Straight Motion of Road Vehicles

An SAE Core Title

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To my family and everyone who has supported me along this (straight) road. Especially Agnese, who ended up knowing most of the pages of this book by heart, I’m afraid.

—Alessandro

To Nettie and Hans Pacejka, remembering the nice times spent together during Simposia around the world and in Italy.

—Giampiero

To Paolo Bandel, for his teaching.

—Giuseppe
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The book deals with the straight motion of road vehicles, with particular focus on the role played by tires, vehicle suspensions, and road cross slope. The aim is to describe in a mathematical, analytical way the phenomenon of straight ahead running of vehicles and the driver’s reactions to achieve this. Since the straight motion is relatively simple to be modeled, even considering rather complex vehicle models, the aim of the book is to provide accurate analytical formulae for hopefully a ultimate engineering contribution on this topic.

The aim is to enable proper engineering solutions for vehicles, which naturally run straight ahead, saving fuel and minimizing tire wear. Since the very beginning of automotive engineering, obtaining the straight ahead running of road vehicles has been a known issue. The book aims at instructing engineers on how to make a vehicle run straight, making the driver feel comfortable and safe.

The aim of the book is to encompass issues pertaining both to current production vehicles and to future automated vehicles. Actually, a full analytical knowledge of the straight ahead running phenomenon is a primary need for the development of any road vehicle.

In the design process of a vehicle, straight running is often obtained after tuning of tires and suspension parameters. The feel of tire pull or weak stiffness at the steering wheel by the driver strongly affects the perceived level of the quality of the vehicle. Presently, a number of complex nonlinear vehicle models are available that can be used effectively to tune relevant parameters affecting straight ahead running of vehicles. However, no analytical formulae are available for the same purpose. This book offers such formulae that highlight the trends and the relationships among parameters, enabling engineers to have an insight into and a sound understanding of the technical solutions they adopt. More specifically, engineers may get in-depth knowledge of the basic interactions between vehicle and tires. Such understanding and knowledge cannot be obtained by numerical simulations.

Authors do believe that this book is a preliminary contribution, able to stimulate future studies for safer, smarter, and more comfortable vehicles.
The book is not to be used as a manual, that is, as a book containing practical instruction on how to build a mechanical system. The publisher and the authors agree that the book has the only aim of explaining to readers both the relevant physical phenomena and how the solution of technical problems can be obtained by means of a scientific approach. Technical applications have then to be realized by experienced engineers only on the basis of national or international standards and/or practical rules that are omitted in the book.

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Vehicle pull arises whenever the driver has to exert a discernible steering torque (called \textit{pull}) in order for the vehicle to move straight ahead, which can become a tiresome task in case of long-distance driving along straight roads (e.g., when traveling on highways). A lateral deviation (called \textit{drift}) occurs when the vehicle, despite being not steered, does not maintain the intended straight path. These two expressions of the same issue represent a critical aspect for vehicle straightability performance [1]. Actually, these handling features are often ascribed among the vehicle (or component) basic needs, or \textit{Must-Be Qualities}, to use the terminology of Kano model of product development [2]: customers expect and take for granted that the vehicle tracks straight and free of pull in the absence of steering inputs and external disturbances. Non-fulfillment of this requisite has deleterious consequences on customers’ opinion and satisfaction, impacting on the perception of both comfort and safety. Therefore, vehicle pull represents a key problem for automotive Original Equipment Manufacturers (OEMs), and it is often examined as a crucial factor during approval tests with tire manufacturers.

The factors producing vehicle pull can be divided into

- \textit{External factors}, such as crosswind or road cross slope, that are part of the boundary conditions or environment in which the vehicle system operates.
- \textit{Internal factors} or vehicle system related parameters. Among them, a key role is played by specific tire properties and vehicle unbalances (e.g. non-symmetric weight distribution, improper suspension alignment, dimensional tolerances).
“Nuisance” is the term that Pottinger juxtaposes to the vehicle pull issue [3]. Nuisance can be related to the continuous driver’s action to keep a straight motion. Understanding such a phenomenon is of crucial importance not only for the comfort of the driver, but also for

- reducing energy losses
- designing future autonomous vehicles

**State of the Art**

Among the different causes of vehicle pull, tire characteristics are of particular interest. In his comprehensive reference [3], Pottinger provides a definition for the *pull forces*, describing them as the offsets in tire side force $F_y$ and aligning moment $M_z$ responsible for vehicle pull. These offsets, which give rise to non-negligible forces and moments when the tire is not steered nor cambered, are inherent characteristics common to all tire constructions. They have become increasingly relevant with the establishment of the radial ply tire as the prevalent tire construction type, supplanting the bias tire [3–6]. Side force and aligning moment offsets are included also in the semi-empirical *Magic Formula Tire models* developed by Pacejka [7], which are widely used as accurate portrayals of steady-state tire force and moment characteristics, for vehicle dynamics analyses and simulations.

Furthermore, the aforementioned tire force and moment offsets are commonly divided into two components, called *ply-steer* and *conicity*, to discern the two characteristically different types of sources generating them [3, 4, 8]

- **Ply-steer** is defined as the lateral force offset contribution whose direction relative to the tire face depends on the direction of rotation. In the axis system attached to the tire, the sign of ply-steer lateral force is independent of the direction of rotation. It is an intrinsic characteristic of the tire structural design, and its effect can be considered analogous to that of a *pseudo-side slip angle*.
- **Conicity** is defined as the contribution of the lateral force offset whose direction relative to tire face is independent of the direction of rotation. In the axis system attached to the tire, the sign of conicity lateral force changes with direction of rotation. It is mainly related to finite manufacturing precision, and its effect is analogous to that of a *pseudo-camber angle*.

Extensive research has been conducted with regard to tire design characteristics producing these two components, in particular for what concerns ply-steer. Among the others, the works performed by Pottinger [4] and Bert [6] are worth mentioning: they made use of the laminated composite theory to describe how the belt layers contribute to the generation of ply-steer side force and moment, with experimental measure validations. However, the subsistence of a considerable influence on ply-steer from tire tread was pointed out experimentally by Matyja [5], and then corroborated with FEM studies performed by Mundl et al. [9] and *Toyo Tire & Rubber Co., Ltd.* [10, 11].

In the last decades, the relationships between tire ply-steer and conicity features and vehicle behavior in straight-ahead motion have been explored. On the one hand, Lindenmuth [12] is indicated as one of the first authors to have evidenced
experimentally the existence of a relationship between vehicle pull and tire conicity and ply-steer [3, 13]. On the other hand, Topping [14] is claimed to be the first author offering an easy grasp of the origin of steady-state tire-induced vehicle pull [3, 4]. Topping’s theory, reported by Pottinger [3], considers front and rear axles as separated entities, and provides a basic explanation of how vehicle pull occurs, looking at tire side force $F_y$ and aligning moment $M_z$ characteristics as functions of side slip angle $\alpha$. The theory is based on the assumption that no lateral deviation occurs if no lateral force acts on the axles of the vehicle [3, 14]. Two kinds of driving conditions are generally considered in literature in which the different expressions of vehicle pull arise

- **Fixed control condition**: in this condition, the driver holds the steering wheel to make the vehicle run along a straight path. Front and rear axles arrange themselves with respective side slip angles $\alpha_1$ and $\alpha_2$ in order for the sum of tire side forces to become null on both axles (front $F_{y1} = 0$, rear $F_{y2} = 0$).

  On the one hand, the front axle side slip angle $\alpha_1$ – nullifying $F_{y1}$ – determines a residual aligning moment $M_{z1}$ on the front axle, since in general either the side force $F_y$ or the aligning moment $M_z$ do not become null at the same slip angle. This has a direct effect on the average steering torque (steering pull) that the driver has to exert during vehicle straight motion, sometimes called Vehicle Residual Aligning Torque (VRAT) in literature [15, 16].

  On the other hand, the rear axle side slip angle $\alpha_2$ determines vehicle attitude $\beta$, causing the vehicle to exhibit the so-called dog-tracking straight ahead motion.

  Finally, the difference between front and rear axle side slip angles causes a non-null steering wheel angle (or misalignment).

- **Free control condition**: in this condition, the driver releases the steering wheel. The front axle arranges itself with a side slip angle $\alpha_1$ for which the aligning moment $M_{z1}$ becomes null, since it is no more counterbalanced by a steering torque.

  The sum of tire side forces is not equal to zero for the front and rear axles, and a lateral deviation (steering drift) from the straight path occurs.

Thereafter, the analyses focus on the connection between vehicle straight motion dynamics and specific tire parameters. Particular relevance was attributed to the tire Residual Aligning Torque (RAT), remaining when side force is null. As an alternative, other related parameters were considered, such as the one introduced by Pottinger [3, 4]: he defined the Aligning Torque Shift Phase (ATSP) as the difference between the slip angle at which side force is null and the slip angle at which the aligning moment is null. Pottinger’s theory, despite being straightforward and sufficiently accurate, does not explain completely the underlying interactions between vehicle and tires in the straight motion [17]. For this reason, an analysis was conducted by Lee [17], who expanded upon Pottinger’s and Topping’s contributions with a rather more complete approach, including tire moments in the equilibrium equations and performing dynamic simulations both with a simple single-track model and with a full-vehicle model. Actually, Lee pointed out that little had been examined up to then on the tire-induced vehicle pull pertaining to dynamic simulations: the same drift experienced in real-life driving situations is obtained when running numerical simulations, in case tire properties from experimental data are used.
Other studies considered experimentally the effect of suspension geometry on vehicle pull, e.g., by examining cross camber, cross caster, and other suspension alignment tolerances [13, 15, 18, 19].

In addition, the effect of road cross slope on vehicle pull has been commonly recognized as non-negligible [3, 16, 19]: original equipment manufacturers (OEMs) specify a limit for the acceptable conicity lateral force for a pair of tires to be installed on a given vehicle axle. Moreover, OEMs specify a target range for tire ply-steer residual aligning torque (PRAT), whose magnitude depends on vehicle weight, which is aimed at countering road cross slope according to the destination market (i.e. left- or right-hand drive countries). Nevertheless, in the abovementioned studies, the road cross slope effect was either not analytically discussed or just included with simplifying considerations. As a consequence, the outcomes turn out to be unsuitable to provide an accurate description of the actual impact of road cross slope on vehicle pull.

It is important to underline that vehicle pull issue is still currently an object of studies and is taken into consideration with particular care in the automotive field. This is confirmed by researches on robust design optimization aimed at steering pull reduction, such as the one conducted by Park et al. [20]. Moreover, in the last few decades, the establishment of the Electric Power-Assisted Steering (EPS) has opened possibilities in the active reduction of vehicle pull. This option to overcome passive control limitations, proposed, just to name a few, by Nissan Motor Co., LTD. [21] and General Motors Co. [2], has proved to be quite effective in the reduction of steering torque (or pull) issue. Nevertheless, as for steering wheel misalignment and vehicle attitude (or dog-tracking) problems, EPS constitutes a solution just to a limited or no extent.

This book is a full rework (revision, correction, and substantial extension with data and full mathematical proofs) of a Master of Science dissertation, produced and discussed at the Politecnico di Milano [22]. A similar dissertation has been discussed publicly at the KTH Royal Institute of Technology in Stockholm [23].

Book Approach and Objectives

The focus of this book is on the influence of steady-state tire characteristics on vehicle pull and straight motion behavior. In particular, the tire-associated pull problem is considered in the free rolling condition, isolating it from the torque steer and the influence of longitudinal tire forces that arise when the vehicle is driven or brakes applied, respectively [3].

The main objective of the book is the study and accurate description of the tire-associated vehicle pull problem, with reference to the effects on vehicle straight motion and on-center handling, based on a thorough theoretical study by using available tire data.

Analytical equations and solutions are derived for the addressed problem. They are obtained by means of the study of a rather complete single-track vehicle model, able to accommodate different left and right tire characteristics and load transfer and static roll induced by road cross slope. The presence of road cross slope effect is extensively considered by pointing out the different effects that descend from it. Moreover, proper
(symmetric) suspension alignment contribution is analyzed in presence of different left and right tire characteristics, which can be due to tire manufacturing tolerances or induced by road cross slope.

The interaction between the tires and vehicle, namely the effect of elastokinematics and compliances in suspension and steering systems, is taken into account by means of the effective axle characteristics. The formulation of effective axle characteristics, described by Pacejka [7], is specifically extended in this book in order to account for the tire force and moment offsets (pull forces), together with the different left and right tire characteristics. The purpose is to draw an analytical representation and explanation for problems still open in literature.

Furthermore, the handling diagram theory [7, 24] is suitably extended and adapted in this book to accommodate the aforementioned tire and effective axle characteristics. The adapted handling diagram provides the possibility of conveniently and simultaneously linking the axle’s side slip angles, steering angle, and steering torque by expressing all of them as functions of vehicle lateral acceleration. For small lateral accelerations, which are the range of interest in this study, the adapted linear handling diagram allows accurate and effective evaluation of all the vehicle pull related parameters, namely steering torque, steering angle and vehicle attitude.

Analytical expressions and a single-track model are developed in MATLAB®. Such expressions are validated by means of proper simulations performed with a full-vehicle model in the multibody dynamics simulation software MSC Adams™. The effect of road irregularity is studied by comparative analyses of the computed variances and the results of full-vehicle simulations.

Finally, the existence of a relationship between the tire offsets and the on-center handling of the vehicle is explored. Based on the company’s experience and available subjective feedback of a test driver, the tire sets with the worst performances with regards to the vehicle pull are also the ones producing the worst results during on-center handling tests. The simulation of an adapted weave test is employed to analyze the correlation between simulated steering torque objective metrics and analytically computed steering torque offsets. The observed results may provide an explanation to the subjective feedback and demonstrate a relationship between tire characteristics offsets and steering feel performance.

**Structure of the Book**

The book is divided into two parts.

The first part is dedicated to the thorough analytical discussion of the various aspects related to tire-induced vehicle pull issue and straight motion

Chapter 1 (at page 9): the ply-steer and conicity components of tire side force and aligning moment are presented, together with the pertaining formulae and description of the test methods used to measure them.

Chapter 2 (at page 25): the effective axle cornering stiffness formulation is extended in order to include the tire force offsets. The single-track vehicle model is introduced.

Chapter 3 (at page 41): the effect of tire characteristics on vehicle straight motion is analyzed. The straight-driving expressions are described and linked to the extended handling diagram theory.
Chapter 4 (at page 53): an expression for the steering torque as a function of tire characteristics is obtained, and combined with the extended handling diagram theory. 

Chapter 5 (at page 69): different test methods for the analysis of vehicle pull are described. A section is dedicated to the on-center handling evaluation. 

Chapter 6 (at page 77): the effects of road cross slope are thoroughly described. 

Chapter 7 (at page 87): contributions of wheel alignment and tire characteristics to straight-driving steering angle, steering torque, and vehicle attitude are examined. Analytical solutions are given. 

Chapter 8 (at page 103): road irregularity (or unevenness) effect is investigated, with single- and double-track excitation, to have a formulation for the variance of tires’ normal load, straight-driving slip angles, and vehicle’s body lateral displacement. 

The second part is dedicated to the numerical simulations, with discussion of the results and comparison between analytical expressions, namely the MATLAB® single-track model and MSC Adams® full-vehicle model. 

Chapter 9 (at page 137): the available data, referring to four different sets of tires, are presented together with test driver’s subjective feedback. 

Chapter 10 (at page 145): the analytical expressions and MATLAB® single-track model are validated by means of null steer test simulations performed with MSC Adams® full-vehicle model. 

Chapter 11 (at page 157): the analytical expressions for straight-driving slip angles, vehicle attitude and steering torque are validated by comparison with fixed control test simulations performed with MSC Adams® full-vehicle model. Furthermore, the influence of road irregularity is examined. 

Chapter 12 (at page 169): an adapted weave test is considered to study on-center handling, and simulations are performed both with MATLAB® single-track model and MSC Adams® full-vehicle model. The results are combined with the analytically computed steering torque offset, showing a relationship between tire characteristics and vehicle on-center handling. 

Chapter 13 (at page 185): the contributions of wheel alignment, highlighted in Chapter 7, are discussed numerically. Moreover, the results provided by analytical expressions, MATLAB® single-track model, and MSC Adams® full-vehicle model are compared to discuss reliability and limitations. 

Finally, in the Appendix (at page 207) further details are provided on how solutions and expressions presented in the analytical part are obtained, on sign conventions adopted and on vehicle and tire parameters.