braking load, as shown in Fig. 18. The relationship between the RRC and wet braking distance (JNCAP test) for the new tires is shown in Fig. 19, together with the relationship for conventional tires using a single rubber compound. The newly developed tires displayed a 5 m reduction in braking distance as compared to tires with an identical RRC, and an 18 reduction in the RRC as compared to tires with identical braking distances.

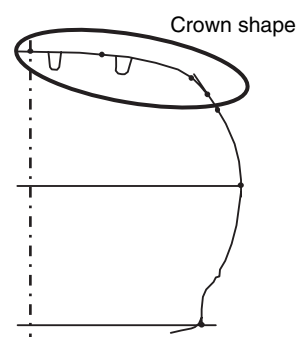


Fig. 17 Cross section of tire forming die

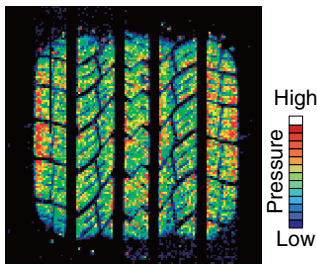


Fig. 18 Contact patch pressure of developed tire at braking load

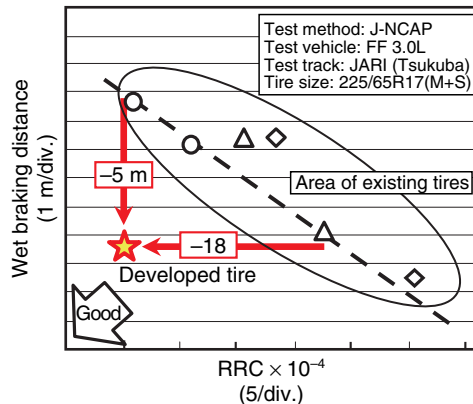


Fig. 19 Relationship between wet braking distance and RRC

These results indicate that this research has been successful in achieving a simultaneous enhancement in two antagonistic parameters, the RRC and braking distance.

The handling of the tires on snow (straight line vehicle stability, turning tracking performance, braking performance, and traction performance) was also verified. Further tests showed that the new tire technology had no adverse effect on the basic performance of the tires (durability, wear resistance, etc.) and their commercial appeal (handling, comfort of ride, road noise, etc.).

## 5. Conclusion

The following are the salient points of the research discussed in this paper.

- (1) The viscoelastic properties of tread rubber compounds place restrictions when trying to ensure adequate handling on snow, and there are difficulties to simultaneously achieve enhancement of the RRC and the braking distance of a tire by controlling the viscoelasticity of the rubber.
- (2) Analyses of the behavior of tires during braking indicated that the shoulder sections of the contact patch made the greatest contribution to braking performance. In addition, it was shown that equalizing the distribution of contact

pressure on the contact patch would be effective in helping ensure adequate friction.

- (3) An FEM simulation conducted under conditions of usual driving showed that the center of the contact patch made the greatest contribution to rolling resistance.
- (4) The center section of the rear tire represents the greater part of the contact patch. Therefore, the low-temperature elastic modulus of the rubber used in the center section makes a significant contribution to helping ensure the snow handling of FF vehicles.
- (5) Tires were constructed by placing rubber displaying properties that were effective in reducing rolling resistance and braking distance and maintaining snow handling in the optimal positions in a segmented structure. Also, using a cross-sectional shape that helped provide uniform distribution of contact pressure on the contact patch. These tires displayed a reduction of 5 m in braking distance on wet roads when compared to tires with identical rolling resistance characteristics, and an 18 reduction in the RRC when compared to tires with identical braking distances.

## 6. Afterword

Tires were developed for a 2.0 L SUV using the methods discussed in this paper. In line with the development goals set for the vehicle, reduction of the RRC was a main focus of the development. The developed vehicle displayed an enhancement of approximately 1.5% in 10-15 mode fuel economy with no decline in braking performance.

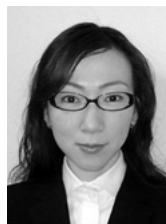
## References

- (1) Futamura, S., Scuring, D.: Rolling Loss of Pneumatic Highway Tires in The Eighties, Rubber Chem. Technol., Vol. 63, p. 315 (1990)
- (2) The Yokohama Rubber Co., Ltd.: Korogariteikou no Mekanizumu, Jidousha-you Taiya no Kenkyuu, Sankaido Publishing Co., Ltd, p. 151-154 (1995) (in Japanese)
- (3) The Yokohama Rubber Co., Ltd.: Korogariteikou no Mekanizumu, Jidousha-you Taiya no Kenkyuu, Sankaido Publishing Co., Ltd, p. 155-156 (1995) (in Japanese)
- (4) Kawakami, A., Hase H., Mizone, T.: Prediction of Braking Distance Temperature Dependence through Bench Test, Honda R&D Technical Review, Vol. 17, No. 1, p. 88-93
- (5) Muramatshu, R., Takahashi, H.: Material Technologies for a Reduction of Rolling Resistance, Journal of The Society of Rubber Industry, Japan, Vol. 73, p. 103-109 (2000)
- (6) Muraoka, K.: Viscoelastic Properties of Rubber Compounds for Tire Application, Journal of The Society of Rubber Industry, Japan, Vol. 74, p. 242-247 (2001)
- (7) Ozawa, Y., Akutagawa, K., Yanagisawa, K., Hiram, Y.: Ecology-Friendly Materials Technologies in Tire, Journal

of The Society of Rubber Industry, Japan, Vol. 77, p. 219-225 (2004)

- (8) The Yokohama Rubber Co., Ltd.: Korogarteikou no Mekanizumu, Jidousha-you Taiya no Kenkyuu, Sankaido Publishing Co., Ltd, p. 117-119 (1995) (in Japanese)
- (9) Bridgestone Corporation: Settiatsu Bunpu to Henmamou-sei, Jidousha-you Taiya no Kiso to Jissai, Sankaido Publishing Co., Ltd, p. 211-213 (2006) (in Japanese)

■ Author ■



Emiko MOGI



Tetsuya MIZONE



Hiroyuki HASE



Koji NISHITANI