Factors influencing tire force, moment characteristics

By Prasenjit Ghosh
and Rabindra Mukhopadhyay
Hari Shankar Singhania Elastomer and Tyre Research Institute

Executive summary

In an automobile, tires play a crucial role in ensuring dynamic stability of the vehicle, which includes cornering, traction, braking, driving and steering, providing lateral and directional stability.

All these criteria are satisfied by lateral and longitudinal properties of the tire. The vehicle handling behavior and thus stability largely depends on tire force and moment (F&M) characteristics. With the development of computational techniques, tire F&M properties have become the key input for multi-body simulation, which is the integral part of any new vehicle development process.

There are multiple parameters related to design as well as operational conditions that influence tire force and moment characteristics. The present work aims to study the influence of design and operational parameters on F&M properties of passenger car tires. The major design parameters like belt angle, belt material and tread material were varied. For operational parameters, load, inflation pressure, fitment rim width and camber were used as variables.

The F&M properties of different tire sizes were measured using flat belt tire testing equipment. The effect of these parameters on various F&M properties such as cornering stiffness, self-aligning stiffness, peak cornering force and relaxation length is reported and discussed in detail. Significant influence of these parameters on F&M properties was observed. Aligning stiffness showed the highest sensitivity toward these variations compared to other F&M properties.

TECHNICAL NOTEBOOK
Edited by John Dick

Tires largely influence the vehicle performance with respect to handling, stability, ride comfort and fuel economy. Tire developers are constantly working for improving the respective tire performance characteristics to keep pace with the emerging requirements from the automobile industry. Very often, it is expected that tires must achieve many of these mutually conflicting properties simultaneously, which is a daunting task for tire designers. Further, the linkages between component properties (tire) to the system (vehicle) level performance aren't well established because of the subjectivity involved in this process. To bring more objectivity in this process, tire developers and vehicle test engineers are constantly working toward more realistic test procedures and enhancing the test matrix.

In vehicle handling performance, tire force and moment properties play a very significant role. Hence F&M properties are of paramount interest to the vehicle dynamics engineers. These properties include cornering stiffness (CS), self-aligning torque (SAT), overturning moment (OTM), peak force (PF) and relaxation length (RL). These properties have an important role in determining lateral acceleration, steering response, yaw and roll behavior of a vehicle.

Xia et al. simulated vehicle handling behavior using four sets of tires, which are varying in F&M characteristics.[1] They discovered that handling performance improves with an increase in cornering stiffness of the tire. Tires with higher cornering stiffness have shown improvement in phase lag and yaw rate, which resulted in better vehicle handling performance.

Schroder et al. performed vehicle dynamics simulation using tires having different F&M characteristics.[2] According to this study, cornering stiffness and its load dependency significantly influences the vehicle handling behavior. They have also demonstrated the role of SAT and relaxation length on handling.

The study by Yum discussed the relationship between vehicle on-center steering response and the tire's SAT value at low slip angle.[3] He carried out sine wave tests of two tire sets having identical cornering stiffness but varying in SAT characteristics. Tires with higher SAT values achieved better vehicle on-center feel characteristics. The role of overturning moment on vehicle handling also was reported by Takahashi et al.[4] and Blue.[5]

Wei et al. described the various methods of determining lateral relaxation length of tires and its influence on vehicle handling.[6] The effect of relaxation length on vehicle handling is not very significant, and may not be perceivable to a driver. Until this point, this discussion brings out a very crucial role of tire F&M characteristics on vehicle handling response.

Further discussion on the effect of tire design, constructional and operational parameters on tire F&M characteristics is also necessary

See **Factors**, *page 21*

Table 1: Parameter details.

Parameters	Control	Experimental
Tread Material (TM)	TM-A	TM-B
Belt Material (BM)	BM-A	BM-B
Belt Angle (BA)	BA –L (21^0)	BA-H (26^0)
Inflation Pressure (IP)	IP-L (210 KPa)	IP-H (240 KPa)
Rim Width (RW)	RW-L (152.4 mm)	RW-H (165.1 mm)
Camber Angle (CA)	CA-L (0^0)	CA-H (5^0)

Fig. 1: Tire F&M curves: (a) Cornering force, (b) Self-aligning torque, (c) Overturning moment.

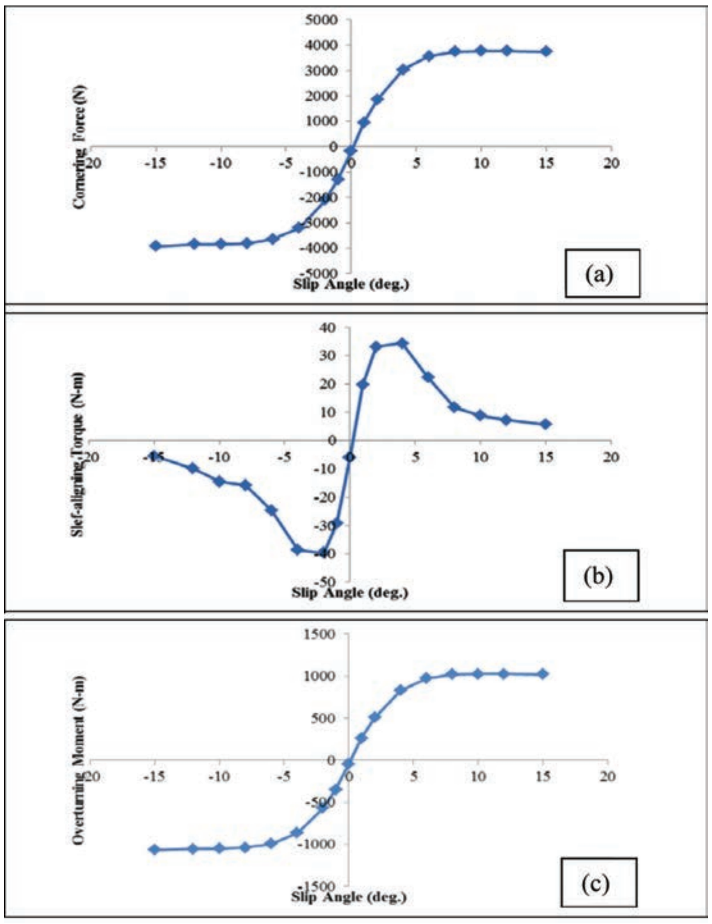
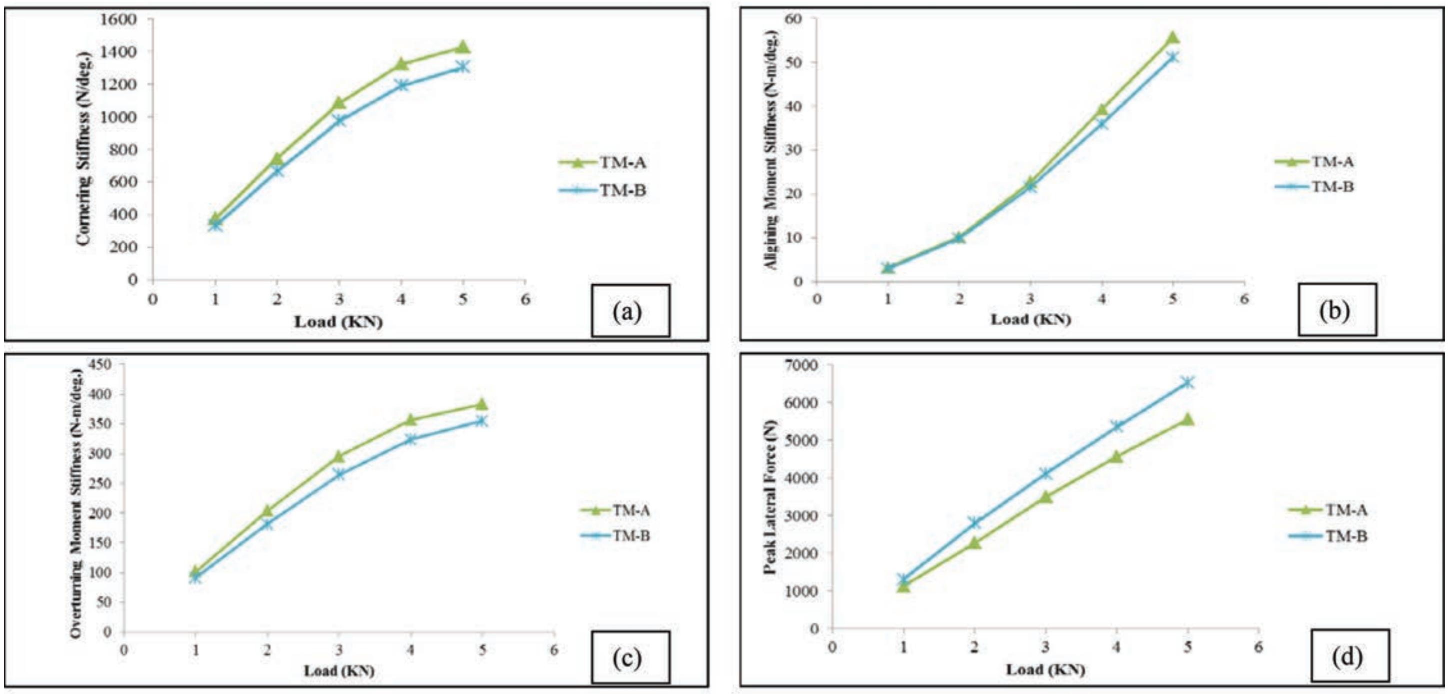


Fig. 2: Tread material variation F&M curves: (a) Cornering stiffness, (b) Aligning moment stiffness, (c) Overturning moment stiffness, (d) Peak lateral force.



The authors


Mukhopadhyay


Ghosh

Rabindra Mukhopadhyay graduated from the University of Calcutta with a degree in chemistry, earned his master's in applied chemistry and a doctorate in rubber technology from IIT Kharagpur, India. He also earned a degree in chemical engineering from the Institution of Engineers.

He has 43 years of experience within the rubber and tire fields, serving in various capacities throughout the industry. He is the director and chief executive of Hari Shankar Singhania Elastomer & Tyre Research Institute (HASETRI) and director of R&D at JK Tyre & Industries Ltd.

He is the chairman of the Indian Rubber Institute and fellow member of various professional bodies. He is a member the Rubber Skill Development Council's governing council. He serves on the Advisory Board of Certification Services, British Standards Institute, India and the BSI APAC Certification Body Impartiality Committee. He is a member of the board of studies at the Institute of Engineering and Technology and the academic council of JK Lakshmipat University in Jaipur, India.

Mukhopadhyay has published more than 175 research and technical papers in national and international journals. He holds seven patents from his research.

Prasenjit Ghosh holds an M.Tech degree from Indian Institute of Technology Kharagpur and a doctorate from Indian Institute of Technology Madras. He currently is working as principal scientist in Hari Shankar Singhania Elastomer & Tyre Research Institute, based in India. He has 19 years of experience in the field of finite element analysis, nonlinear material modeling, fatigue crack growth and wear mechanisms of rubber material. He has about 20 research publications to his credit.

Fig. 3: Belt material variation F&M curves: (a) Cornering stiffness, (b) Aligning moment stiffness, (c) Overturning moment stiffness, (d) Peak lateral force.

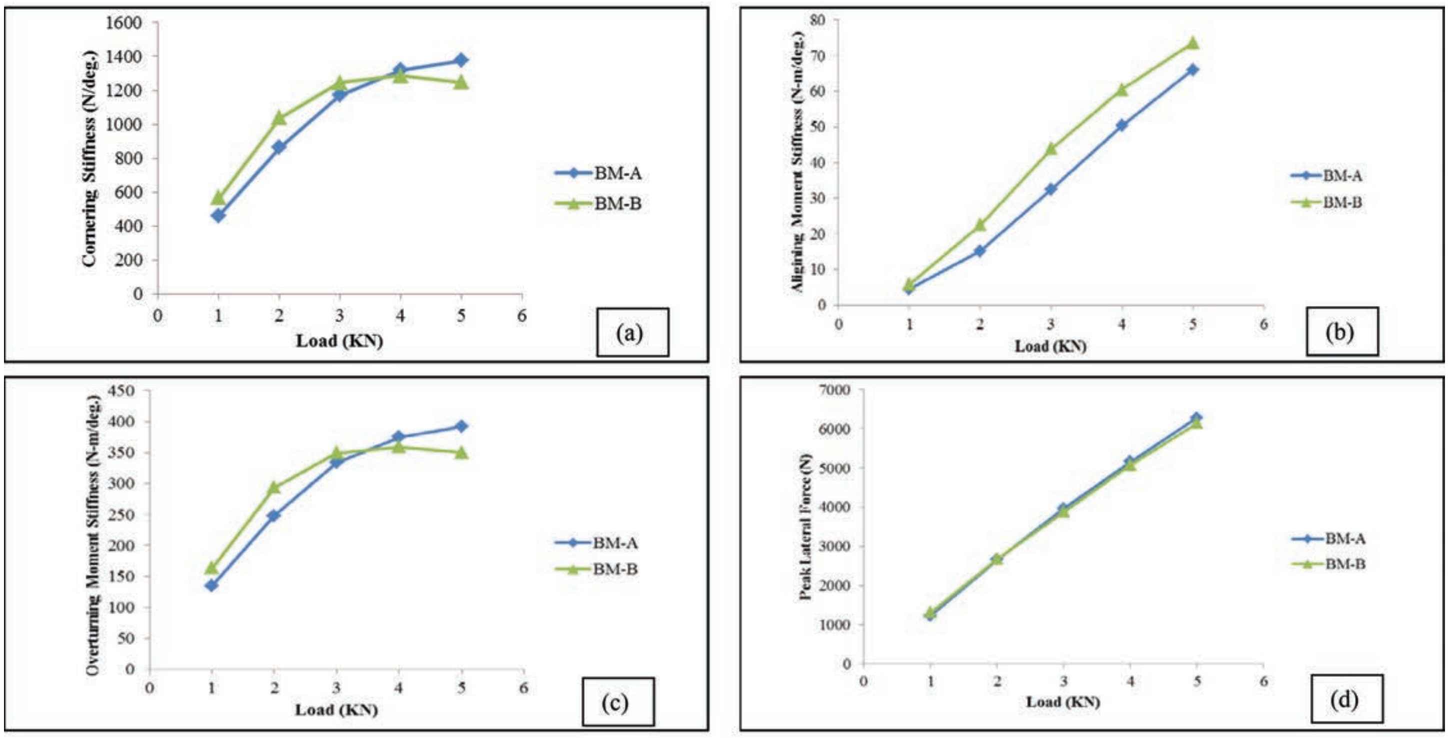


Fig. 4: Belt angle variation F&M curves: (a) Cornering stiffness, (b) Aligning moment stiffness, (c) Overturning moment stiffness, (d) Peak lateral force.

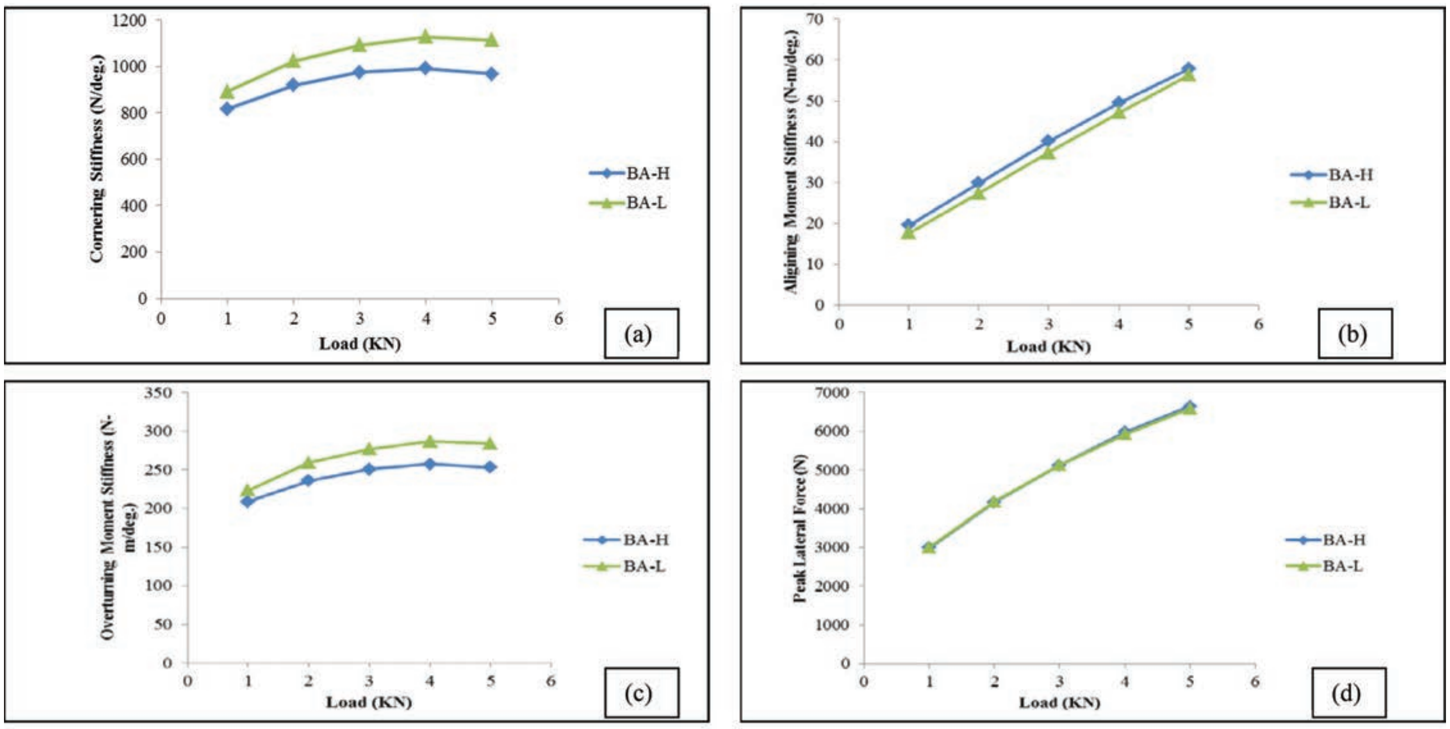
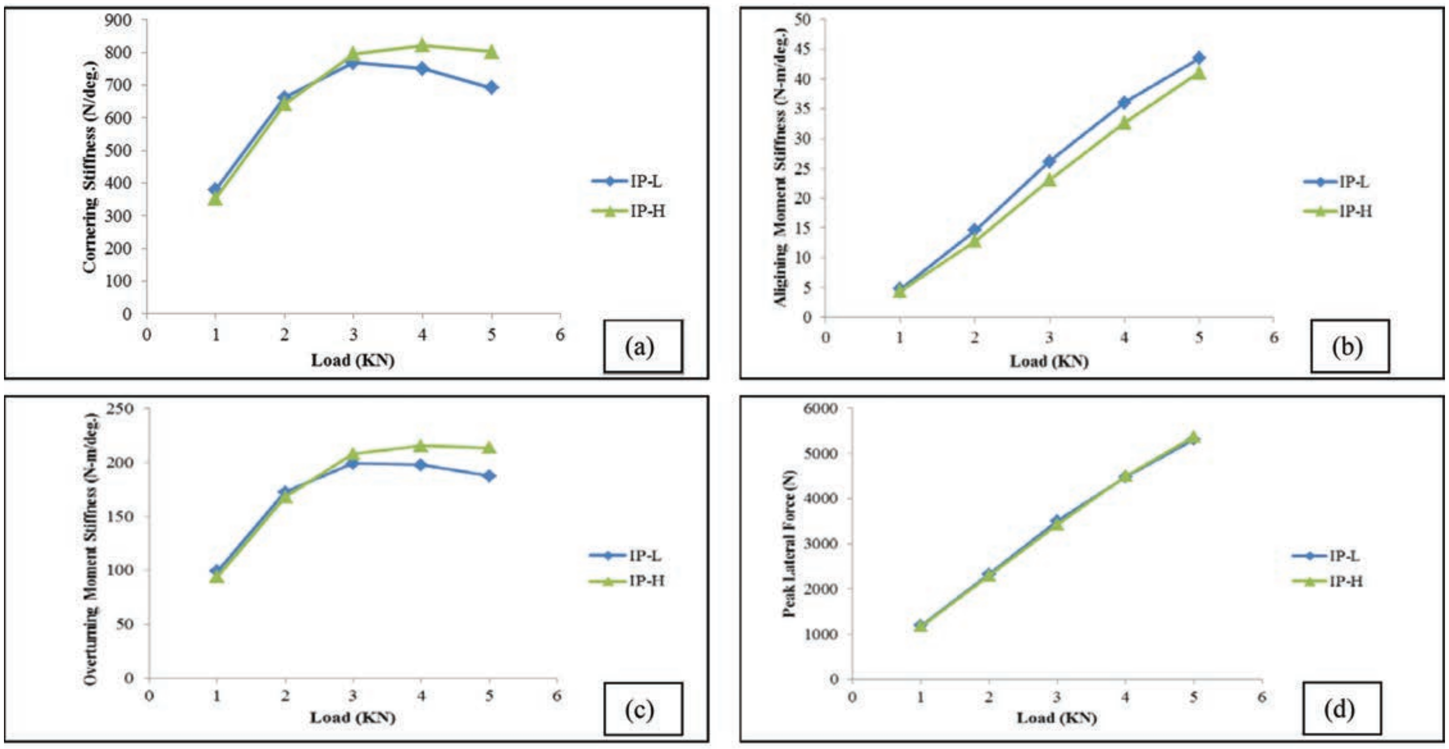


Fig. 5: Inflation pressure variation F&M curves: (a) Cornering stiffness, (b) Aligning moment stiffness, (c) Overturning moment stiffness, (d) Peak lateral force.



Factors

Continued from page 19

here. A literature search reveals that researchers have investigated the influence of various parameters like tire tread properties, tire contour, belt angle and body ply material. Walter has shown that tire mold and construction have a significant influence on tire cornering stiffness and self-aligning torque.[7] He also has concluded that SAT is more sensitive toward these changes compared to the cornering stiffness.

Pottinger et al. related the tire tread physical properties with F&M properties.[8] They concluded that lateral force linearly increases with tread hardness, whereas, it shows a nonlinear relationship with tangent delta of the tread compound. Olatunbosun et al. also studied the influence of various constructional and operational parameters on tire F&M characteristics using a finite element analysis tool,[9] while Angrick et al. studied the influence of tire core and surface temperature on lateral tire characteristics and observed a significant decrease in cornering stiffness with an increase in temperature.[10]

The majority of the previous work discussed so far on the various parameters influencing F&M characteristics could be considered a very wide range that may not be of interest from the practical application and manufacturing point of view. Tire designers always strive to keep the balance with other conflicting properties, which indirectly impose the restriction on range selection of various parameters. Considering these points, in this work, parameters and their ranges were selected in such a way that it is feasible from both application and manufacturing perspectives.

In this study, tread material, belt material, belt angle, inflation pressure, fitment rim widths and camber angle ware varied. The details of these parameters are given in **Table 1**. The levels of some of the parameters are indicated as L (low) and H (high). The remaining variables are represented as 'A' and 'B.' In the case of relaxation length measurement, only variation of tread material with respect to load has been measured.

Experimental

Steady state F&M tests were carried out on a flat belt tire testing machine having 3M 80 grit surface installed on the steel belt surface. All the tests were carried out at 3.6 kmph speed as per the GMW15204 standard.[11] The room temperature was maintained at 23±2°C. All the test samples were mounted on the test rims and stored for three hours in the room to achieve thermal equilibrium state. Vertical loads were varied from 1 KN to 5 KN with 1 KN load interval. Slip angle was varied from +15° to -15°.

Results and discussion

The variation of cornering force, self-aligning torque and overturning moment with slip angle at 3 KN load are shown in the **Figs. 1a-1c**. as a representation for data analysis in the subsequent sections. Cornering stiffness, aligning stiffness (AS) and overturning stiffness (OS) values were calculated in the slip angle zone of ± 1° for all the loads. For peak force, average cornering force at ± 15° slip angle is reported here, except in the case of camber where averaging was done at ± 12° slip angle. In the subsequent sections, individual effects of various parameters on F&M properties will be discussed.

The influences of tread material on various F&M characteristics were provided in **Figs. 2a-2d**. **Fig. 2a** shows the variation of cornering stiffness with load for both tread materials. It can be seen that the cornering stiffness of the tread material TM-A showed

See **Factors**, *page 22*

Factors

Continued from page 21

about 10 percent higher stiffness in the entire load range. This may be attributed to the higher stiffness of the TM-A.[8]

In the case of aligning stiffness (**Fig. 2b**), there is about 8 percent higher values displayed by TM-A in the entire load range. The overturning moment stiffness follows the same trend as observed in the case of cornering stiffness. Interestingly, the TM-B showed higher peak lateral force in the entire load range than that of TM-A. This indicates that TM-B has higher friction potential at high slip angle. The capability of higher peak force generation will be beneficial in the vehicle limit handling situation.

The influences of belt material on various F&M characteristics were provided in **Figs. 3a-3d**. The belt material, BM-B, is showing about 5-20 percent higher cornering stiffness till 3 KN load compared to belt material, BM-A (**Fig. 3a**). However the cornering stiffness values of BM-B at higher loads are 2-10 percent lower than that of BM-A. In the case of aligning stiffness, BM-B exhibited 10-50 percent higher values than that of BM-A. The higher values of both CS and AS for BM-B will help in vehicle handling characteristics. The overturning moment stiffness followed the same trend as that of the cornering stiffness. In the case of peak lateral force, there was no difference observed between these two belt materials.

Fig. 6: Fitment rim width variation F&M curves: (a) Cornering stiffness, (b) Aligning moment stiffness, (c) Overturning moment stiffness, (d) Peak lateral force.

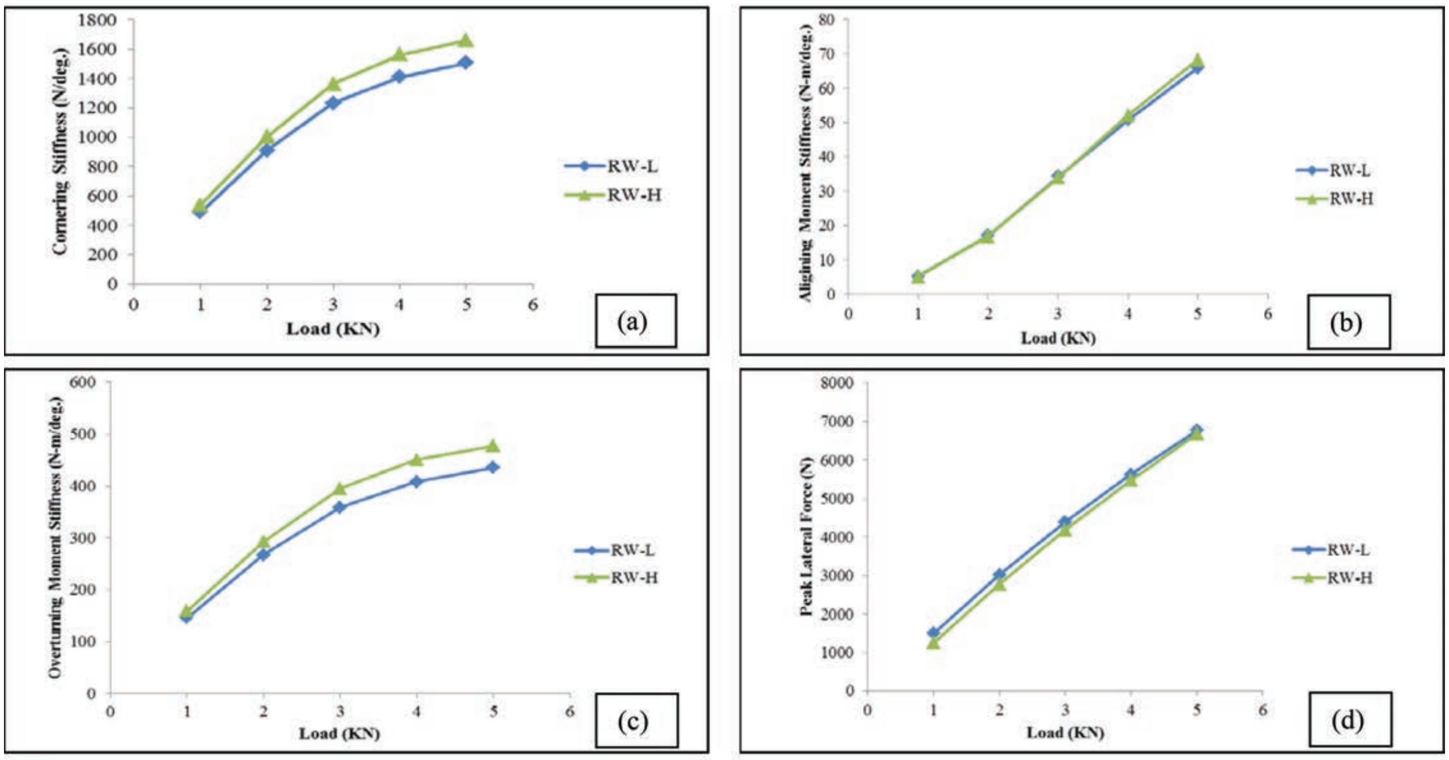


Fig. 7: Camber angle variation F&M curves: (a) Cornering stiffness, (b) Aligning moment stiffness, (c) Overturning moment stiffness, (d) Peak lateral force.

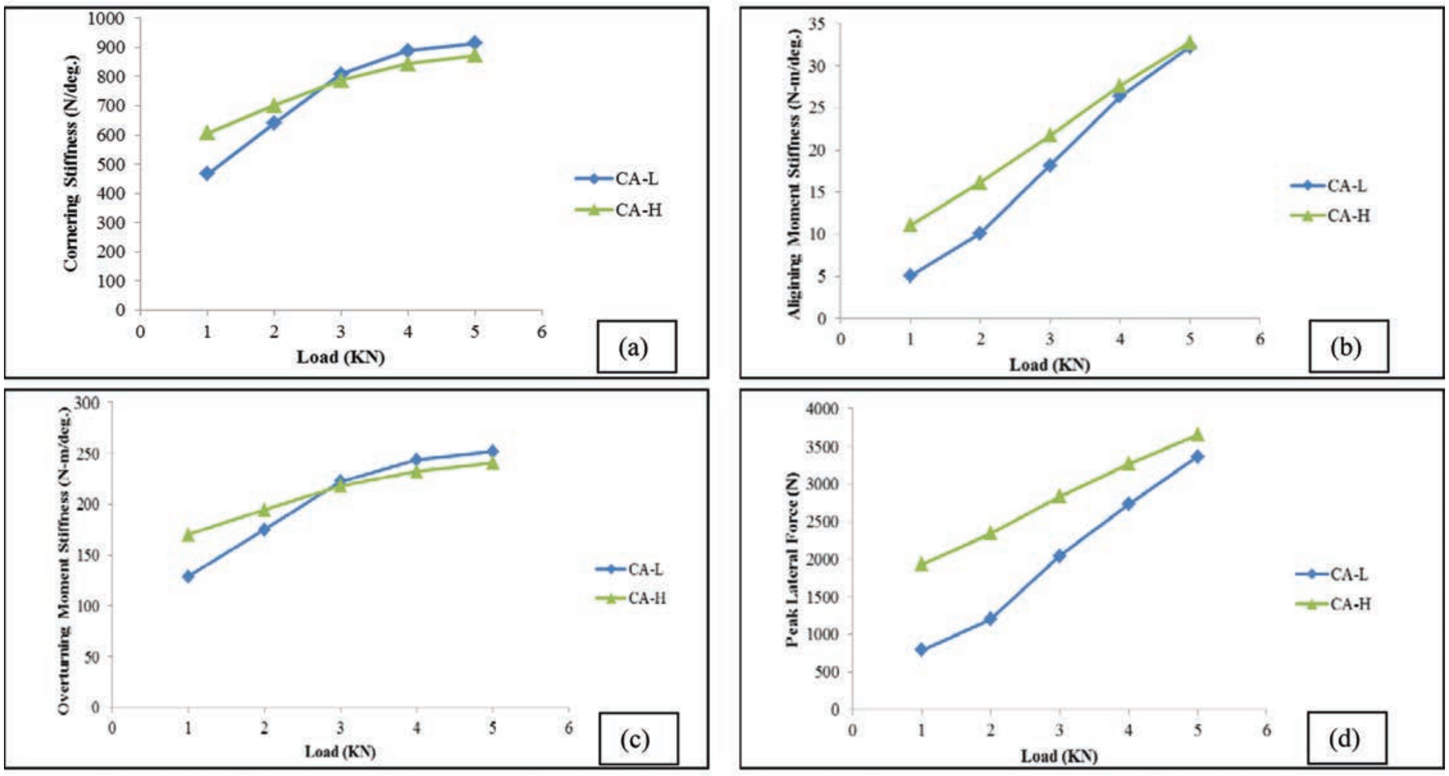
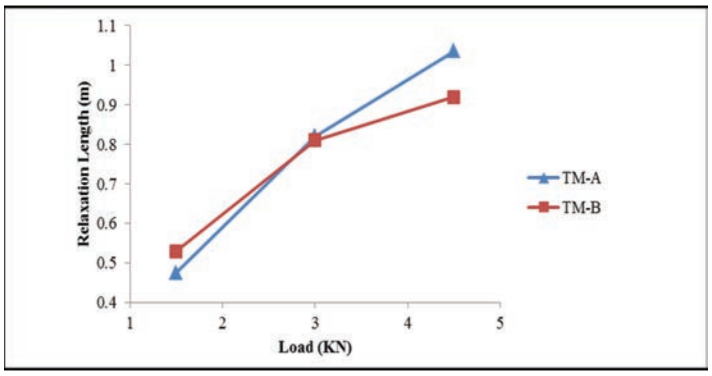


Fig. 8: Relaxation length of two tread materials.



The influences of belt angle on various F&M characteristics are provided in **Figs. 4a-4d**. The tire with low belt angle i.e. BA-L shows 10-15 percent higher cornering stiffness in the entire load range in comparison with the higher belt angle tire. The reverse trend was observed in the case of belt angle influence on aligning stiffness. The higher belt angle tire, BA-H achieved 2-10 percent higher aligning stiffness than the lower belt angle tire, which may be due to the increase in contact area in the former tire. The overturning moment stiffness followed the same trend as that of the cornering stiffness. In the case of peak lateral force, no influence of belt angle was observed.

The influences of inflation pressures on various F&M characteristics were provided in **Figs. 5a-5d**. The lower inflation pressure shows about 2-6 percent higher cornering stiffness at lower loads and the trend reverses at higher loads. At higher loads the differences in cornering stiffness also widens as the decrease is in the range of 3-15 percent. This occurred because the cornering stiffness depends on the contact area and the stiffness of the tire (tread area and carcass).[12] At lower loads and low inflation pressure, with the contact area being higher, it dominates. As the load increases, the contact area increase is not proportional to the decrease in carcass stiffness in comparison with higher inflation pressure. This is the reason for the sharp fall of the CS curve at higher loads.

In the case of aligning stiffness, lower inflation pressure showed 5-12 percent higher stiffness in the entire load range because the contact area dependence of SAT—with an increase in inflation pressure—the pneumatic trail reduces. The overturning moment stiffness followed the same trend as that of the cornering stiffness. In the case of peak lateral force, no influence of inflation pressure was observed.

The influences of fitment rim widths on various F&M characteristics were provided in **Figs. 6a-6d**. The lower fitment rim width, RW-L showed about 10 percent lower cornering stiffness in the entire load range in comparison with the higher fitment rim width, RW-H. However, the aligning stiffness showed very negligible dependence on fitment rim width. The overturning moment stiffness followed the same trend as that of the cornering stiffness. In the case of peak lateral force, slight differences can be observed.

Variation of F&M characteristics due to camber angle variation is shown in **Figs. 7a-7d**. CS is higher at lower loads and starts decreasing at higher loads. In the case of SAT, higher camber angle, CA-H achieved higher values throughout the load ranges. In the case of OS, it follows the same trend as that of CS. Peak lateral force values also are higher for higher camber angle

The variation of relaxation length with load is shown in **Fig. 8**. The relaxation length increases with an increase in load for both the materials. At lower load, TM-B is having higher relaxation length but the trend got reversed at higher load.

Conclusion

It is evident from this study that the parameters discussed here have shown significant influence on F&M characteristics. It also has been observed that some of the parameters, mainly CS and OS, exhibited nonlinearity with respect to vertical load variation. In the case of peak lateral force, it has shown very less sensitivity toward these parameters, except for tread material variation. Aligning stiffness showed the highest sensitivity toward these design and operational parameters variations compared to other F&M properties.

Acknowledgment

The authors thank the Managing Committee of Hari Shankar Singhania Elastomer & Tyre Research Institute (HASETRI) for permission to publish this research work.

References

1. X. Xia, and J. Willis, SAE Technical Paper 950313 (1995).
2. C. Schroder and S. Chung, Tire Sci. Technol 23, 2 (1995).
3. K. Yum, SAE Int. J. Passeng. Cars - Mech. Syst. 9(2) (2016).
4. T. Takahashi and M. Hada, Review of Toyota, CRDL, 38, 4 (2003).
5. D.W. Blue, Tire Sci. Technol 39, 3 (2011).
6. T. Wei and R.H. Dorfi, Tire Sci. Technol 4 (2014).
7. S.L. Walter, SAE Technical Paper 830160 (1983).
8. M.G. Pottinger and A.M. Fairlie, Tire Sci. Technol 17, 2 (1989).
9. O.A. Olatunbosun and O. Bolarinwa, Tire Sci. Technol 32, 3 (2004).
10. C. Angrick, S.V. Putten and G. Prokop, SAE Int. J. Passeng. Cars - Mech. Syst. 7(2) (2014).
11. Tire Steady-State Force and Moment Standard, GMW 15204, October, 2007.
12. M.G. Pottinger, "Forces and Moments," In A.N. Gent, J.D. Walter (eds.), The Pneumatic Tire. NHTSA, Washington, 2005.