Preface

The operational properties of the road vehicle are the result of the dynamic interaction of the various components of the vehicle structure, possibly including modern control elements. A major role is played by the pneumatic tire.

"The complexity of the structure and behavior of the tire are such that no complete and satisfactory theory has yet been propounded. The characteristics of the tire still presents a challenge to the natural philosopher to devise a theory which shall coordinate the vast mass of empirical data and give some guidance to the manufacturer and user. This is an inviting field for the application of mathematics to the physical world".

In this way, Temple formulated his view on the situation almost 50 years ago (Endeavor, October 1956). Since that time, in numerous institutes and laboratories, the work of the early investigators has been continued. Considerable progress in the development of the theory of tire mechanics has been made during the past decades. This has led to better understanding of tire behavior and its role as a vehicle component. Thanks to new and more refined experimental techniques and to the introduction of the electronic computer, the goal of formulating and using more realistic mathematical models of the tire in a wide range of operational conditions has been achieved.

From the point of view of the vehicle dynamicist, the mechanical behavior of the tire needs to be investigated systematically in terms of its reaction to various inputs associated with wheel motions and road conditions. It is convenient to distinguish between symmetric and anti-symmetric (in-plane and out-of-plane) modes of operation. In the first type of mode, the tire supports the load and cushions the vehicle against road irregularities while longitudinal driving or braking forces are transmitted from the road to the wheel. In the second mode of operation, the tire generates lateral, cornering, or camber forces to provide the necessary directional control of the vehicle. In more complex situations, e.g. braking in a turn, combinations of these pure modes of operation occur. Moreover, one may distinguish between steady-state performance and transient or oscillatory behavior of the rolling tire. The contents of the book have been subdivided according to these categories. The development of theoretical models has always been substantiated through experimental evidence.

Possibly one of the more difficult aspects of tire dynamic behavior to describe mathematically is the generation of forces and moments when the tire rolls over rough roads with short obstacles while being braked and steered in a time-varying fashion. In the book, tire modeling is discussed while gradually increasing its complexity, thereby allowing the modeling range of operation to become wider in terms of slip intensity, wavelength of wheel motion, and frequency. Formulas based on empirical observations and relatively simple approximate physical models have been used to describe tire mechanical behavior. Rolling over obstacles has been modeled by making use of effective road inputs. This approach forms a contrast to the derivation of complex models, which are based on more or less refined physical descriptions of the tire.

Throughout the book, the influence of tire mechanical properties on vehicle dynamic behavior has been discussed. For example, handling diagrams are introduced for both cars and motorcycles to clearly illustrate and explain the role of the tire non-linear steady-state side force characteristics in achieving certain understeer and oversteer handling characteristics of the vehicle. The wheel shimmy phenomenon is discussed in detail in connection with the non-steady-state description of the out-of-plane behavior of the tire and the deterioration of ABS braking performance when running over uneven roads is examined with the use of an in-plane tire dynamic model. The complete scope of the book may be judged best from the table of contents.

The material covered in the book represents a field of automotive engineering practice that is attractive to the student to deepen his or her experience in the application of basic mechanical engineering knowledge. For that purpose, a number of problems have been added. These exercises have been listed at the end of the table of contents.

Much of the work described in this book has been carried out at the Vehicle Research Laboratory of the Delft University of Technology, Delft, the Netherlands. This laboratory was established in the late 1950s through the efforts of professor Van Eldik Thieme. With its unique testing facilities realistic tire steady-state (over the road), transient, and obstacle traversing (on flat plank) and dynamic (on rotating drum) characteristics could be assessed. I wish to express my appreciation to the staff of this laboratory and to the Ph.D. students who have given their valuable efforts to develop further knowledge in tire mechanics and its application in vehicle dynamics. The collaboration with TNO Automotive (Delft) in the field of tire research opened the way to produce professional software and render services to the automotive and tire industry, especially for the *Delft-Tire* product range that includes the *Magic Formula* and *SWIFT* models described in Chapters 4, 9, and 10. I am indebted to the Vehicle Dynamics group for their much appreciated help in the preparation of the book.

Professors Peter Lugner (Vienna University of Technology) and Robin Sharp (Cranfield University) have carefully reviewed major parts of the book (Chapters 1–6 and Chapter 11, respectively). Igo Besselink and Sven Jansen of TNO Automotive reviewed the Chapters 5–10. I am most grateful for their

valuable suggestions to correct and improve the text. Finally, I thank the editorial and production staff of Butterworth-Heinemann for their assistance and cooperation.

Hans B. Pacejka
Rotterdam,
May, 2002

NOTE ON THE SECOND EDITION

In this new edition, many small and larger corrections and improvements have been introduced. Recent developments on tire modeling have been added. These concern mainly camber dynamics (Chapter 7) and running over three-dimensional uneven road surfaces (Chapter 10). Section 10.2 has been added to outline the structure of three advanced dynamic tire models that are important for detailed computer simulation studies of vehicle dynamic performance. In the new Chapter 12, an overview has been given of tire testing facilities that are designed to measure tire steady-state characteristics both in the laboratory and over the road, and to investigate the dynamic performance of the tire subjected to wheel vibrations and road unevennesses.

Hans B. Pacejka
Rotterdam,
September, 2005

NOTE ON THE THIRD EDITION

In this new edition, again many improvements have been introduced. Some chapters have been reorganized, notably Chapter 10, and a new Chapter 13 has been introduced outlining three advanced dynamic tire models. We express our thanks to the two guest authors Michael Gipser and Christian Oertel (the original model developers) for their contributions in this chapter. Igo Besselink has contributed to the preparation of the new edition. He wrote his part of Chapter 13 and the extended Appendices.

We much appreciate and are grateful for the help provided by TNO Automotive, Helmond, the Netherlands, especially for making available motorcycle tire measurement data obtained with the new test facility that can handle large camber angles. An image of the device appears on the front cover of the book. This TNO facility is shown mounted on the old Delft Tire Test Trailer but is now installed in the new TNO Tire Test Semi-Trailer, cf. Chapter 12. We also thank TNO for allowing us to use their vehicle measurement data. We are grateful to Antoine Schmeitz, who checked and made important remarks, notably on Chapter 4 and on the revised Chapter 10.

We thank Manfred Plőchl of the Vienna Technical University for carefully checking Chapters 1 and 11. Bill Milliken (now 101 years old! See his wonderful engineering autobiography (2006)) responded very competently on a question of mine regarding the origin of the *Similarity Method*. We are also grateful to readers who sent – often small – remarks that have served to improve the book.

In the book, vehicle dynamic problems have been addressed and a number of tire models have been discussed. Applications of these tire models serve to illustrate their use and the influence of relevant aspects in vehicle dynamic behavior. Two tire models are not in the first place meant to be used seriously in applications. They have been discussed for providing insight and for studying the main typical aspects of tire force and moment generation in the steady state (the *Brush Model*, Chapter 3) and in the transient state (the *String Model*, Chapter 5). In Chapter 1, the basic form of the *Magic Formula* has been introduced. This empirical model is well suited to be applied in vehicle dynamics studies. For high standard applications requiring great accuracy, the full model discussed in Chapter 4 may be employed. For relatively low frequency and larger wavelength phenomena, the transient tire model featuring the relaxation length, developed in Chapter 7 and applied in Chapter 8, is often sufficiently accurate. In case one is interested in higher frequency and shorter wavelength responses of the tire with the first natural frequencies included, the advanced dynamic tire model developed in Chapter 9 is recommended. This so-called *SWIFT* model works in conjunction with the *Magic Formula*. Rolling over uneven roads including short obstacles can be handled by using the special geometric filtering technique treated in Chapter 10.

Hans B. Pacejka
Rotterdam,
August, 2011