Classification and Testing of Paved Road Surfaces for Vehicle and Tire Modeling

by

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Classification and Testing of Paved Road Surfaces for Vehicle and Tire Modeling

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Dedication

This thesis is dedicated to my wife, Christina.

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Ford Motor Company supported this thesis. Through their generosity many investigations, like this one, are conducted in the academic environment to not only develop new ideas and solutions to current problems but to educate the next generation of research scientists. In particular, I would like to thank Jerri Paul and John Joyce. Through their effort and generosity many students, like myself, are able to realize career milestones and goals.

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This thesis presents a method to classify and test paved road surfaces with respect to a particular tire. This method was developed to augment existing tools used in mathematical vehicle models undergoing virtual simulation. The method is intended to facilitate a parameter surface change for a given tire model to both provide more accurate measurements of the resultant forces characterizing a particular tire-road combination, and to improve the fidelity of the vehicle simulation as a whole. The classification and testing of a paved road surface is based on the relative identification of a surface's micro and macro texture through two locked-wheel skid resistance tests at low and high vehicle speeds.

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CHAPTER 1: Introduction

1.1 Thesis Background and Description

The inability to fully characterize the frictional force between a tire and a road surface makes it difficult to incorporate surface characteristics into predictive tire models based purely on first principles. Consequently engineers evaluating the tire component system must rely on models containing some empiricism [1]. Currently, empirical tire models, which are those that form a continuous approximation to the discrete data obtained through testing, are used to estimate the tire-road reaction forces for automotive analysis and design purposes [2]. However, these predictive models come at a price: they are only as good as the formulations used to approximate the physical dynamics they represent. Often, the parameters used in an empirical tire model have little relationship to the physical parameters that describe the actual system. This dichotomy makes it difficult to examine specific parameters related to the road surface or tire for comparative analysis in a vehicle simulation, which would make it possible to quantify advantages and/or disadvantages any of these parameters have on overall vehicle design. This thesis proposes that through a standard road classification and test method a methodology can be developed using the relevant knowledge base found in the open literature to effect a parameter surface change in an empirical tire model.

1.2 Thesis Focus

Traditionally pneumatic tires have been one of the only vehicle components designed and manufactured independent of a specific vehicle design. As such, tire manufacturers are obliged to provide a report (or tire model), to vehicle manufacturers, quantifying a tire's performance capabilities. This information is then ideally assessed, in a vehicle simulation, to identify the compatibility of a specific tire with a specific vehicle model and its components. However, in practice, the tire manufactures often provide tire data measured on laboratory test facilities whose frictional properties can be quite different from actual road conditions [3]. This discrepancy adversely affects the fidelity of the vehicle simulations. In response to this dilemma has been the production of predictive mathematical models capable of relating the tire-road relationship. These predictive models are being pursued through purely computational methods, such as Finite Element Models, analytical methods, such as the Brush Model, and through empirical methods, such as the Pacejka Tire Model [4]. Without a doubt great progress has been made in each of the preceding methods to describe tire-road behavior, however, empirical methods currently represent the most reliable method for vehicle applications [1]. To this end there is evidence that the variability of road surfaces can be integrated into a description of a particular tire using empirical tire models. A recent publication by P. Van der Jagt and A.W. Parsons [3] specifically isolated two model parameters that facilitate the adjustment of a tire model to a different road surface. However, the full potential of this model extension has not yet been realized, as there is no standard distinguishing one surface from another according to the specific characteristics that are known to affect the friction between a tire and a road surface.

This thesis proposes that through the use of a standard for which a paved road surface can be classified and tested, the technology developed by P. Van der Jagt and A.W. Parsons [3] can be significantly expanded. The standard classification and test method specifically addresses, as this thesis will show, the two most dominant road surface characteristics contributing to the development of tire-road friction, namely micro and macro texture. Through the use of a low and high vehicle speed locked-wheel skid resistance test, a paved road surface can be uniquely identified and used to facilitate the adjustment of the Pacejka Brake Tire Model from one surface to another. This methodology requires as much full-scale testing as would be needed to assess the effect of a parameter surface change on the Pacejka Brake Tire Model. Nevertheless the approach purposed could be used with surface measurement technology being developed by the Texas Department of Transportation (TxDOT) that may greatly reduce the amount of testing needed to effect the surface change. As this thesis will show, the proposed classification and testing method for a paved road surface is based on the relative identification of a surface's micro and macro texture through two locked wheel skid resistance tests at low and high vehicle speeds. Coincidently the TxDOT technology under development uses road profiles obtained through optical measurement, in combination with a neural network program, to directly identify a surface's skid number, which is the result obtained from a skid resistance test of a surface [5]. Significant success has been achieved for smooth tires, which are commonly used in skid tests, and it is intended that future versions of the technology will have the capacity to represent ribbed tire designs. A proposed flowchart for a methodology to effect a parametric surface change in the Pacejka Brake Tire Model that incorporates this future technology is presented in Figure 1.1. Within the flowchart a skid number is denoted as SN.

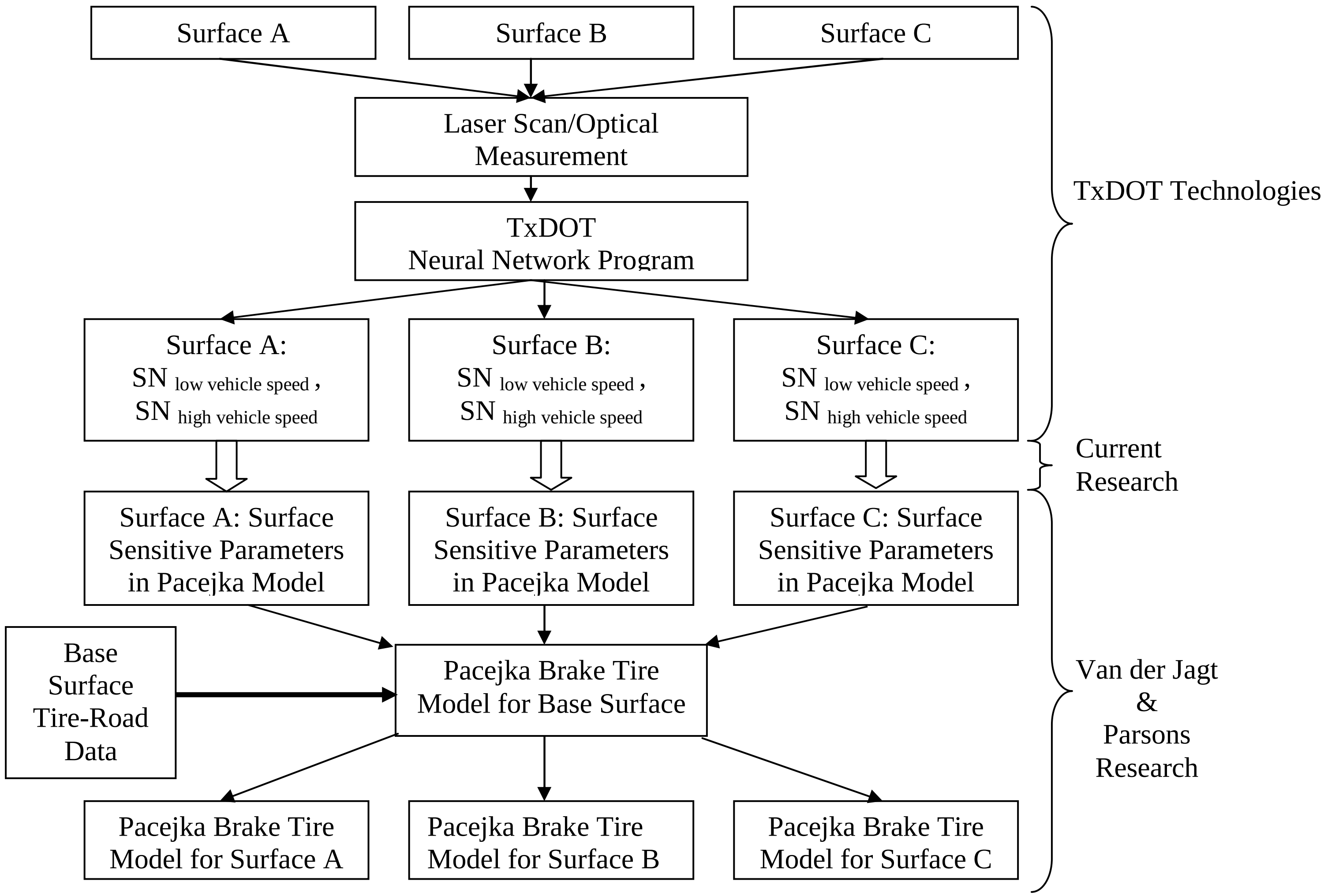


Figure 1.1. Proposed Methodology to Effect a Parameter Surface Change in the Pacejka Brake Tire Model

1.3 Thesis Relevance

Empirical tire models are highly dependent on the particular surface for which they were developed. The result of a more accurate tire-road interaction model implies a better capacity for predicting how a vehicle will respond on a specific road surface. With such a methodology, vehicle makers can improve and tune specific component designs within a vehicle that are influenced by the tire-road interaction. Whereas on the opposite side of the same "coin," a road maker could begin to use this methodology in conjunction with vehicle simulations to test surfaces against a standard tire in order to determine safe driving conditions and or evaluate the quality of a road surface. The ability to link these two engineering activities has been discussed for many years, but its realization is a daunting task. This thesis takes a small but positive step in this direction.

1.4 Thesis Presentation

This thesis is divided into five chapters. The first chapter presents the premise and background of the thesis. The second chapter presents a review of friction, tire mechanics and tire models relevant to this thesis. The third chapter presents a standard method for which paved road surfaces may be classified and tested along with the experimentation supporting this method. The fourth chapter presents a methodology proposed for effecting a parametric surface change in a particular empirical tire model called the Pacejka Tire Model [4]. The selection of this model was not based on preferential treatment; rather the Pacejka Tire Model [4] is a representation of a prototypical empirical tire model used in vehicle simulation. Both chapters three and four include the relevant literature supporting the arguments made in each of those chapters. The fifth chapter presents the conclusions of this thesis along with recommendations for future work.

CHAPTER 2: Tire-Road Review

2.1 Introduction

This chapter presents three sections that review the current knowledge in friction, tire mechanics, and tire models. These chapters only intend to relate the necessary knowledge needed to understand the concepts and tools relevant in the derivation of a road classification and test method for use in empirical tire models. Each section provides a reference for the reader to locate if further knowledge on the particular topic is desired. Each of these areas is the subject of a very extensive literature base.

2.2 Friction

An understanding of the friction generated from a rolling tire on a road surface is complicated and not yet fully understood [6]. However, a review of friction's origins in the literature, a brief description of rubber's visco-elastic behavior and the current representation of friction used to describe the interaction between the tire and the road is presented in this section. This brief treatment of friction is intended to motivate the discussion concerning tire-road friction and is in no way an adequate overview of tribology, the study of friction, lubrication and wear. If more information is needed concerning friction in general the reader is asked to reference [7] for the state of the art in tribology.

2.2.1 Brief History of Friction

The mathematical description relating that the sliding force of one material against another is proportional to the applied load times a constant material property is universally called "Coulomb friction." However, Coulomb (1736-1806), a French physicist-engineer, was not the first to describe or investigate the relationship of the friction force. While Coulomb considered friction to be due to the interlocking of asperities, Amontons (1663-1705), also a French physicist-engineer, considered friction to be the collision of surface irregularities and reached approximately the same conclusion, namely $F_{friction}$ is proportional to F_{normal}, nearly a century earlier in 1699. Both of these scientists asserted that the friction force was independent of the area of contact between the two sliding surfaces. Coulomb went as far as to say that he "discounted adhesion (which he called cohesion) as a source of friction and like many others of his time considered the actual surfaces to be frictionless," which clearly contradicts modern theories of friction [7]. Nonetheless, Coulomb is recognized with the dry friction approximation. In addition to these separate descriptions of friction was the idea presented by the distinguished mathematician Euler (1707-1783) who attributed the phenomenon of friction to hypothetical surface ratchets. Later Samuel Vince (1749-1821) published a paper describing the static friction of two materials as a function of both the kinetic friction and the adhesion between those two materials. From this point on the subject of adhesion's role in the description of friction would be polemic. Leslie (1766-1832) argued against adhesion by asserting that adhesion could not have an effect in a direction parallel to the surface since adhesion is a force perpendicular to the surface [7]]. While Sir W.B. Hardy argued that friction was due to molecular attraction operating across an interfaces. Hardy also made another important distinction by asserting that the molecular attraction operates over short distances, which in turn differentiates between real area of contact and apparent area of contact. Tomlinson further tested these ideas stating that the adhesion approach is based on the partial irreversibility of the bonding force between atoms. The idea of adhesion, as the source of friction, developed into the Adhesion Theory of Friction by the significant contributions made by Beare, Bowden and Tabor. They found that friction is proportional to the true contact area and the shear strength of the bonds in that area. They also recognized that "the physical process occurring during sliding is too complicated to yield easily to a simple mathematical treatment" [7]. This statement still persists today and can be seen readily in complications arising from the description of visco-elastic materials traversing quasi-rigid surfaces or better known as the tire-road friction problem.

2.2.2 Tire Visco-Elasticity and the Road Surface

Pneumatic tires are polymers. Specifically pneumatic tires are a combination of rubber, carbon black, and oil. The additives of carbon black and oil improve wear resistance and increase the overall friction between a tire and a road surface, respectively. Polymers, in general, are visco-elastic, which means that they mechanically appear to be elastic under high strain rates and viscous under low strain rates [7]. This relationship is typically non linear and as such there are no simple quantitative relationships for the deformation of such materials. However, visco-elastic behavior is often modeled as arrays of springs and dashpots to mirror these characteristic properties of polymers. A mechanical model of rubber is presented in Figure 2.1. Incidentally, pneumatic tires are also often modeled as arrays of springs and dashpots; however, these models are attempting to represent the resistance stemming from the pressurized inner area of the tire carcass and the compliance of the tire material itself.

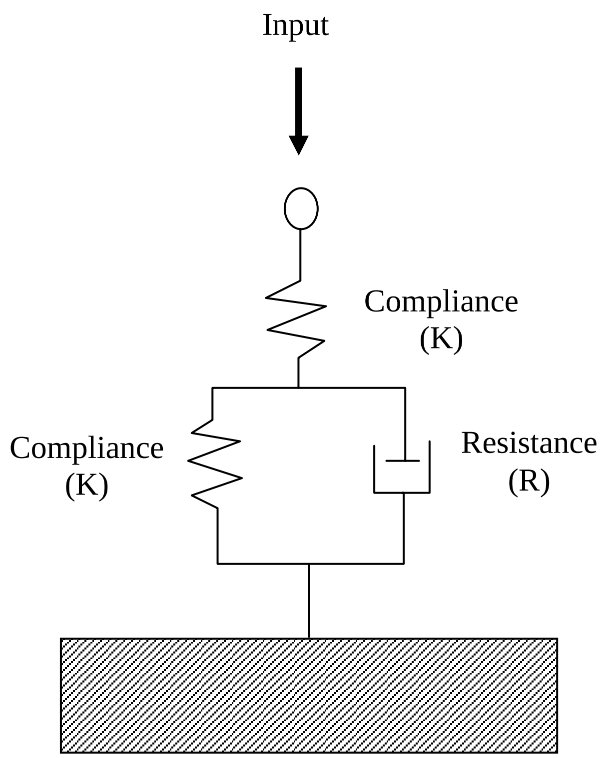


Figure 2.1. Mechanical Model of Rubber

A characteristic behavior of visco-elastic materials is their dependence on strain rate and temperature. It has been well observed that the Young's Modulus of polymers decreases over time of loading, which is drastically different from the plastic deformation of metals. If a pure rubber is given a laboratory sliding friction test against a "smooth" surface in clean conditions, the frictional coefficient is found to depend on the sliding speed and temperature. Curves for various temperatures can be reduced to a single master curve using a Williams-Landel-Ferry (WLF) transformation, which is based on the visco-elastic model of rubber. If the rubber were then tested on a rough surface the WLF transformation would still be successful, however, the master curve would take on a different shape. The new shape is due to rubber distortion around the rough asperities, while the previous much smaller scale molecular effects contributing to the friction are of diminished importance. Both resultant master curves have a very strong correlation between the equations of visco-elastic behavior and of rubber friction, which "suggest that at the very least the phenomena have a common origin, and possible that the visco-elasticity is the cause of rubber sliding friction" [7]. Additionally, these simple sliding friction tests point out the importance surface geometry has in the development of friction between two surfaces.

The geometry of a road surface has several scales that range from about 0.01 mm to 100.0 m in terms of wavelengths, a range of 10,000 to 1. Within this range exist two dominant scales, classified as micro and macro texture, that greatly affect the frictional development of a pneumatic tire and a road surface [8]. Macro texture is a measure of the surface relief of a pavement, while micro-texture is a measure of the degree of polishing of a pavement surface or of the aggregate at the surface [9]. In other words the individual asperities or stones in a road surface constitute the macro-roughness, which range from 6 to 20 mm in size, while the geometry at the tips of the asperities or stones constitutes the micro-texture, which range from 10 to 100 microns [8]. Figure 2.2 illustrates these two scales.

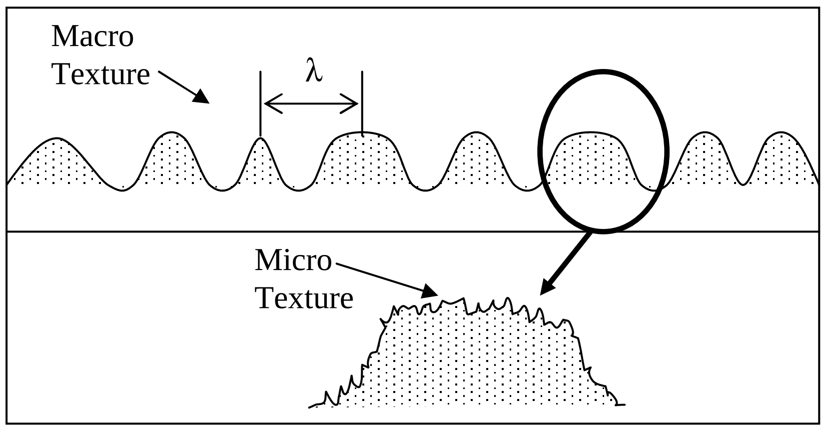


Figure 2.2. Micro and Macro Surface Texture

2.2.3 Tire-Road Friction

The typical model used to describe a pneumatic tire sliding over a paved road is based on the Adhesion Theory of Friction [10]. This model is often mislabeled as the Coulomb Law of Friction. The Adhesion Theory of Friction owes much of its development to Bowden and Tabor. The theory asserts that the force of friction, $F_{friction}$, is the product of the real area of contact, A_r, and the shear strength, S_s, of the bond in that region. This relationship is mathematically described as,

$$F_{friction} = A_r \times S_s. \qquad (2.1)$$

The remaining part of the theory asserts that load, W, is the product of the average pressure of contact, P_f, over the tips of the asperities that comprise an area of contact, A_r, equivalent to the shear strength. This relationship is mathematically described as,

$$W = A_r \times P_f. \qquad (2.2)$$

Together these relationships relate a ratio that has come to be known as the coefficient of friction, μ, between two sliding surfaces. Thus altogether,

$$\mu = \frac{F_{Friction}}{W} = \frac{A_r S_s}{A_r P_f} = \frac{S_s}{P_f} \ . \qquad (2.3)$$

Per this equation, μ is constant, independent of the vertical weight. However, the friction phenomenon between rubber and solids does not necessarily obey the above theory, namely because the theory is valid only for materials possessing a definite yield point (such as metals) and it does not apply to elastic and visco-elastic materials (such as rubber) [8]. In practice this theory is still used frequently as it presents a simple quantitative expression for the sliding friction force in the absence of a unifying theory for the rolling and sliding friction of visco-elastic materials on quasi-rigid roads.

Currently three mechanisms are seen to contribute to the friction developed between a pneumatic tire and a paved road: adhesion, hysteresis and cohesion [10]. Surface adhesion arises from the intermolecular bonds between the rubber and the aggregate developed where the tire and road surface meet (commonly known as the contact patch). The hysteresis mechanism represents energy loss in the rubber as it deforms when sliding over the aggregate in the road at the contact patch. Cohesion represents the rupture of tread rubber by sharp road asperities and is responsible for wearing of the tire tread. Figure 2.3 [10] illustrates these three mechanisms.

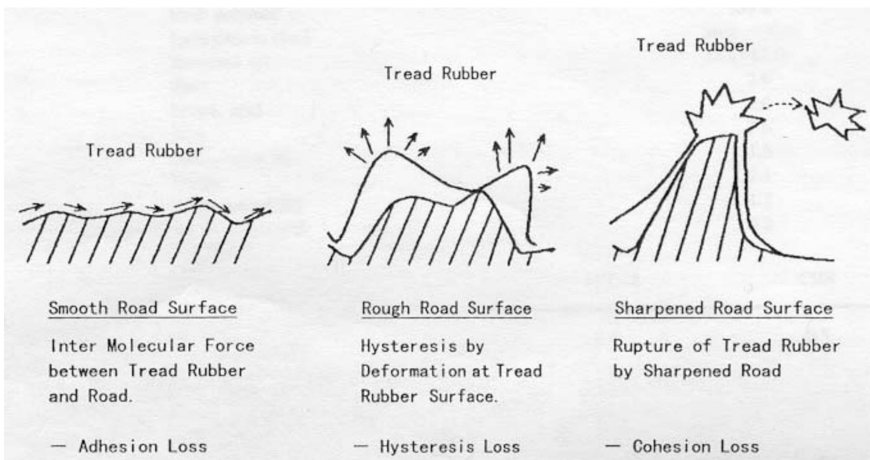


Figure 2.3. Mechanisms Contributing to Tire-Road Friction [10]

2.3 Longitudinal Mechanics of Pneumatic Tire

The following section is a brief overview of the relevant knowledge required to gain a physical understanding of the mechanics involved in the longitudinal motion of a pneumatic tire. While the previous section concerned itself with describing the sliding friction of objects, the following section will consider how friction plays a role in vehicle dynamics when partially sliding, i.e. rolling. Since the information about the mechanics of tires is quite extensive, further knowledge can be obtained from the following references: [2] and [11].

2.3.1 Axes and Notation

The Society of Automotive Engineers (S.A.E.) axis system for the tire component of a vehicle is illustrated in Figure 2.4. Based on a right-hand reference scheme, the wheel is represented in its simplest state—standing vertically and rolling in its plane of symmetry. The force exerted on the tire by the road along X’, denoted by F_x, is called the longitudinal force. Divergence from the plane of symmetry by a rotation about the z-axis causes a non-zero slip angle (α). The resulting force along Y’, denoted by F_y, is called the cornering force. Additionally, a wheel may be inclined by a rotation about x-axis, at the hub axis of the wheel, causing a camber angle. The resulting force here, along Y’, is called the camber force. More generally the forces along Y’, either resulting from a non-zero slip angle, a camber angle or both are called lateral forces. The force along negative Z', denoted by F_z, is called the normal force, which is typically comprised of the static or dynamic weight of a vehicle. The aligning moment, M_z, and the overturning moment, M_x, act clockwise, positive to their respective axes. Worth mentioning again, is that all the forces and moments, mentioned thus far, are exerted by the road on the tire.

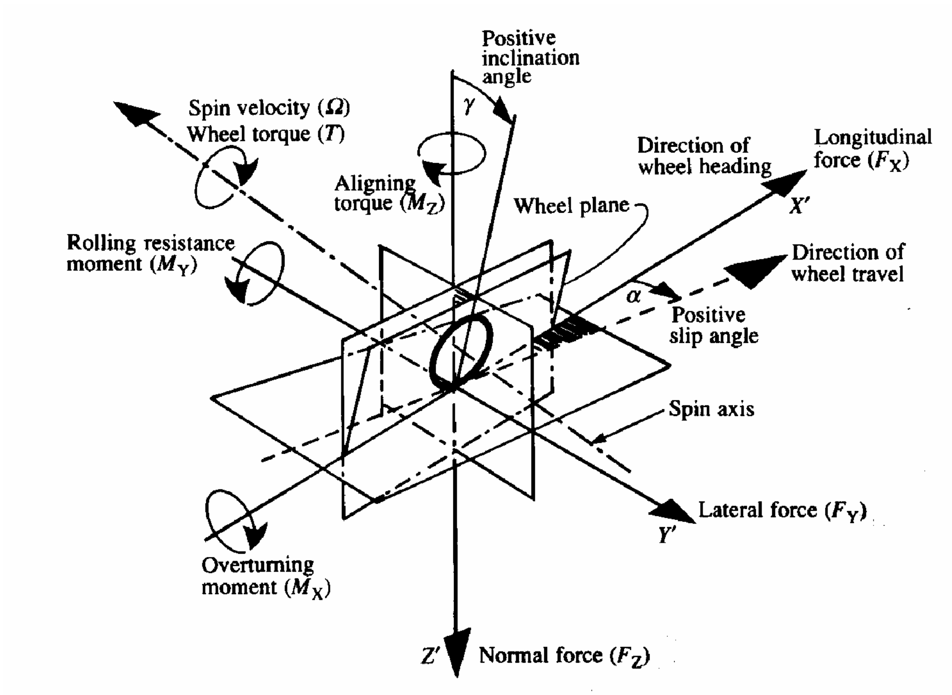


Figure 2.4. S.A.E. Tire Axes and Terminology [2]

Important to this study is an understanding of the forces in the longitudinal direction. These forces are created by the application of torques about the wheel spin axis derived from a corresponding power flow. This power flow is either providing kinetic energy from the engine or dissipating energy through the brakes. S.A.E. terminology uses ‘longitudinal’ to denote the tire forces acting in the X’ direction and also to denote the heading vector of the vehicle as a whole. Specifically, a forward driving force acts in the positive vector heading along X’, while a braking force acts in the negative vector heading along the X’.

A further modification of the axes generates yet more terminology. Of relevant importance is the modification of the XYZ (unprimed) axes to the X”Y”Z” axes generated by realigning the unprimed axes to the motion of the individual wheel. As illustrated in Figure 2.5 [2], the component forces in the X” and the Y” are called the tractive force and the central force, respectively. These forces combined represent the tire force, generally referring to the total force exerted by the ground on the tire. In the absence of engine or brake action and neglecting rolling resistance the longitudinal force is zero with the tire force perpendicular to the wheel. The tractive force, for this case, is then negative and called the tire drag force.

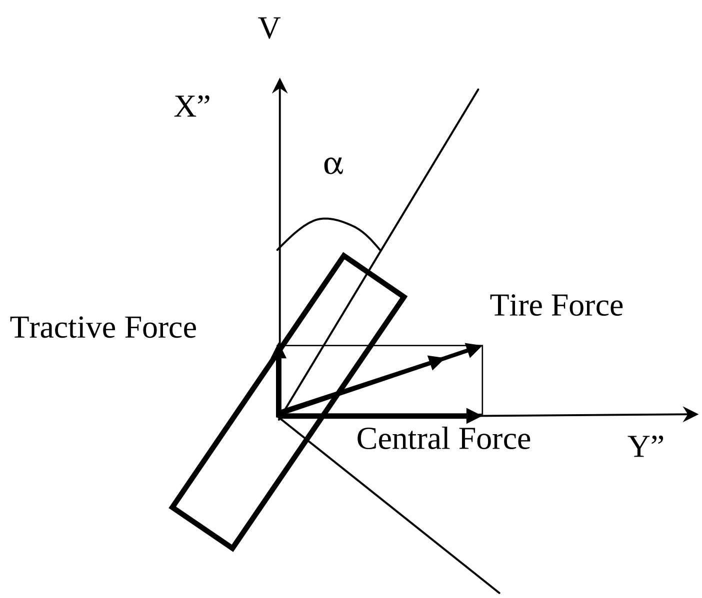


Figure 2.5. Tractive and Central Force Components of a Tire [2]

2.3.2 Wheel Dynamics

To further the understanding of the tire component a dynamic equation (neglecting aerodynamic effects on the tire) for the angular motion of the wheel (tire and rim inclusive) is presented in equation (2.4).

$$\frac{d\omega_{wheel}}{dt} = \frac{\left(T_{engine} - T_{braking} - R_{wheel}F_{friction} - R_{wheel}F_{RR}\right)}{J_{wheel}} \qquad (2.4)$$

Equation (2.4) represents the angular acceleration (or deceleration, -dω/dt) of the wheel, which is comprised of the total torque acting on the wheel divided by the moment of inertia of the wheel. Incidentally, the expression representing the sum of the total torques on the wheel is often referred to as the tractive effort or tractive force on the wheel. In equation (2.4), the non-force quantities represented by ω_{wheel}, J_{wheel} and R_{wheel} are the angular velocity of the wheel, the moment of inertia of the wheel and the radius of the wheel respectively. The total torque acting on the wheel consists of the shaft torque from the engine (T_{engine}) minus the sum of the brake torque ($T_{braking}$) and the torque components due to the tire friction force ($F_{friction}$) and the rolling resistance of the wheel (F_{RR}).

The effects of the driving and brake forces depend on the unique parameterization of a given vehicle set up. The engine torque and the effective moment of inertia of the driven wheel depend on the gearing in the transmission. The torque produced by the engine is typically transmitted, say for a rear wheeled vehicle, by the driveshaft to the differential to the axel shaft. The braking torque refers to the actual application of either disc brakes or drum brakes. Depending on the brake proportioning of a braking system, the vehicle actuates a mechanism (brake calipers or a spring loaded resistor plate) to make contact with an adjacent plate rigidly connected to the wheel inducing friction forces between the two moving surfaces to dissipate energy.

On the other hand, the rolling resistance force and friction force depend on the unique interrelationship between tire and road surface properties. The rolling resistance, present from the instant the wheel begins to turn, depends on the complicated and interdependent physical properties of the tire and ground that act to dissipate energy from the tire. There are at least seven mechanisms, according to [11], responsible for the rolling resistance of a tire. These mechanisms are: energy loss due to the deflection of the tire sidewall near the contact area, energy loss due to the deflection of the tread elements, scrubbing in the contact patch, tire slip in the longitudinal and lateral directions, deflection of the road surface, air drag on the inside and outside of the tire, and energy loss on bumps. It is also worth mentioning that the energy lost by the tire material as a result of rolling resistance is converted into heat within the tire, which subsequently reduces the abrasion resistance and the flexure fatigue strength of the tire material [11]. The friction force is predominantly due to three mechanisms: adhesion, hysteresis, and cohesion (see Section 2.2.3). Of these, adhesion and hysteresis are most dominant. Both of these mechanisms depend on some small wheel slip. The friction force can thus be said to be modulated by a friction coefficient, μ, which is in itself a function of wheel slip (μ(slip)). The tire friction force is expressed as,

$$F_{friction} = \mu(slip)F_{normal}\,, \qquad (2.5)$$

where F_{normal} represent the normal force acting on the tire. When applied to a vehicle, the normal force, F_{normal}, depends on parameters such as the mass of the vehicle (tire and wheel inclusive), location of the center of gravity of the vehicle, and the forces induced by the steering and suspension dynamics.

Wheel slip arises when a driving or braking torque is applied to a pneumatic tire. The driving torque produces compression at the tire tread in front of and within the contact patch. Consequently, the tire travels less distance than it would if it were free rolling. Similarly, when a braking torque is applied, it produces tension at the front of and within the contact patch. However, in the case of braking, the tire travels more distance than it would if it were free rolling. This discrepancy in the distance traveled by the tire tread can be expressed mathematically as the normalized difference between the braked or driven wheel's angular velocity and the corresponding free rolling angular velocity. An angular velocity is defined as the ratio of the forward velocity of a wheel to the radius of the wheel. Equation (2.6),

$$Slip_{driving} = \frac{\omega_{driven\_wheel} - \omega_{free-rolling\_wheel}}{\omega_{driven\_wheel}} \times 100\,, \qquad (2.6)$$

represents the slip relationship for a driving situation and equation (2.7),

$$Slip_{braking} = \frac{\omega_{free-rolling\_wheel} - \omega_{braked\_wheel}}{\omega_{free-rolling\_wheel}} \times 100\,, \qquad (2.7)$$

represents the slip relationship for a braking situation. Note that slip is expressed as a percentage and the denominator can never be zero. The coefficient of friction, μ(slip), and more specifically the friction phenomenon, is not only dependent on percent longitudinal slip (for braking) but on other parameters including, but not limited to tire inflation pressure, pavement type, tire type, tire tread depth, wheel vertical load, vehicle speed, and the thickness of water film on the road surface. Figure 2.6 illustrates the forces and relative slip present during a braking action.

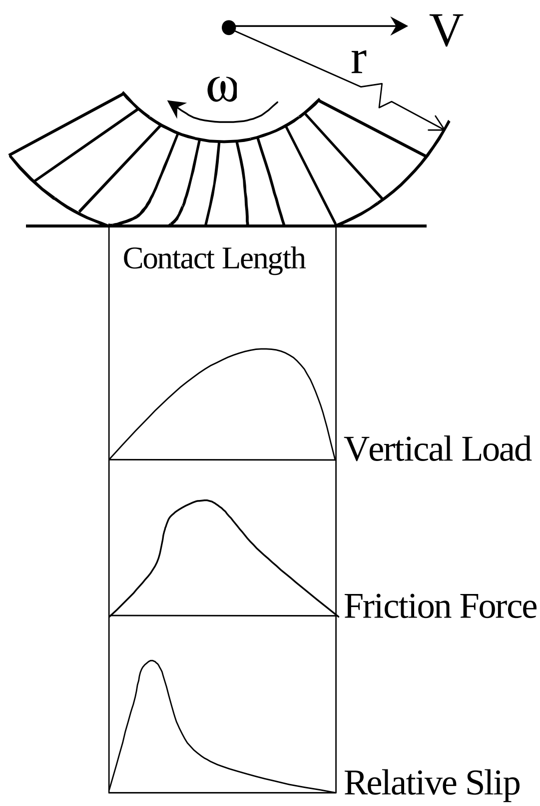


Figure 2.6. Braking Impact on the Tire [11]

The amount of braking force due to the hysteresis is controlled by the design of the tire's material properties, whereas the amount of adhesion produced is controlled by both tire and road surface properties. Extreme cases of driving slip present a situation where the tire is not moving directionally forward, it is merely turning in place. The extreme case of braking slip presents a situation where the tire is not rotating, it is merely skidding or sliding across the road directionally forward.

2.3.3 Braking Characteristics

Of particular importance to this investigation are the braking characteristics of a pneumatic tire. An informed view on the parameters influencing the relationship arising between the tire's friction force and the percentage of slip allow for greater insight to the problem this thesis addresses. The braking force of a tire on a surface changes non-linearly with slip. Various curves representing the characteristic brake force versus slip trend on a variety of surfaces is presented below in Figure 2.7 [12].

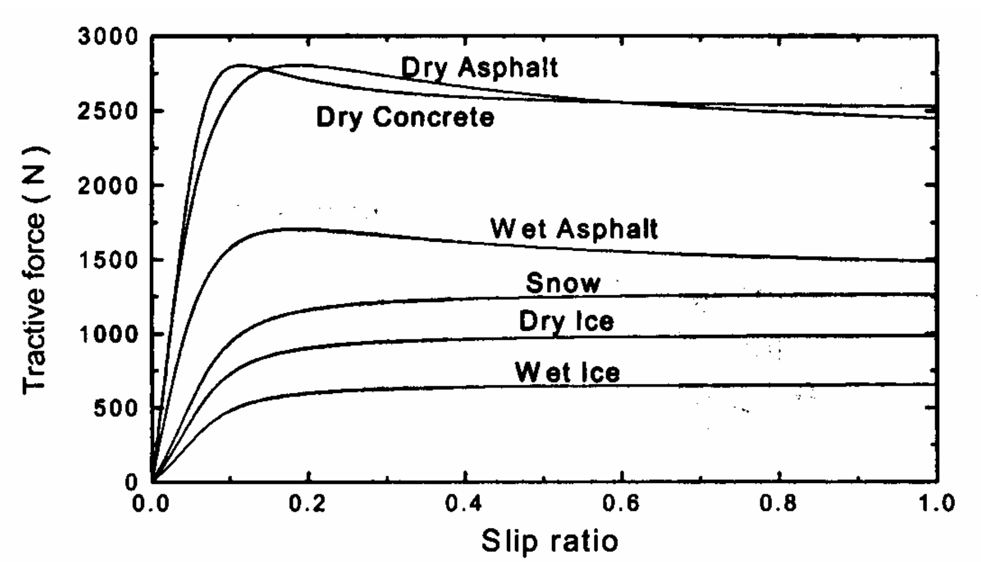


Figure 2.7. Characteristic Brake Force vs. Variable Slip for Pneumatic Tires on Different Surface Types [12]

The representation of the brake force versus variable slip curves can be generalized to embody a characteristic trend. This trend, as illustrated in Figure 2.7, has three distinct regions. Region I, occurring for low slip values, is characterized by a linear relationship representative of the initial flexing and stiffness of the tire-road interaction [2]. Region II, occurring between 10 and 30% slip, is associated with the area of the curve where the slope starts to diminish until a peak is reached. This peak represents the maximum braking or friction force and is associated with the peak friction coefficient, denoted by μ_p [11]. Beyond the peak friction force is Region III, where the relationship between the friction force and percent slip are dominated by the partial sliding of the tire elements in the contact patch area. With increasing slip comes a decrease in the ability to generate friction between the tire and the road. Figure 2.8 shows a continually decreasing slope, however some tire road combinations reach a minimum threshold of friction force prior to skidding (100% slip) that is maintained by the tire until full slip. The area beyond the peak friction value of the friction force is highly unstable and skid can occur quickly when the resultant torque on the tire is increased without a matched friction force to maintain a constant slip percentage.

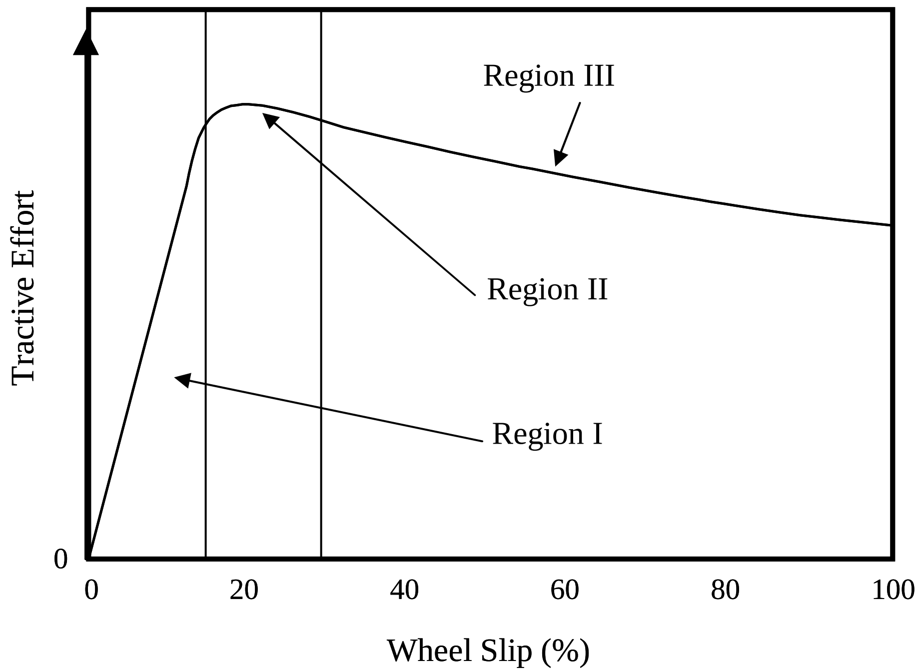


Figure 2.8. Regions Comprising Characteristic Brake Force vs. Slip Curve

2.4 Mathematical Tire Models

In general, mathematical tire models provide a construct within which some physical aspect of the tire component system can be studied. The mathematical tire models of importance to this thesis are those that relate the frictional force developed between a pneumatic tire and a paved road surface. Moreover, it is the tire model that can be easily incorporated into a vehicle simulation accurately and reliably to predict the frictional force relationship that presents the best platform to investigate and realize a tire model's ability to adapt a surface variation. A brief review of the literature representing the alternative methods used to model tires, a comparative assessment of those models with respect to vehicle simulation, and a review of the empirical tire model chosen, The Pacejka Tire Model [4], are presented in this section.

2.4.1 Alternatives

There exist different types of tire models that aid the analysis of different problems conducted by tire designers, vehicle dynamicist, and rolling contact specialist [2]. For instance there are tire models that can inform on the dynamic response of a tire, important when designing for ride comfort or noise reduction while other tire models can predict the life expectancy of a tire, important when designing for safety or warranty. The tire models relevant to a study focusing on the effects a road surface has on the performance of a tire are those that relate the frictional forces developed between a pneumatic tire and a paved road surface. In general, the development of tire models can be categorized into one of the following types: computational tire models (physically founded tire models that require computation for their analysis), analytical tire models (physically founded tire models that allow for analytic solutions), and empirical tire models (formula based tire models derived by empirical methods). A brief synopsis of each type of model is provided and then a review of a study [1] comparing the different modeling aspects of tire models for vehicle simulation is presented. In essence the comparative study [1] found that empirical tire models present the best opportunity to investigate the effects tires have on vehicle dynamics within the framework of vehicle simulation.

2.4.1.1 Computational

Computational tire models, in general, are based on the viewpoint that the mechanical behavior of the pneumatic tire is connected essentially to its deformation resulting from the elastic and geometric properties of the carcass and inflation pressure. The formulations predicting the shear force development depend on the pressure that exists where the tire and pavement meet (contact patch) and on the adhesion and sliding friction coefficients found therein. Computational tire models involve extensive calculations but, because of the repetitive nature of these computations, these models are ideally suited for programming within a computer environment. Typically, computational tire models allow for a wide parameterization of the design variables effecting a detailed representation of the tire structure and the interactions of the tread with the ground [1]. Computational tire models are widely used by tire manufactures for the structural design and analysis of the tire and have presently been a platform on which the modeling of industrial tires (e.g. farm equipment tires, tractor tires, etc…) traversing soft soil is being conducted. Finite Element Method (FEM) and multi-spoke tire models are representative of the computational tire models used in industry to relate the frictional forces developed between a pneumatic tire and a paved road surface [1].

2.4.1.2 Analytical

Analytical tire models are based on the viewpoint that to sufficiently describe the behavior of a tire only the dominant mechanisms present in the kinematics and dynamics of a rolling deformable disc are needed. As such, analytical tire models are quite idealized and simplified versions of the physical phenomenon they describe. Analytical tire models were historically first developed to understand the basic phenomenon related to the shear force and moment generating properties of the tire [1]. Modern analytical tire models address a wide array of issues ranging from the very focused model to a model describing the general behavior of the tire. The Brush Tire Model and variations thereof is representative of the analytical tire models used to relate the frictional forces developed between a pneumatic tire and a paved road surface [1]. Analytical tire models, often called semi-empirical tire models, parameterize the design variables using data acquired through full-scale experimentation. Most analytical tire models are used to explain and obtain the solution for very specific phenomenon resulting from specific operating conditions.

2.4.1.3 Empirical

Empirical tire models are based on the viewpoint that to realize the total effects of the tire-road interaction, a mathematical fit to experimental data of an actual tire operating in a real world environment is needed. Mathematical functions, such as polynomials, exponential, arctangents, and hyperbolic tangent functions, are used to fit the discrete experimental data with a continuous formulation representing the behavior of a specific tire under specific operating conditions [1]. Modern empirical tire models have the ability to capture the physical significance of some parameters enabling vehicle designers a more fundamental appreciation for the mathematical formulae [4]. Most empirical tire models are used to relate the dependence of design parameters to the performance of a tire under actions of driving, braking or steering. As such, empirical tire models are used extensively by both tire and vehicle design engineers. The Pacejka Tire Model [4] and the Exponential Model [22] are representative of the tire models found in industry today relating the frictional forces developed between a pneumatic tire and a paved road surface.

2.4.2 Comparative Review for Vehicle Simulation

A standard to classify and test paved road surfaces with respect to their frictional capacity with a particular tire cannot realize improving vehicle safety if it cannot be integrated into the platform from which tires are designed and analyzed for vehicle use. As such, the tire model chosen is crucial to the process of realizing improved vehicle safety. A recent study, by R.S. Sharp and H.B. Pacejka [1], compared and reviewed the extensive research and technologies developed for computational, analytical, and empirical tire models. The study [1] focused on models dealing with the shear (friction) force development of a tire on a road surface. A specific result of the study [1] identified empirical tire models to be the most suitable platform to investigate a tire's influence on the response of a vehicle in a dynamic simulation environment.

Criteria were developed in [1] to compare a tire model's usefulness to vehicle simulation studies. The criteria considered accuracy, range of behavior, number of parameters, physical significance of the parameters, the ease by which the parameters and data could be obtained, the capability and simplicity to cover behavior outside the range of working conditions used for parameter evaluation, and the computation load (time and resources required). The comparative study [1] subsequently described the main physical features and ideas of those models from the literature "which appear to have the most advantageous combinations of properties" in areas of computational, analytical, and empirical tire model development. Table 2.1 presents an interpreted summary of the results found in the comparative study [1], since there was no formal graphical presentation of the results. To create Table 2.1 three subjective rankings were developed to relate the information found in the study [1]. A plus (+) ranking indicates a benefit to the tire model, a minus (–) ranking indicates a disadvantage of the model, and a zero (0) ranking indicates a nominal feature in comparison to the other tire models.

Comparison Criteria	Tire Models		
	Computational	Analytical	Empirical
Computational Load	-	0	+
Accuracy	+	-	0
Range	0	-	+
Parameter Complexity	-	0	+
Parameter Identification	0	-	+
Extended Model Capabilities	+	0	-
Parameter Physical Significance	0	+	-

Table 2.1. Interpreted Summary of Comparison Study [1]

The comparative study [1] identified that computational tire models are powerful in terms of accuracy and extended capabilities given their explicit physical modeling. However, computational tire models encounter "significant penalty in terms of computational load, which make them an unlikely candidate to provide a basis for dealing with the tire forces in a vehicle simulation" [1]. Additionally, the comparative study [1] identified that the strength of analytical tire models, representing the tire in vehicle dynamic studies, lies in "their good representation of the basic geometry of rolling distributed contact and the competition between elastic forces and friction forces showing qualitatively reasonable correspondence with experimentally found tire characteristics" [1]. However, the comparative study found that the required simplification of the physical phenomenon and the difficulty obtaining suitable values for the parameterization of analytical tire models limit their ability to adequately describe the behavior of the tire for vehicle dynamic studies and subsequently advise against their use. Finally, the comparative study [1] identified that the strength of empirical tire model's lie in their inherent ability (through the mathematical fit of experimental data) to fully capture the physical phenomenon resulting from the interaction of a tire with a road surface. Though paradoxically, it is the specificity of empirical tire models that give it their greatest shortcomings. Using a mathematical fit to experimental data greatly limits the physical significance of the variables that make up an empirical tire model. Consequently, a parameterization, changing one or more operating conditions (e.g. changing tire material, tire structure properties, air pressure, road surface, vehicle speed, etc.) of an existing empirical tire model often requires a new tire model to be formed from new experimental data reflecting the change in operating conditions. Withstanding, the comparative study [1] finds that tire models formed using empirical methods provide the most pragmatic platform to pursue tire studies for vehicle simulation.

Without question the complexity of the pneumatic tire and its effects on vehicle dynamics demands simplification. The tire is a multi-layered, non-uniform, anisotropic, visco-elastic material interacting with a quasi-rigid road, whose properties continually change according to local environmental conditions, use and maintenance [2]. To overcome such complexities tire models are formed to address specific issues pertaining to the tire component system. It is the tire model whose specific objective is to relate the shear force development between a pneumatic tire and a paved road surface that is of importance when seeking to quantify the effects a surface variation has on the tire forces generated in a vehicle simulation. The comparative study [1], reviewed in this section, provides the basis for choosing an empirical tire model as the platform to investigate surface variation to ultimately provide a more descriptive vehicle simulation. However, in the future, as computing speeds, computing techniques, and more accurate tire mechanics continue to evolve, computational and analytical tire models may potentially provide a better platform to describe the shear force development of a pneumatic tire on a road surface for vehicle simulation. The empirical tire model chosen for this investigation is the Pacejka Tire Model [4].

2.4.3 The Pacejka Tire Model

Like many engineering technologies, the Pacejka Tire Model [4] is the product of a demand—to improve vehicle safety. Specifically, the authors of the Pacejka Tire Model wanted to address the growing field of dynamic safety by introducing a comprehensive description of a tire's behavior, where the safety of a vehicle could be realized after optimizing stability, steering and brake performance by tuning the chassis design to each other. The Pacejka Tire Model is based on the empirical method of fitting formulae containing special functions to experimental data. The basic formulation encompasses a model representing the longitudinal force under pure braking, the lateral (side) force under pure cornering, and the self-aligning torque under pure cornering. The basic Pacejka Tire Model has since evolved to describe the tire horizontal force generation at combined slip [14] and the non-steady-state behavior of the aligning torque [13]. The particular structure of the Pacejka Tire Model provides great accuracy in describing the measured data and contains a few parameters related to physically identifiable quantities in a simple manner. This section provides an explanation of the Pacejka Brake Tire Model [4].

2.4.3.1 Formulation of Pacejka Brake Tire Model

The Pacejka Tire Model's formulation is remarkably similar for the three cases of longitudinal (brake) force versus slip, lateral (side) force versus slip angle and aligning torque versus slip angle. The basic formulation of the Pacejka Tire

Model was first presented in a 1987 SAE paper titled "A New Tire Model with an application on Vehicle Dynamic Studies," by H. B. Pacejka, E. Bakker and L. Lidner.

The formulation of the Pacejka Brake Tire Model describes a tire's steady state behavior traveling over a dry hard smooth surface under the vehicle action of pure braking [4]. The brake tire model cannot deal with road surface irregularities of high frequencies, such as road bumps, or off road (soft soil) conditions. Furthermore, and in general, suspension design parameters (such as camber angle and inflation pressure), and operating conditions (such as type of road surface, vehicle speed, and ambient temperature) must be set in advance of the collection of experimental data. For the purposes of this study, an explanation of the Pacejka Brake Tire Model,

$$F_B = D \sin(C \arctan(B\{(1-E) X + (E/B) \arctan(BX)\}), \qquad (2.8)$$

is sufficient. The above result is an equation relating the brake force, F_B, to longitudinal slip, X, by four coefficients and is dependent on the vertical load used to obtain the experimental data (the Pacejka Brake Tire Model expressed as a function of the vertical load can be found in [4]). The four coefficients: B,C,D, and E are chosen in such a manner to match the formula to the experimental data. Once matched the coefficients represent the relative longitudinal stiffness of the tire (B), the brake shape factor (C), the relative peak brake force (D), and the curvature factor facilitating a local extra stretch or compression of the curve (E).

In general the Pacejka Tire Model makes the provision to correct ply steer, conicity and rolling resistance effects by introducing a horizontal shift variable (S_h) and a vertical shift variable (S_v) into the model formulation. The addition of these variables shifts the gross curve horizontally or vertically as needed to allow the net curve to pass through the origin. The result is for the pure braking case is,

$$F_B = D \sin(C \arctan(B\{(1-E)(X+S_h) + (E/B)\arctan(B(X+S_h)\}) + S_v. \quad (2.9)$$

A curve representing the typical characteristic brake force versus slip is shown below in Figure 2.9. The characteristic curve has a distinct local maximum (or peak) at X^*. A plot of a the basic trigonometric function, y = sin(arctan(x)), used by the Pacejka Tire Model is presented in Figure 2.10. It is clear from a comparison of the two plots that with the help of scaling and forcing factors; the special trigonometric function can be made to fit the characteristic brake force versus slip curve.

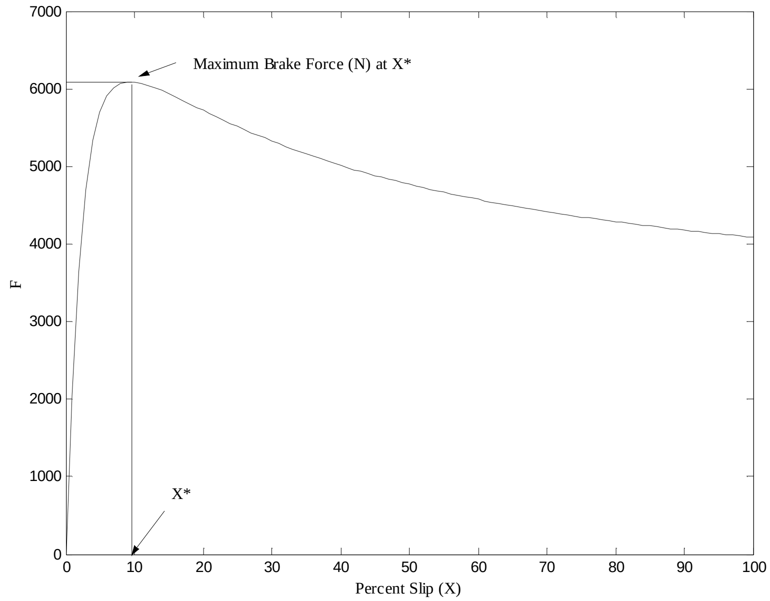


Figure 2.9. Characteristic Brake Force vs. Longitudinal Percent Slip Curve

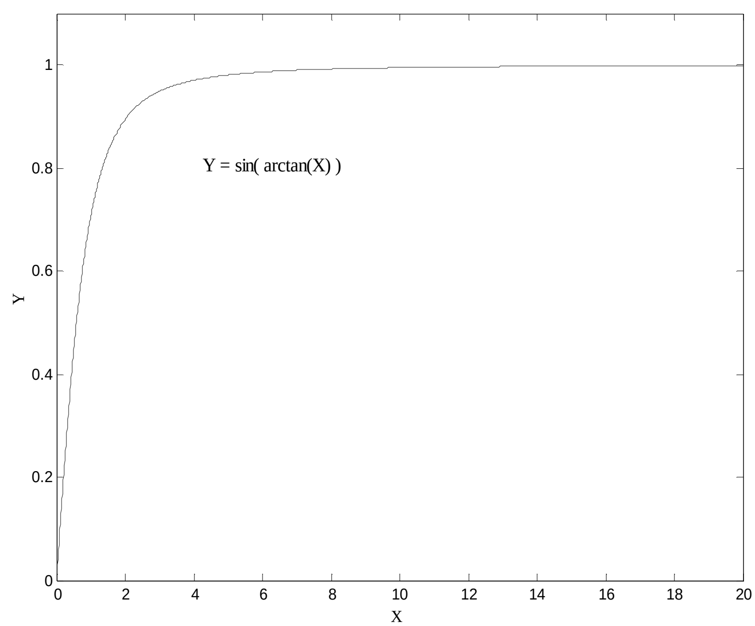


Figure 2.10. Sine Inverse Tangent Function

2.4.3.2 Generating a Pacejka Brake Tire Model

The basis for any Pacejka Tire Model is a full-scale test of the force and moment response of a tire under the actions of either pure braking or cornering. To obtain experimental brake force data, the force or pressure applied to the braking mechanism of a tire is gradually increased beginning at a constant vehicle speed. The brake force and longitudinal slip are continually measured at discrete increments from a free rolling (no brake) condition to a lockup condition, 100% slip or skidding.

After the brake force versus slip data is obtained, a Pacejka Brake Tire Model can be generated. A fitting process using the variables B, C, D, E and if necessary $S_{h,}$ and S_v are used to match the trigonometric function with the experimental data. Incidentally, the brake shape factor, C, which controls the brake characteristic trend of the curve, is typically 1.65. The value for the brake shape factor, C, has been established through extensive modeling of tires. Also the value associated with the vertical shift variable, S_v, typically accounts for the rolling resistance. Using a base Pacejka Brake Tire Model to work from often facilitates the acquisition of the coefficients and the two shifts variables. However, more refined techniques have been developed to process the coefficients and shift values using optimization schemes [4] and more recently a software package called Tyre Gene was released by Yearstretch Limited that uses a genetic algorithm to obtain the coefficients.

Once a Pacejka Brake Tire Model is established, it can then be integrated into a vehicle simulation program, such as Carsim, PNGV Systems Analysis Toolkit (PNGVSAT), DADS or ADAMS to provide the necessary force input for vehicle simulation or used independently to provide knowledge about the capabilities and shortcomings of a particular tire and surface combination. A more in-depth description of the complete Pacejka Tire Model can be found in [4].

To date the Pacejka Tire Model is one of the most widely used tire models in the automotive industry. The model's success comes from its ability to provide vehicle engineers an accurate, compact, physically meaningful and easy to use model. By the model's strong appeal to vehicle engineers in the automotive industry, the model's use has expanded into auxiliary automotive industries such as the tire and highway/road infrastructure industries, which is evidence to its widespread effectiveness and worth.

CHAPTER 3: Road Classification and Test Method

3.1 Introduction

The following chapter presents the research and experimentation conducted in support of the hypothesis presented in Chapter 1 of this thesis. The hypothesis states, in essence, that a road surface can be identified and subsequently categorized by two skid resistance tests, conducted at low and high vehicle speeds. The method used to classify and test a road surface is developed anticipating its use in assisting the adjustment of empirical tire models to a road surface variation. The development of the road classification and test method is presented in Section 3.2. The experimentation supporting the road classification and test method is presented in Section 3.3.

3.2 Development of Paved Road Classification Method

The following sections present the argument and supporting literature for using low and high vehicle speed skid resistance tests to identify and classify a road surface. Presented as a derivation beginning with the main variables affecting longitudinal braking, skid resistance tests at low and high vehicle speeds are shown to represent the dominant surface characteristics contributing to the development of the friction force between a road surface and a pneumatic tire.

3.2.1 Main Variables Affecting Longitudinal Braking

The characteristics of the frictional force developed between a pneumatic tire and a road surface are a result of driving, steering, and braking actions applied to a vehicle. The friction force resulting from the braking of a pneumatic tire traveling along a paved road surface is in itself a result of many variables acting in concert. The main independent variables affecting longitudinal tire braking, $F_{B,}$ according to [15], can be expressed in equation form as,

$$F_B = \text{fcn}\{\text{Tire Type, Tire Tread Depth, Inflation Pressure, Pavement Type, Wheel Vertical Load, Vehicle Speed, Water Film Thickness, Operation Temperature, Longitudinal Slip}\}. \quad (3.1)$$

The combination of these variables represents a system having at least nine degrees of freedom. The effects of these independent variables and their interdependent relationships are not completely understood [6]. However, the voluminous material available in this research area indicates these variables can be studied to formulate an understanding of their effects on tire-road dynamics.

3.2.2 Dominant Surface Properties Affecting Longitudinal Braking

This section reduces the main variables affecting longitudinal braking, presented in Section 3.2.1, to two geometric surface properties. The following presents the supporting literature for the preceding argument.

To fully realize the specific effects a pavement has on the frictional forces generated under a pure braking action, all variables, excluding Pavement Type, must be constrained or held constant. Imposing this requirement on (3.1) gives rise to,

$$F_{B[\text{constant parameters}]} = \text{fcn}\{\text{Pavement Type}\}. \tag{3.2}$$

Furthermore if (3.2), which is essentially a skid resistance test when conducted at 100% longitudinal slip, is expanded to include the constituent properties that represent a Pavement Type [17] it will give rise to,

$$F_{B[\text{constant parameters}]} = \text{fcn}\{\text{Type, Binder, Aggregate, Pavement Texture, Roughness, Topography}\}. \tag{3.3}$$

The expanded form of (3.2) presented in (3.3) excludes those variables pertaining to road design (e.g. curve, grade, tangent, crown, etc.) as their impact is more readily seen at the full vehicle system scale.

Expression (3.3) includes Pavement Texture, which is "perhaps the most important single variable determining the magnitude of the friction forces between tire and road" [8]. It is therefore asserted that the geometry of a surface dictates the frictional development between a tire and a road surface and not the Aggregate, Type, Binder, of the road. These properties of the road have "little effect because of the great difference in hardness between tire rubber and road materials" [17]. Roughness and Topography do not significantly contribute to tire road interaction as the effects of Roughness are governed by the dynamic effect caused by the imbalances in the drive train from surface geometry ranging from 0.1 m to 10 m [16], whereas topography refers to the more regional effects of climate and regional disposition (e.g.

hills, planes, mountains) that effect the interaction of the tire and road on a more systems level. Thus Pavement Texture, and in specific micro and macro texture are seen as the two most influential scales of Pavement Texture contributing to the development of the friction force between a tire and a road surface [8]. See Section 2.2.2 for a more detailed description of micro and macro texture.

It is now possible to re-write expression (3.3) from the above perspective to formulate an expression for the braking force of a tire as a function of the micro and macro texture properties of the pavement,

$$F_{B[\text{constant and negligible parameters}]} = \text{fcn}\{\text{Micro Texture, MacroTexture}\}. \qquad (3.4)$$

Equation (3.4) represents a relationship in which the magnitude of the brake force is a function of the micro and macro texture of a road surface. Equation (3.4) is possible only if Tire Type, Tire Tread Depth, Inflation Pressure, Wheel Vertical Load, Vehicle Speed, Water Film Thickness, Operation Temperature, and Longitudinal Slip are not varied, and the effects of Type, Binder, Aggregate, Roughness, and Topography are considered negligible in relation to Texture as asserted by [8] and [17].

It is worth noting that the aforementioned constraints imposed to a braking maneuver are representative of those placed on skid resistance tests. In addition, the constraint of maintaining Water Film Thickness constant in equation (3.4) does not restrict it to be any value in particular, only that it must be maintained constant. This observation provides significant ramifications as it can be construed, at least theoretically, that with knowledge of the amount of water present in the contact patch, water as a parameter can be quantified and related back to the brake or friction force developed between a road surface and a pneumatic tire.

3.3 Development of Paved Road Test Method

Equation (3.2), presented in section 3.2.2, prescribes a braking action as a function of Pavement Type whose required constraints are similar to a standardized road test procedure called Skid Resistance Testing. The literature [9] supports that when conducted at both low and high vehicle speeds these tests are indicative of a surface's micro and macro texture. Moreover, as it will be shown in this section, when the vehicle speeds are chosen appropriately, the low vehicle speed skid test can give a relative measure of the maximum braking (or peak friction) force of a vehicle traveling at a speed coinciding with speed for the high vehicle speed skid test. The use of these two values is central in classifying and testing road surfaces to estimate the characteristic brake force versus slip curve and subsequently to facilitate the adjustment of an empirical tire model to a surface variation.

Skid resistance tests, in the United States and abroad, are typically conducted by road makers at high vehicle speeds on wet roads to assess the wet-pavement traction of road surfaces. These tests are carried out with the more hazardous road conditions in mind—a car skidding (100% slip) at high velocities (40-50 mph) on wet surfaces (nominal water depth of 0.15 inches) [6]. Research into models predicting the dependence of the friction force on water film thickness and vehicle speed is ongoing with promising studies already present [18]. However, for the purposes of developing a test method to evaluate the friction performance of a tire on a road surface, it must be made clear whether the tests reflect dry or wet road conditions, and if wet roads are prescribed the thickness of the water film applied during testing must be stated. Thus the Water Film Thickness used while testing a particular tire will delineate the classification of road surfaces by skid resistance tests into different categories. The preceding can be asserted for two reasons. First, under wet road conditions the characteristic brake force versus slip shape (see Section 2.3.3) is still retained, only categorically (with respect to slip) diminished due to the lower overall contribution of adhesion to the friction force [11]. Second, irrespective of whether a skid resistance tests is performed on a dry or wet surface, the results of these test still relate a ratio of the friction force to the normal force. When a standard tire and standard test conditions are utilized in a measurement of pavement traction, the results are reported as the skid number (SN) of the pavement as a function of vehicle test speed (V),

$$SN_v = (F_{friction}/F_{normal}) \times 100, \tag{3.5}$$

or alternatively,

$$SN_v = (\mu) \times 100. \tag{3.6}$$

"Skid resistance is therefore a pavement characteristic and is a function of the surface properties, which can be modified by the presence of contaminants" [6].

The speed dependence of the skid number determines whether micro texture or macro texture is being evaluated. To be certain, "micro texture is predominate in determining the skid resistance of a road surface at low vehicle speeds (up to about 50 km/h)," while "macro texture is predominant in determining how well the skid resistance of a road is maintained as the vehicle speed increases" [9]. This qualitative assessment of the speed dependence of the skid number is present in both dry and wet road surface conditions, but more pronounced under wet conditions. Central to the use of skid numbers for the classification of road surfaces is the concept that the friction of a tire in longitudinal braking on wet and dry pavements is solely a function of the velocity of the tire surface relative to the pavement. It is then possible to approximate the friction force between a tire and a road surface at any slip percentage using a skid resistance test [6]. This concept is described by J. Henry [6] in terms of a Brake Slip Number (BSN), determined from skid resistance tests that maintain constant slip values for the tire other than the full locked condition or 100 % slip of a traditional skid test as,

$$\text{BSN (X \% slip, V)} = \text{SN (100\% slip @ } V_{SN}\text{)}, \qquad (3.7)$$

where

$$V_{SN} = X\,\% \times V. \qquad (3.8)$$

The BSN is defined, and presented below, at a particular percent slip, X, and vehicle speed, V,

$$\text{BSN (X \% slip, V)} = (F_{friction} / F_{normal\ Load}) \times 100. \qquad (3.9)$$

Thus to approximate the friction force at a percent slip other than one hundred for a vehicle with speed V, one would only have to perform a skid resistance test at a lower vehicle speed equal to the product of the desired percent slip, X, and vehicle speed V. The following explicitly states this relationship.

$$F_{friction} = (SN\ (100\%\ slip\ @\ V_{SN}) \times F_{normal\ Load})/100. \qquad (3.10)$$

For example, “one can approximate a brake slip number at 25% for a vehicle traveling 40 mph using a locked wheel skid number at 10 mph (10 mph = 25% × 40 mph)” [6].

The approximation in (3.10), presented by J. Henry [6], has been found elsewhere substantiating its validity. For example, T. Bachmann [20], provides a graphical representation of (3.10) can be found and is presented below in Figure 3.1 for a particular tire on a wet road surface. The importance of (3.10) is significant when coupled with the knowledge that the peak friction force typically occurs between 10 and 20 % slip [11] for any given tire. In essence, a relative measure of the peak friction force can be approximated for any given tire road combination with the help of (3.10). With the ability to evaluate the friction force at low (between 10 and 20% slip) and full (100%) slip values for a given speed tire and road surface a description of the characteristic brake force versus slip curve can be revealed [19]. The implication of this provides a basis for using two skid resistance tests conducted at low and high vehicle speeds to classify and test a road surface with respect to a tire.

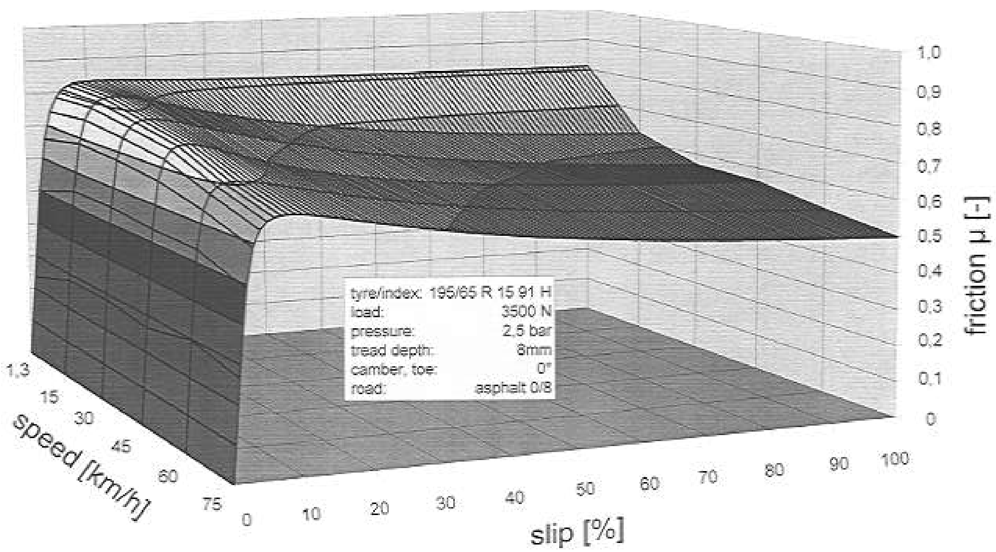


Figure 3.1. Speed Dependence of Friction for Wet-Pavement [20]

Expression (13), from Section 3.2.2, can be re-written to incorporate the above assertion as,

$$F_{B[\text{constant and negligible parameters}]} = \text{fcn}\{SN_{\text{low speed}}, SN_{\text{high speed}}\}, \qquad (3.11)$$

Expression (3.11) provides the construct—skid resistance testing, within which a relative measure of the peak friction force and an exact measure of the skid friction force may be tested and subsequently classified for a paved road surface with respect to a particular tire. The vehicle speed, V, chosen for the $SN_{\text{high speed}}$ test, representing the skid (sliding) friction force, is a free variable while the vehicle speed for the $SN_{\text{low speed}}$ test, representing the region of maximum attainable friction force, is constrained by V and is estimated by equation (3.8). In essence, the road classification method is providing the remaining two points, as the first is the origin or zero force zero slip point, needed to estimate each of the three regions that make up the characteristic brake force versus slip curve. The three regions are: the initial region characterized by a positive linear slope beginning at the origin and ending slightly before the peak friction value, the middle region characterized by negative quadratic slope (opening downward) with the peak friction force value as its maximum point, and the final region characterized by a negative linear slope converging to the skid friction force value (see Section 2.3.3). Therefore the road classification method, encompassing the two values represented by the skid tests at low and high vehicle speeds, together with the zero slip zero force starting point determine the beginning, the middle and the end of the characteristic brake force versus variable slip curve.

The test method, locked wheel skid resistance test, prescribed in this thesis to classify a paved road surface, is fortunately one of the most recognized surface testing procedures in the world. As such, many standards have been developed to conduct these tests for which the method proposed here will take full advantage of to reduce any confusion as to how this test method should be carried out. Specifically, the proposed method will adhere to the American Society for Testing and Materials (ASTM) E 274 – 97 Standard Test Method for Skid Resistance of Paved Surfaces using a Full-Scale Tire. The only variability allowed in the test method is the vehicle speed at which the tests are conducted and the level of water film thickness used, if any. The standard with all its provision can be obtained from the American Society for Testing and Materials through various outlets.

3.4 Experimentation

There are multiple factors affecting tire-road friction. However, as proposed in Section 3.2 of this chapter, evaluating the micro and macro texture of a paved road surface, while maintaining tire and environment parameters constant, can sufficiently distinguish one surface from another with respect to a particular tire. It was further revealed by Kennedy, et al [9] that skid resistance tests conducted at low and high vehicle speeds can account for the influence a surface's micro and macro texture has on the development of tire-road friction, respectively. Carefully selecting the two different speeds at which a particular tire is skid tested will provide two values that in combination with the zero force zero slip origin determine three distinct points in the three main regions governing the characteristic brake force versus slip curve. It is predicted that the brake or friction force obtained from a high and low vehicle speed skid test are sufficient to classify various paved road surfaces with respect to a particular tire. This section presents the results of skid test experiments conducted at high and low vehicle speeds using a smooth (no tread) pneumatic tire on five different paved road surfaces with zero and 0.15 inches of water film thickness. The results indicate that the use of a high and low vehicle speed skid number to classify a paved road surface is in fact sufficient to distinguish one surface from another with respect to a particular tire for both dry and constant water film thickness paved road surfaces. However, the accuracy of the estimated characteristic brake force versus variable slip of a surface using the two skid numbers to actual brake force versus variable slip data could not be compared and established because the equipment needed to acquire these results was not available at the time of testing. A summary of the experiments carried out and the analysis of the data collected is presented in the following sections.

3.4.1 Skid Test Specifications

Five different paved road surfaces were tested using skid resistance tests performed with the help of the Texas Department of Transportation, Construction and Pavement Division (Austin, Texas). A picture of each road surface, labeled Surface A through Surface E, is provided in Appendix A. The skid resistance tests were conducted, as mentioned in Section 3.2, in accordance with the American Society for

Testing and Materials (ASTM) E 274 – 97 Standard Test Method for Skid Resistance of Paved Surfaces using a Full-Scale Tire in conjunction with the ASTM E 524 – 88 Standard Specification for Use of Smooth Tires for Pavement Skid Resistance Tests. Again these ASTM testing standards can be obtained from various outlets with only the appropriate designation reference (E 274-97 and E 524-88 respectively). These two standards contain the information on the equipment and protocol to conduct and acquire a skid number from a paved road surface. It is worth noting that the normal load applied to the wheel by the TxDOT test trailer used in these experiments was 1108 lbs force, which can then be used to plot the friction coefficient, μ, versus the longitudinal slip by the relationship expressed in .

3.4.2 Skid Test Schedule

The skid resistance tests were conducted on paved roads around Austin, Texas in late October with similar compositions (standard hot mix formula). The tests were all conducted within a five-hour test period. Within this time frame the weather and environment conditions remained relatively constant with an ambient average temperature of 72°F and no rainfall.

The tests were performed over the worn tire path in the road that is produced by vehicle travel and representative of the most likely trajectory of tire travel. Incidentally, this portion of a road surface has the lowest skid number value of any other part of the road surface as the effects of polishing and wear are most profound and subsequently varies considerably with time.

A series of five dry and wet skid resistance tests were conducted for the five different road surfaces. The series of skid resistance tests were conducted in an effort to compare the tire-road friction developed by different paved road surfaces to establish whether high and low vehicle speed skid numbers were sufficient to distinguish one surface from another. In particular the dry and wet skid tests were performed using 50 mph as the high vehicle speed test value. The high vehicle speed was chosen at 50 mph, as it was the standard vehicle speed for which road surfaces are tested according to the Texas Department of Transportation. However, because only one tire was available during testing, a 50 mph dry skid test was not performed since the extent to which the tire would be worn under these conditions could have significantly changed the tire properties from the first test to the last. This scenario would have conflicted with the requirement to maintain tire properties constant. Therefore the dry skid tests were performed for the following vehicle speeds: 6 mph, 10 mph and 20 mph. The value for the 50 mph skid test can be assumed to converge on the skid number for which the 10 and 20 mph skid tests approach. While this would appear to hinder the experiment, the reality is that using these test speeds allows a test on predictability of the characteristic brake force versus variable slip curve. The wet skid resistance tests were conducted for 6 mph and 50 mph. The low vehicle speed, 6 mph, represents the friction or brake force value that would be approximately obtained at 12% longitudinal slip for a 50 mph variable slip test [6]. A

12% longitudinal slip is representative of the middle region in which the peak friction force occurs during a pure braking maneuver [11]. The vehicle speed selection in the skid tests is essential, as low vehicle speed skid resistance tests give an indication of the middle region containing the peak friction force and reflect the quality of the micro texture of a paved road surface, whereas high vehicle speed skid resistance tests determine the skid friction force and reflect the quality of the macro texture of a paved road surface (see section 3.2).

3.4.3 Skid Test Results

The complete skid test data collected from the skid tester is presented in Appendix B. The average of the five tests for each vehicle speed tested was calculated to obtain a mean skid number for the surface at a particular speed. The results are presented below in Table 3.1, for the series of wet skid resistance test, and Table 3.2, for the series of dry skid resistance tests. Recall that the skid number, denoted by SN, is the quotient of the friction force to the normal force times one hundred. The quotient of the friction force to the normal force is traditionally referred to as the coefficient of friction, μ, found in the Coulombic friction model.

	Surface A	Surface B	Surface C	Surface D	Surface E
SN @ 6mph	73	77	91	66	81
SN @ 50mph	45	22	36	17	46

Table 3.1. Wet Skid Resistance Test Results

	Surface A	Surface B	Surface C	Surface D	Surface E
SN @ 6 mph	66	90	87	95	91
SN @ 10mph	66	79	76	86	84
SN @ 15mph	65	77	76	86	83

Table 3.2. Dry Skid Resistance Test Results

On average a standard deviation of 2 SN was observed. This standard deviation is representative of the expected accuracy of a skid resistance tests [6]. Therefore, a meaningful distinction between any two surfaces must have at the very least a difference of 2 skid numbers for either the high vehicle speed skid tests or the low vehicle speed skid tests. A comparison of each paved road surface to one another reveals that two skid numbers are in fact sufficient measures to distinguish one paved road surface from another. However, it remains plausible for two road surfaces to have the exact same skid numbers for both the high vehicle speed test and the low vehicle speed skid test. Having the same skid numbers for both tests would indicate that the two road surfaces are identical with respect to the friction force they develop at the two vehicle speeds with respect to a particular tire. These results could not be taken to the next step to evaluate the accuracy they provide in adjusting the brake force versus variable slip data of one surface to another, since the equipment measuring the brake force as the tire is partially slipped from zero to hundred percent was not available at the time these tests were conducted.

The result provided by these skid tests suggests that the road classification method, presented in Section 3.2, can be used to distinguish one road surface from another. Additionally, the results show that there are substantial gains that can be realized toward describing the interaction between the tire and paved road for scenarios modeling a constant water film thickness road condition. This assertion comes from the considerable difference present, especially at higher slip percentages, between the dry skid numbers and wet (0.15 inches) skid numbers. Therefore, while the experimentation with the road classification and test method was not fully realized due to the absence of data relating the brake force exerted on the tire as the slip is incrementally increased from zero to one hundred percent, the results indicate favorably that road surfaces can be tested and subsequently categorized by those test values (i.e. $SN_{low\ speed}$, $SN_{high\ speed}$) to distinguish one road surface from another. The next chapter will discuss how the surface classification and test method, presented in Section 3.2, can be used to adjust a specific empirical tire model called the Pacejka Brake Tire Model.

CHAPTER 4: Integration of Road Classification and Test Method into the Pacejka Brake Tire Model

4.1 Introduction

The pneumatic tire is unique in that it is one of the only vehicle components designed and manufactured independent of a specific vehicle design. As such, tire manufacturers are obliged to provide a report, to vehicle manufacturers, quantifying a tire's performance capabilities [3]. This information is then assessed, in a vehicle simulation, to identify the compatibility of a specific tire with a specific vehicle model. However, in practice, the tire manufacturers often provide tire data measured on laboratory test facilities whose frictional properties can be quite different from actual road conditions. The use of this tire data can reduce the fidelity of vehicle simulations [3]. An impasse is reached when one realizes that it would not be feasible for a tire manufacture to measure, with a road tire test vehicle, every tire type and size it produces on the many different proving grounds used by the various vehicle manufacturers. Considerable attention by both vehicle and the tire manufacturers has been given to rectifying this impasse. Specifically, Van der Jagt and Parsons [3] looked into this problem and found that for a particular empirical tire model, called the Pacejka Tire Model (see section 2.4.3), the adjustment of two parameters sufficiently changes the tire model representing one surface to another with respect to a particular tire. Withstanding its widespread use is the absence of a standard method that can test and classify road surfaces so that the correction factors themselves could be categorized and subsequently used to adjust the tire model for any particular surface with respect to a particular tire. The construction of a road surface classification method begs a subsequent question, namely if particular vehicle types and thus particular tire types tend to be driven on particular road surfaces in the United States. To address these issues the following sections present a review of a method for correcting a Pacejka Tire model for a surface variation, the methodology effecting a surface change in the Pacejka Brake Tire Model using the road classification and test method, presented in Section 3.2, in conjunction with the surface correction method developed by Van der Jagt and Parsons [3]. In addition the last section of this chapter provides the results of a brief investigation into statistical that relate current driving densities of particular vehicle types on particular roads in the United States.

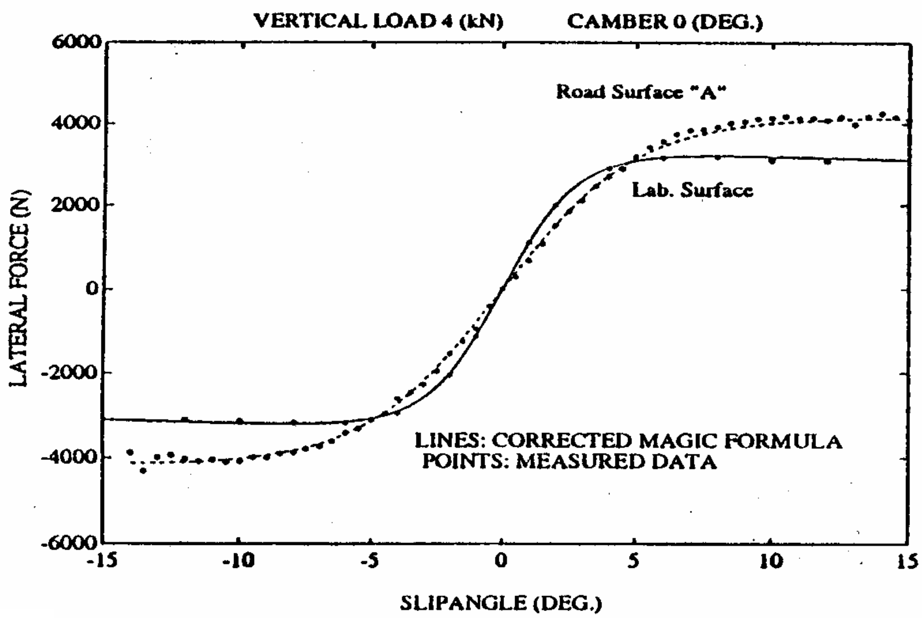
4.2 Review of Road Surface Correction in Pacejka Tire Model

The investigation by Van der Jagt and Parsons [3] isolated two parameters in the Pacejka Tire Model sensitive to surface variation when testing a tire under a cornering maneuver. The two parameters, D, the peak factor, and the product BCD, associated with the tire stiffness, were found to transform a tire model representing one surface to another by the linear approximations C_1 and C_2,

$$D_{\text{Actual Road}} = C_1 (D_{\text{Test Facility}}) \text{ and} \qquad (4.1)$$

$$(BCD)_{\text{Actual Road}} = C_2 (BCD_{\text{Test Facility}}). \qquad (4.2)$$

C_1 and C_2 represent the correction factors for a surface variation. To obtain these correction factors two steps were taken. First, a full-scale force versus slip test of the tire on an actual road surface was conducted. Second, the base or original Pacejka Tire Model, developed on a test facility surface under a cornering maneuver, was adjusted to approximate the recently conducted force versus slip data, developed from the actual road surface. Specifically, by optimizing the two road correction factors C_1 and C_2 the error between the calculated tire model forces (derived from the test facility surface) and the measured forces (derived from the full-scale test on an actual road surface) was minimized. Figure 4.1 from Van der Jagt and Parsons [3] illustrates the accuracy and predictability of using the BCD and D parameters to adjust a tire model from one surface to another. More recently Domenichini, et al, [19] investigated the applicability of the results established by Van der Jagt and Parsons for the longitudinal case. Domenichini, et al, [19] found that the parameters BCD and D could also be used to vary a road surface within the Pacejka Tire Model when testing a tire under a pure braking action. They also established that a minimum set of two experimental measures are required to represent the pavement characteristic within the Pacejka Brake Tire Model. The development of the road classification and test method, presented in Section 3.2, complement the preceding argument made in [19].



(a) Example of the accuracy of a "Magic Formula" tire model.
(b) Example of the corrected "Magic Formula" tire model.

Figure 4.1. Pacejka Model Adjustability [3]

The proposed methodology by Van der Jagt and Parsons has a significant shortcoming. Since the correction factors are for a particular surface they can only be used for a limited time as the difference between the two surfaces is subject to change according to weather, wear, and substantially different operating conditions. The limited use of C_1 and C_2 to adjust a tire model from a reference surface to another can be rectified if a standard is created to measure and test a road surface so that the correction factors retain their meaning beyond a particular surface to a measure of a surface that can be quantified at any time. By generalizing the condition of a road surface to accommodate a classification and test method the correction factors can be associated to a measurable characteristic of a road surface through a prescribed classification criteria.

Van der Jagt and Parsons [3] identified that tire models based on data measured on a surface other than the one on which the instrumented test was performed can contribute to very large differences between simulation and instrumented tire test results. This conclusion can be carried a step farther to say that the difference between the brake force versus slip relationship from one surface to another, whether going from a lab test surface to a real surface or from one real surface to another, is significant enough to provide substantial gains in the fidelity of vehicle simulations if corrected. The correction is accomplished by the manipulation of two parameters sensitive to surface variation within the Pacejka Tire Model, BCD and D [3]. This method should be valid for both the lateral and longitudinal force case [19]. However, because there is no standard for which road surfaces can be classified the use of these correction factors has a limited use. In response to this shortcoming and with the claim made by Domenichini [19] that a minimum of two experimental measurement are required, a basis for using the proposed road surface classification and test method (see Section 3.2) to adjust a Pacejka Brake Tire Model for a surface variation change is identified.

4.3 Integration

This section presents a methodology in which the road classification and test method, presented in Section 3.2, can be used in conjunction with the method formulated by Van der Jagt and Parsons [3] to effect a surface change in an empirical tire model. However, before an explicit methodology is described, this section must prove, if even for a fictitious road surface, that the Pacejka Brake Tire Model can be adjusted using two values representative of the middle and final stage of the characteristic brake force versus friction curve in accordance with the method developed by Van der Jagt and Parsons [3].

4.3.1 Pacejka Brake Tire Model Adjustability Study

In order to proceed with a methodology effecting a surface change within the Pacejka Brake Tire Model, it must be shown that the BCD and D parameters can be scaled to adjust a tire model representing one surface to a new surface by using two values classifying the new road surface coinciding with the friction force at low (between 10 and 20%) and full (100%) slip percentages. Therefore this section presents a case study conducted to evaluate whether the Pacejka Brake Tire Model can be adjusted to go through the two arbitrary friction force values chosen at low and full slip percentages. The case study was performed in Matlab using an actual Pacejka Brake Tire Model developed by Pacejka, et al, [4] from tire measurements taken on a dry asphalt road.

In order to substantiate the use of the correction methodology in conjunction with the road classification method four scenarios must be validated. The friction force values classifying a road surface in these scenarios were hypothetically conceived and are not representative of actual skid test results. The first hypothetical surface is one in which the friction force values at low and full slip percentages are greater than their counterparts in the base Pacejka Brake Tire Model ($F_{@\ 10\%\ slip}$ = 6500 N, $F_{@\ 100\%\ slip}$ = 5000 N). The second hypothetical surface is the reverse case of the first surface ($F_{@\ 10\%\ slip}$ = 5000 N, $F_{@\ 100\%\ slip}$ = 3800 N). The third hypothetical surface is one in which the friction force value at the low slip percentage is greater than its counterpart in the base Pacejka Tire Model whereas the friction force value at the full slip percentage is less than its counterpart in the base Pacejka Brake Tire Model ($F_{@\ 10\%\ slip}$ = 6500 N, $F_{@\ 100\%\ slip}$ = 4000 N). The fourth hypothetical surface is the reverse case of the third surface ($F_{@\ 10\%\ slip}$ = 5500 N, $F_{@\ 100\%\ slip}$ = 5000 N). Figures 4.2 and 4.3 show the results of this case study for the first and fourth surface scenarios. The remaining two surface scenarios along with a representative Matlab script used to generate the figures can be found in Appendix C.

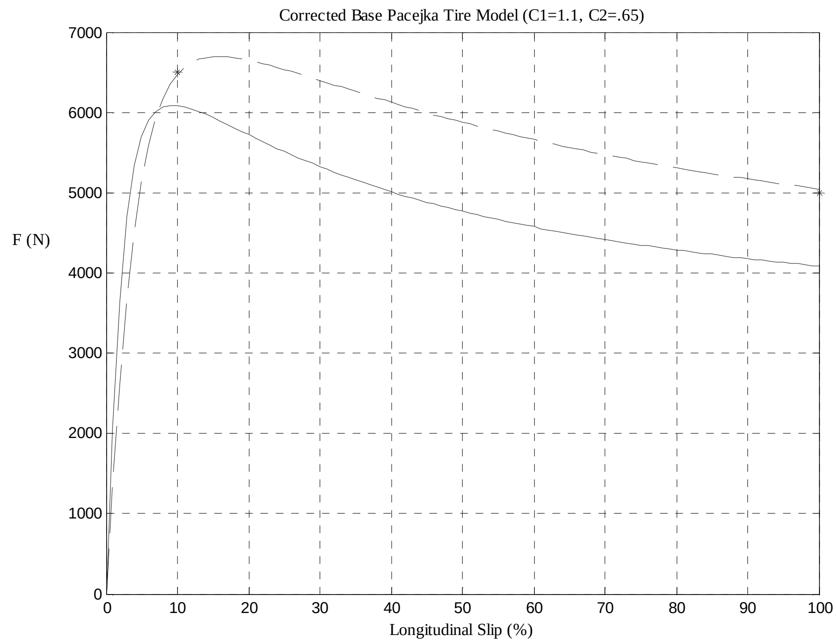


Figure 4.2. Corrected Base Pacejka Brake Tire Model for Surface Scenario 1

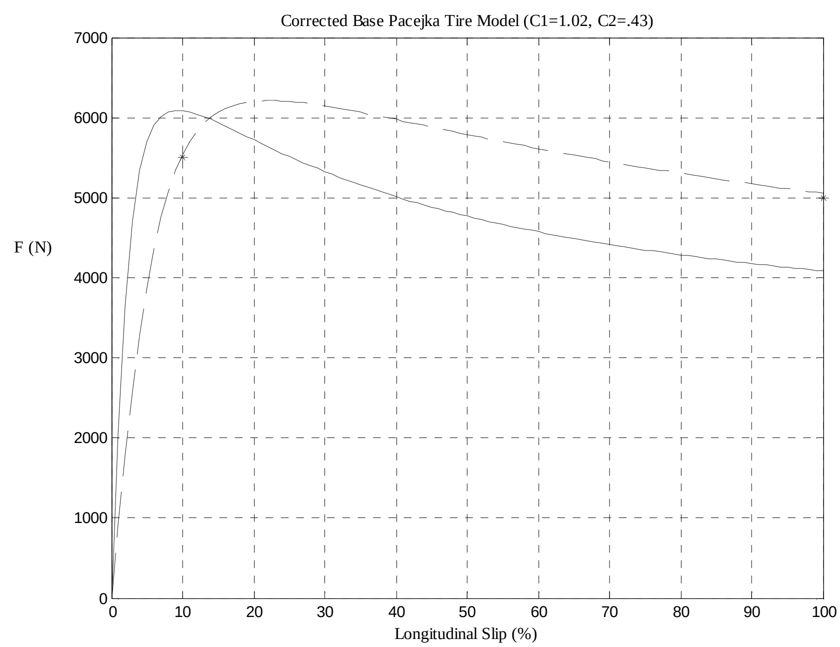


Figure 4.3. Corrected Base Pacejka Brake Tire Model for Surface Scenario 4

The results of this study indicate that the Pacejka Brake Tire Model can be adjusted, using the BCD and D parameters, to two friction forces at low (between 10 and 20% slip) and full (100%) slip percentages, which can be obtained from two skid tests at low and high vehicle speeds. It is foreseen that a computer program could facilitate the calculation of the correction factors for a particular tire, independent of running physical tests, as the correction based on two skid values is a determinant system since skid numbers are integers ranging form 1 to 100 (i.e. all possibilities are finite). Moreover it was inferred, from the above study, that the Pacejka Tire Model might retain the information determining the slopes and inflection points of the three regions making up the characteristic curve. Without the appropriate data to validate this conjecture this thesis will assume that the adjusted tire model is actually a representation of the new surface. However, the extent to which the correction factors accurately predict a different road surface is unknown without performing a comparison to the actual brake force versus variable slip data of a given surface. An effort was made to perform a comparison study in the experimentation phase of the road classification and test method, but it was not realized, as the appropriate testing equipment to obtain brake force versus variable slip data was not available. Consequently the comparison study is left to a subsequent investigation.

4.3.2 Assumptions and Constraints

A few assumptions are required in order to progress to a final methodology. These assumptions are presented below.

- The use of the BCD and D parameters to adjust a base Pacejka Brake Tire Model can be used to approximate any surface.
- The approximation of a new surface in a Pacejka Brake Tire Model, using the two skid resistance values, is a sufficiently accurate prediction of the new surface brake force versus variable slip behavior.

Along with the preceding assumptions, some constraints must be imposed on the methodology varying the Pacejka Brake Tire Model for surface variations if using the standard road classification and test method presented in Section 3.2 of this thesis. These constraints are listed below.

- The locked wheel skid resistance test must follow ASTM standard E 274 - 97.
- The same tire (tread and compound) must be used to acquire the skid numbers as was used to develop the base Pacejka Tire Model.
- The equivalent normal force must be used when adjusting the Pacejka Brake Tire Model as was used when the skid numbers were acquired.
- The vehicle test speed used to obtain $SN_{high\ speed}$ must be equal to the vehicle speed used to develop the base Pacejka Brake Tire Model. Consequently, the second skid resistance test must be conducted at a low vehicle speed equal to

the product of the high vehicle speed and the percent slip where the maximum friction force is obtained in the base Pacejka Brake Tire Model.

- For the case dealing with wet surfaces, both the base Pacejka Brake Tire Model and the skid resistance tests must use the same Water Film Thickness. (Note: the Pacejka Tire Model cannot predict the resulting force when water depth is introduced or changed during testing. However, the Pacejka Tire Model can model the behavior of the brake force versus variable slip if the water film thickness is held constant throughout testing and hydroplaning does not occur. This is a result based on the fact that the characteristic brake force versus slip shape for a given water film thickness is retained although categorically diminished (see Figure 2.7).)
- Knowledge of the environment conditions producing the skid resistance values used to alter the base Pacejka Brake Tire Model should be reported, as they inform on the relative conditions producing a given set of skid numbers.

4.3.3 Methodology

The premise of the methodology is that for a particular tire the appropriate correction factors for adjusting a Pacejka Brake Tire Model from one surface to another can be predicted with the help of a standard classification and test method. The classification and test method classifies a paved road surface according to two (locked-wheel) skid resistance tests taken at different vehicle speeds with a particular tire. The (locked-wheel) skid resistance test for the high vehicle speed identifies the friction force corresponding to the skid point or end point of the characteristic brake force versus slip curve while the low vehicle speed identifies a friction force corresponding to the peak friction region of the characteristic brake force versus slip curve. The use of these two friction forces, estimated by skid values, in conjunction with the zero force zero slip origin give a relative measure of how the characteristic brake force versus slip curve should behave in the beginning, middle and end for a particular tire and surface combination. The following describes a methodology to effect a parametric surface change in the Pacejka Tire Model.

Part One

- Step One

  A tire of interest is chosen.

- Step Two

  A base Pacejka Brake Tire Model is developed from brake force versus variable slip data for the tire chosen on a road surface.

- Step Three

  A reference table with high and low skid numbers is constructed for the particular tire chosen. An example table is presented below in Figure 4.4.

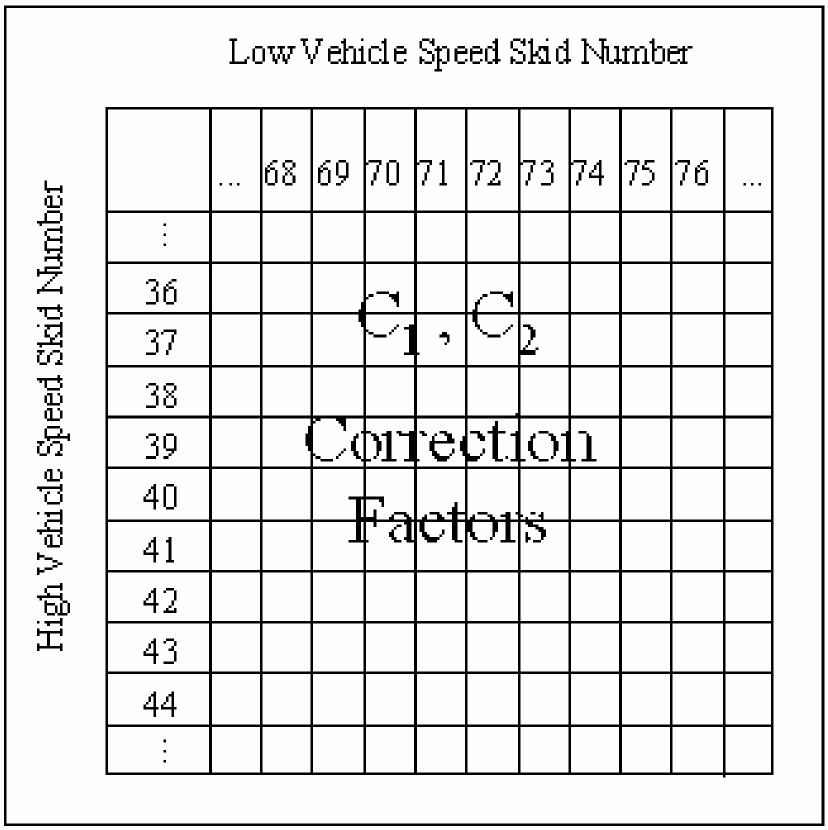


Figure 4.4. Example of Reference Table

Part Two

- Step One

  A surface of interest is chosen.

- Step Two

  The surface of interest is tested using two standard locked wheel skid resistance test conducted at a high and a low vehicle speed (see Section 3.2).

- Step Three

  The high and low vehicle speed skid numbers obtained from the test results are used in conjunction with the reference table, obtained in Part One, Step Three, to determine the correction factors needed to adjust the base Pacejka Brake Tire Model to the new surface of interest.

The preceding methodology effecting a parametric surface change in the Pacejka Brake Tire model has two important parts. The first part is a reference table that contains the correction factors for any given combination of high and low vehicle speed skid numbers with respect to a particular tire. This reference table identifies the correction factors to the BCD and D parameters of the Pacejka Brake Tire Model for any particular high and low skid number combination. Incidentally, the reference table, in theory, would have 10,000 entries of correction factors for the different combination resulting from a 100 by 100 array of skid numbers (skid numbers range from 1 to 100). However, the capability and accuracy of C_1 and C_2 to describe all of these scenarios is highly questionable. It would be useful to have knowledge of the road surfaces a specific vehicle type is likely to traverse so as to provide a relevant range of skid numbers in the reference table. To address this specific issue, Section 4.4 describes statistical studies furnished by the Federal Highway Administration on driving density in the United States. It is left to a subsequent investigation to determine the extent to which the correction factors can accurately predict a surface change.

The second part is the testing of a paved road surface to identify its high and low vehicle speed skid number with respect to the same tire. It is important that the vehicle speed, V, normal force, F_{Normal}, and water film thickness, t, if any used to determine the base Pacejka Tire Model are also used when classifying and testing a paved road surface with respect to a particular tire. Additionally the low slip number, which is established to correspond with the low vehicle speed skid test, must be consistently maintained for each surface tested with respect to a particular tire. The choice of the low slip value, and consequently the low vehicle speed, can be anywhere from 10 to 20% [11], with 15% being a good representation of the peak friction force region of the characteristic brake force versus slip curve. See equation (3.8) for the formula approximating the friction force using a low vehicle speed skid test. Together these two pieces of information allow a base Pacejka Tire Model to be adjusted to represent any paved road surface. It is important to stress that the reference table, the testing method, and the base Pacejka Brake Tire Model must be developed and performed with respect to the same tire, normal force, vehicle speeds and water film thickness.

4.4 Driving Densities in the United States

In general knowledge of the road surface a specific vehicle type will traverse allows engineers developing vehicle simulations the ability to improve the tire models that describe the interaction between the tire and road surface in an effort to better assess the actual response of a vehicle in a particular environment. However, in order to use this knowledge of vehicle driving densities in a vehicle simulation, a methodology to test, classify, and adjust tire models according to different road surfaces must be available. Section 4.3 presents such a methodology. In order to determine these driving densities it was hypothesized that the statistical studies published by the Federal Highway Administration (FHWA) and the Bureau of Transportation Statistics were capable of relating the relevant road surfaces a particular vehicle type is likely to drive on during normal use. It is the purpose of this section to present the available information useful in identifying the road surfaces vehicle types are likely to drive on and the extent to which this information can be used to relate the trends for specific vehicle types. It was determined that, as of the most recent FHWA study, only the number of miles traveled on specific functional roadway systems by a particular vehicle type can be related. Further information regarding the composition of roadways exists, but this information cannot be connected to the driving trends of a particular vehicle type. A future statistic relating the vehicle types traversing the different road surface types among the different functional roadway systems across the United States is determined necessary to give relevance to the road surface a specific vehicle type will traverse.

4.4.1 Highway Statistics Background

Highway statistics come from various administrative agencies within the 50 states, over 30,000 units of local government, Federal agencies, and the five U.S. territories [21]. The Office of Highway Policy Information publishes the findings in *Highway Statistics*. The statistical studies are provided by the FHWA under a directive by Congress to aid in highway planning, programming, budgeting forecasting, and fiscal management. The information presented in *Highway Statistics* "meets the Federal need of providing a national perspective on highway program activities" [21]. The statistical information, presented in this section, is based on the *Highway Statistic* report for the year 1999.

4.4.2 Vehicle Type Classification

The specific vehicle types identified by the statistical studies are classified into passenger cars, motorcycles, other 2-axle 4-tire vehicles, buses, single-unit 2-axel 6-tire or more trucks, and combination trucks. The number of current vehicle registrations from each of the fifty states accounts for the number of vehicles in the study. Of particular note is the grouping of other 2-axle 4-tire vehicles, which includes vans, pick-up trucks, and sport-utility vehicles.

4.4.3 Functional Roadway Systems

The functional roadway systems contain rural and urban stratifications. This initial distinction is determined by the number of persons per square mile that encompass at a minimum the land area delineated by the results from the last U.S. census. The cut-off of inhabitants distinguishing an urbanized area from a rural one is a population of 50,000 people. Within these two areas, urban and rural, is a functional grouping or system of public roads according to the character of service the roads are intended to provide. The functional systems are: (1) arterial highways, which handle long distance travel; (2) collector facilities, which collect and disperse traffic between the arterials and the lower level roads; and (3) local roads, streets, and other public ways, which serve a land access function to homes, businesses, individual farms and ranches, and other uses [21].

4.4.4 Road Surface Classification

The road surfaces identified by these statistical studies are classified according to their composition. The classification of road surfaces exists within the different functional roadway systems. Figure 4.5 provides a visual description of the following stratification of road surfaces. Paved and unpaved road surfaces represent the first stratum, with unpaved roads having no other substrata. Under paved roads, the second stratum classifies paved roads as low, intermediate and high type. A low type paved surface is defined as an earth, gravel, or stone roadway having a bituminous (a black, tarry mineral substance used in cements and in the construction of pavement) surface course less than one inch thick. An intermediate type paved surface is a mixed bituminous or bituminous penetration roadway on a flexible base having a combined surface and base thickness of less than seven inches. Under high type paved road, a subsequent stratum is defined classifying a high type road surface to be of flexible, composite, or rigid design. A high type paved road of flexible design is a mixed bituminous or bituminous penetration roadway on a flexible base having a combined surface and base thickness of seven inches or more, which includes brick, block, or combination roadways. A high type paved road of composite design is a mixed bituminous or bituminous penetration roadway of more than one inch compacted material on a rigid base with a combined surface and base thickness of seven inches or more. A high type paved road of rigid design is a Portland Cement concrete roadway with or without a bituminous wearing surface of less than one inch.

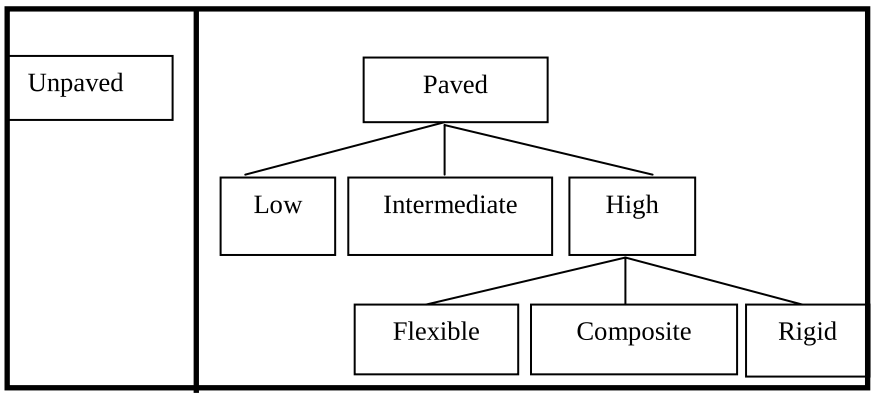


Figure 4.5. Stratification of Road Surface Classification

4.4.5 Relevant Statistical Studies and Analysis

The purpose of researching these statistical studies is to determine whether vehicle designers can be informed of the likely road surface a specific vehicle type will traverse. With this in mind, a search of relevant statistical studies presented in the *1999 Highway Statistics Report* was undertaken. Three studies were identified, and can be found in their entirety in [21], as potentially useful: (1) *State Motor-Vehicle Registrations-1999 1/* [21], which relates the number of motor vehicles and the distribution of those vehicles into the specific types of vehicles for each state; (2) *Annual Vehicle Distance Traveled in Miles and Related Data – 1999 1/ By Highway Category and Vehicle Type* [21], which relates the number of miles traveled by specific vehicle types over specific functional roadway systems; (3) *Public Road Length– 1999 1/ Miles by Type of Surface and Ownership/ Functional System National Summary* [21], which relates the length, measured in miles, of a particular road surface type present in the different functional roadway systems.

The first statistical study, *State Motor-Vehicle Registrations-1999 1/* [21], gives the most accurate account of the number of vehicles on roadways today. This statistical study also has the potential to describe a regional demographic of vehicle use and potentially inform on how to better design for local environment use by measure of the density of specific vehicle types in certain regional areas. Figure 4.6 displays a comparison of the number of automobiles to the number of trucks in from a sample of U.S. States. The information plotted comes directly from the statistical study without manipulation. The inferred use of this study is to use the number of registered vehicles in use in a particular state to obtain the total national miles traveled on functional roadway systems in the United States by specific vehicle types from the average number of miles driven by a specific vehicle type on a functional roadway system in a particular state.

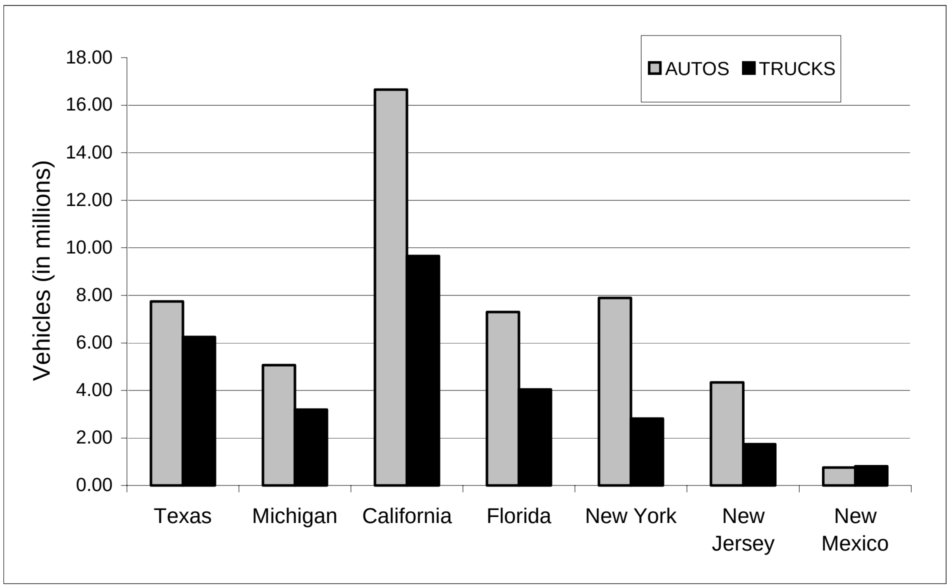


Figure 4.6. Number of Cars and Trucks Registered in a Sample of States Across the United States

The second statistical study, *Annual Vehicle Distance Traveled in Miles and Related Data – 1999 1/ By Highway Category and Vehicle Type* [21], gives the most accurate account of how and to what extent our nation's roadways are used. This study reveals the driving trends of specific vehicle types on specific functional roadway systems. This study however, does not provide further information as to what roadways specific vehicle types are traversing. The intent of this investigation into vehicle driving trends was to identify the composition of road surfaces specific vehicle types are traversing. Figures 4.7 display the average number of miles driven by passenger cars and other 2-axle 4-tire vehicles on the variety of functional roadway systems in the United States. In addition these results can be obtained for any state listed in the study without further manipulation of the statistics.

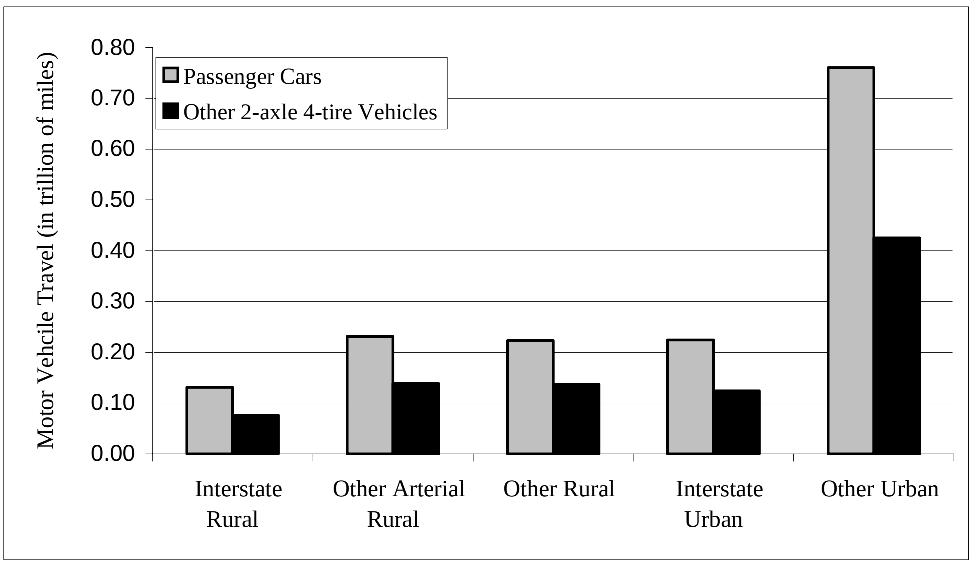


Figure 4.7. Average Miles Driven by a Passenger Car and a Other 2-Axle 4-Tire Vehicle on the Different Functional Roadways in the United States

The third statistical study, *Public Road Length– 1999 1/ Miles by Type of Surface and Ownership/ Functional System National Summary* [21], relates the composition of the road surfaces that make up the functional roadway system, as described in Section 3.2.4. Figure 4.8 presents the distribution of specific road compositions among the specific functional urban roadway systems in the United States. Although this study relates the physical composition of the roads among the different functional roadway systems, which provides the required information to begin to infer the frictional potential between a tire and a road surface for vehicle simulation, it does not relate this information to the driving trends of specific vehicle types. The resulting impasse cannot be surmounted, as there is no clear indication to the number of miles driven by a specific vehicle type on a specific functional roadway with a specific road composition.

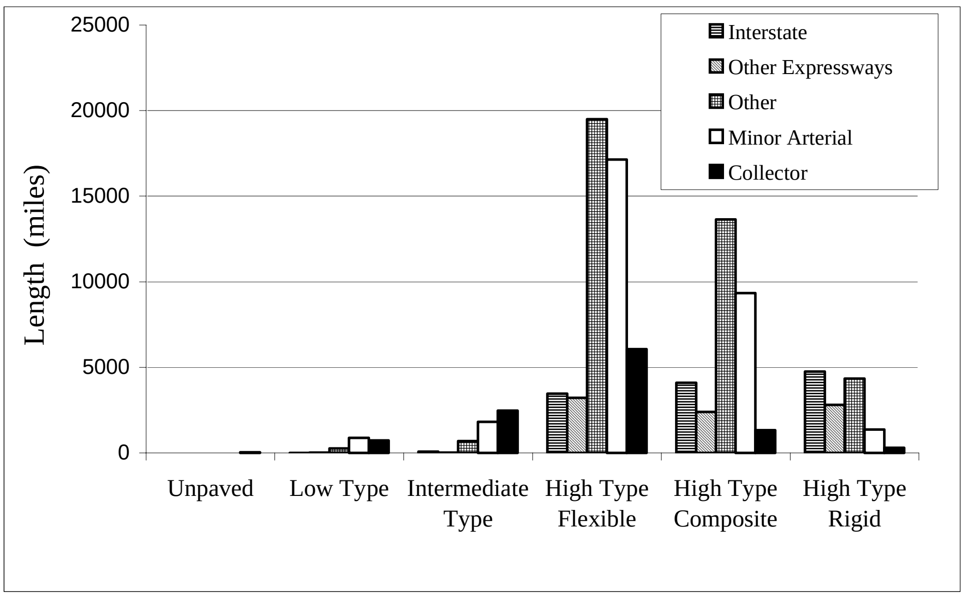


Figure 4.8. Distributions of Road Surface Types among Functional Roadway Systems

While this investigation into the statistical breakdown of public road use did not produce the intended statistic—the number of miles traveled by a specific vehicle type on a specific functional roadway composed of a specific road type; this study did account for the number of specific vehicle types in use in each of the fifty states in the United States, the number of miles traveled by specific vehicle types on specific functional roadway systems and a system stratifying the composition of road surfaces among the different functional roadway systems. Unfortunately, without the intended statistic, an assessment of the relevant range of road surfaces a specific vehicle simulation should consider when using the methodology effecting a parametric surface change in the Pacejka Tire Model, presented in Section 4.3, could not be established. The prospect that the required statistic will be made available in the near future is not unlikely, as there is already a way to account for the number of vehicles traversing a known roadway type and there is also a way of differentiating the different road compositions present among the different functional roadway systems. However, in order to see the fruition of this statistic, road makers and local governments must be made aware of the potential safety benefits resulting from such a statistic.

CHAPTER 5: Recommendation for Future Work and Conclusion

5.1 Paved Road Classification and Test Method

The objective for this thesis has been met. A paved road classification and test method identifying the dominant surface characteristics contributing to the development of friction with respect to a pneumatic tire was developed. This method classifies and tests paved road surfaces using a high and low vehicle speed skid test. The potential of this thesis to be of relevant use to vehicle, tire and road makers will be realized when the technologies facilitating the acquisition of skid numbers from optical measurements comes to fruition. A methodology effecting a parameter surface change in the Pacejka Brake Tire Model is proposed. This methodology combines the classification and test method developed in this thesis with a surface correction method to the Pacejka Tire Model, developed by [3]. It is forecasted that vehicle makers could use such a methodology to improve and tune specific component designs within a specific vehicle design that are influenced by the tire-road interaction. While road makers could use this methodology in conjunction with vehicle simulations to test surfaces against a standard tire in order to determine safe driving conditions and or evaluate the quality of a road surface.

5.2 Future Work

There is considerable work left before this paved road classification and test method can be fully implemented. First and foremost the application of the classification and test method used to approximate another surface in the Pacejka Tire Model must be checked and its accuracy to actual tire test data must be established. Once this classification and test method has been verified, research into the use of different tires may be pursued as well as extending the methodology to the cornering or lateral force case. This section briefly goes over the aforementioned future work.

5.2.1 Verification of Proposed Methodology

It is imperative that the conjectures and assumption asserted in this thesis be verified. In particular are the two assumptions needed to apply the paved road classification and test method to effect a parameter surface change in the Pacejka Brake Tire Model. First the extent to which the correction method can be used to approximate a new surface must be examined. Next the approximation of a new surface in a Pacejka Brake Tire Model, using the classification and test method, must be compared to actual brake force versus variable slip tire data to determine the accuracy and range of adaptability of a new surface.

5.2.2 Evaluating Other Tire Types

The development of this thesis based its conclusions by maintaining the same tire type and properties. The paved road and classification method is thus developed to represent the behavior of a specific tire with respect to a specific surface. However, if this classification and test method is to have any widespread success it must be developed to account for tires with variable tread depth and patterns.

5.2.3 Extending Classification and Test Method to Lateral Force Case

The development of this thesis was based on a pure braking vehicle action. However, many vehicle situations call for both pure braking and cornering analysis. As such it would be of interest to investigate the adaptability of this classification and test method to the lateral force case. To this end there exist side force skid testing methods and testing equipment already in use by various departments of transportation.

5.3 Conclusion

The classification and test method developed in this thesis can facilitate the adjustment of the Pacejka Tire Model due to a surface variation when combined with the tire data correction method developed by Van der Jagt and Parsons [3]. This approach requires as much full-scale testing as is currently needed to generate a new Pacejka Tire Model on a given surface, and it still requires verification. However, this may change as new technologies will facilitate the acquisition of skid numbers from optical measurements. In this way, the classification and test method formulated here represents advancement in the tools available to vehicle and road makers to improve predictability of tire forces over different surfaces. In this way, the safety of vehicles on roadways and an understanding of how the two are interrelated can be gained.

Appendix A: Images of Tested Road Surfaces

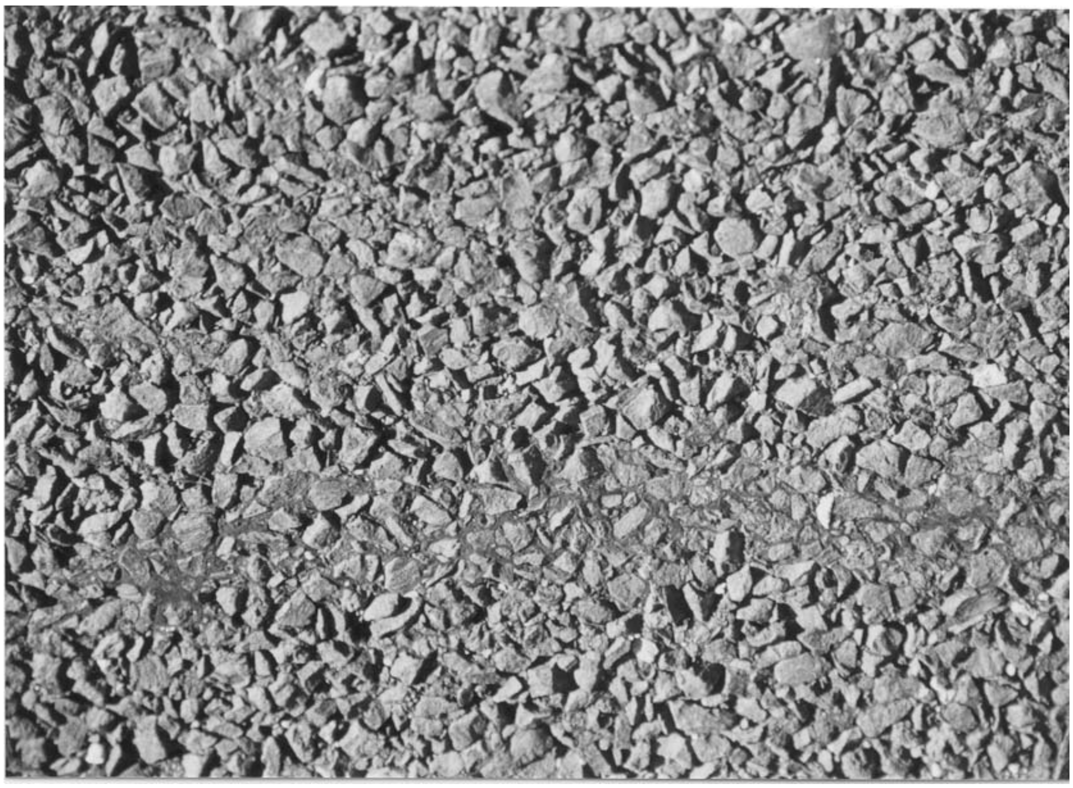


Figure A.1. Test Surface A

Figure A.2. Test Surface B

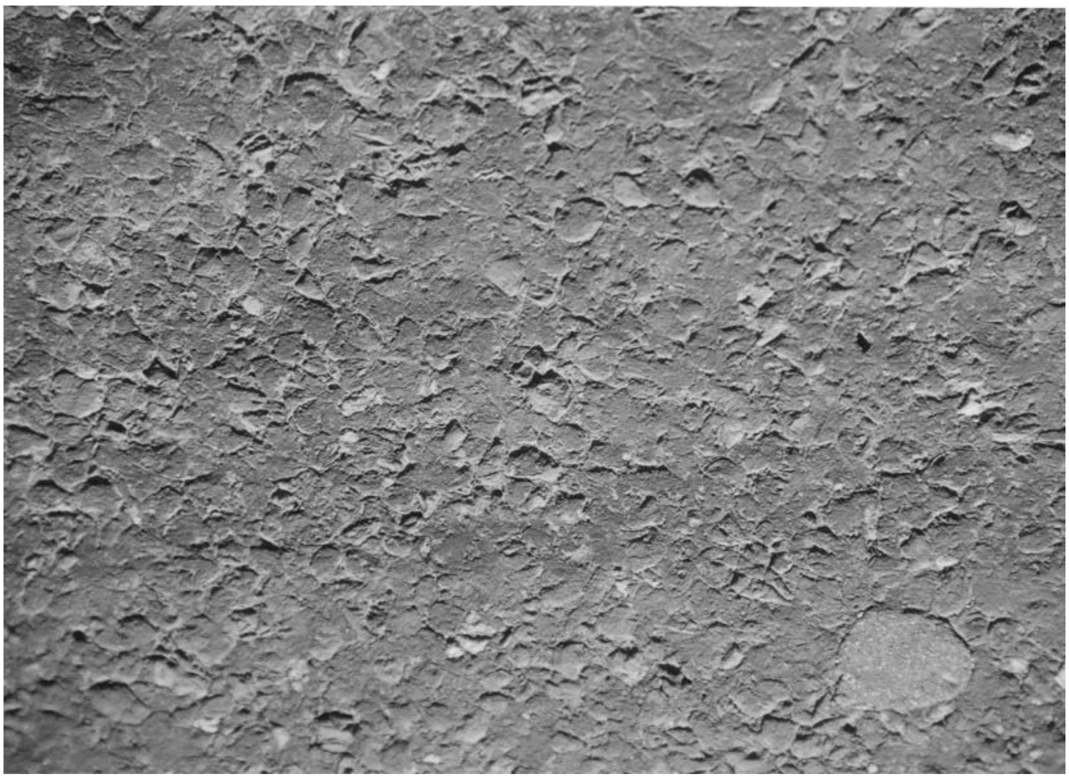


Figure A.3. Test Surface C

Figure A.4. Test Surface D

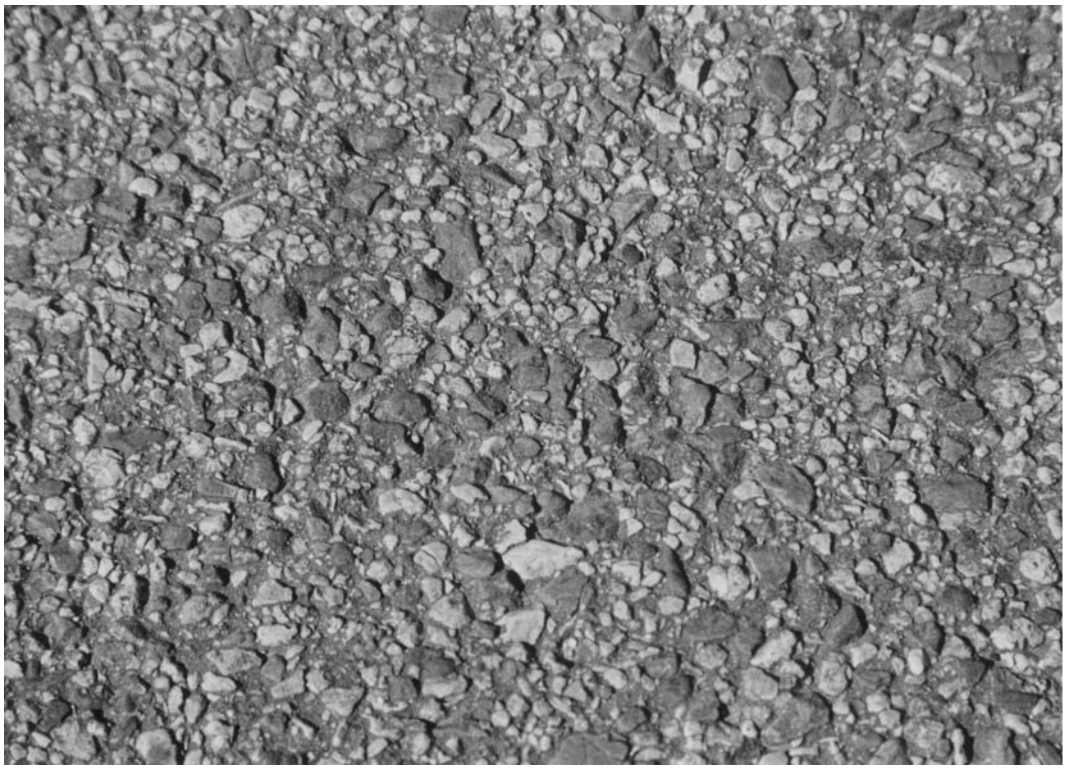


Figure A.5. Test Surface E

Appendix B: Skid Test Data

WET Skid Resistance Tests

	LOW Vehicle Speed MPH	SN	HIGH Vehicle Speed MPH	SN
	6	73	50.1	47
	6.9	73	50.3	43
	6.8	73	50.2	45
	6.8	74	50.2	44
	6.7	72	50.1	46
	6.8	74		
AVERAGE	6.7	73	50.2	45
standard deviation		0.8		1.6

DRY Skid Resistance Tests

	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN
	5.2	69	10	64	15.5	68
	5.5	65	10.1	70	16.4	65
	5.6	68	10.6	66	15.8	64
	5.4	64	10.7	63	15.6	65
	5.5	64	10.8	67	16.6	64
	5.5	68	10.9	64	15.9	63
	5.8	64	10.4	67	16.2	63
	5.8	62	10.8	66	15.5	64
			10.4	68		
AVERAGE	5.5	66	10.5	66	15.9	65
standard deviation		2.5		2.2		1.6

Table B.1. Skid Test Data and Analysis for Test Surface A

WET Skid Resistance Tests

	LOW		HIGH	
	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN
	5.6	80	50.2	19
	6.7	77	50.1	24
	5.8	78	50.1	23
	5.9	76	50.3	24
	6.2	75	50.2	22
AVERAGE	6.0	77	50.2	22
standard deviation		1.92		2.07

DRY Skid Resistance Tests

	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN
	6.3	91	10.8	82	15.1	80
	5.1	88	11.1	77	15.2	76
	5.5	90	11.2	77	16.1	75
	5.5	93	11	79	15.5	77
	5.1	90	10.5	82	15.9	77
AVERAGE	5.5	90	10.9	79	15.6	77
standard deviation		1.82		2.36		2.16

Table B.2. Skid Test Data and Analysis for Test Surface B

WET Skid Resistance Tests

	LOW		HIGH	
	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN
	5.5	89	50.6	35
	5.4	91	50.4	37
	5.5	92	50.4	35
	7.2	90	50.8	32
AVERAGE	5.9	91	50.5	35
standard deviation		1.29		2.06

DRY Skid Resistance Tests

	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN
	5.9	89	10.4	78	15.1	76
	5.9	88	11.2	75	15.6	78
	6.6	88	10.7	76	15.9	75
	5.8	85	10.3	78	15.6	78
	6.1	86	10.5	75	15.2	75
AVERAGE	6.1	87	10.6	76	15.5	76
standard deviation		1.64		1.52		1.52

Table B.3. Skid Test Data and Analysis for Test Surface C

WET Skid Resistance Tests

	LOW Vehicle Speed MPH	SN			HIGH Vehicle Speed MPH	SN
	5.3	64			50	16
	5	68			50.8	18
	5.9	66			50.6	16
	6.9	70			50.5	17
	5.6	69			50.6	16
	6.4	63				
	5.5	65				
AVERAGE	5.8	66			50.5	17
standard deviation		2.64				0.89

DRY Skid Resistance Tests

	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN
	6.4	96	10.7	88	14.1	88
	7	94	10.5	87	14.4	85
	7.3	92	10.7	84	15.1	85
	6	94	10.2	85	14.8	87
	5.7	97	9.9	88	15.6	84
AVERAGE	6.5	95	10.4	86	14.8	86
standard deviation		1.95		1.82		1.73

Table B.4. Skid Test Data and Analysis for Test Surface D

WET Skid Resistance Tests

	LOW		HIGH	
	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN
	5.6	81	50.6	45
	6.5	79	50.7	46
	5.4	85	51	47
	5.5	82	50.8	46
	5.6	80	50.5	47
AVERAGE	5.7	81	50.7	46
standard deviation		2.30		0.84

DRY Skid Resistance Tests

	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN	Vehicle Speed MPH	SN
	5.2	93	10.1	86	14.9	84
	6.5	88	10.8	85	15.7	83
	4.8	92	11	82	15	81
	5.6	91	11.4	82	15.3	82
AVERAGE	5.5	91	10.8	84	15.2	83
standard deviation		2.16		2.06		1.29

Table B.5. Skid Test Data and Analysis for Test Surface E

Appendix C: Pacejka Brake Tire Model Adjustability Study

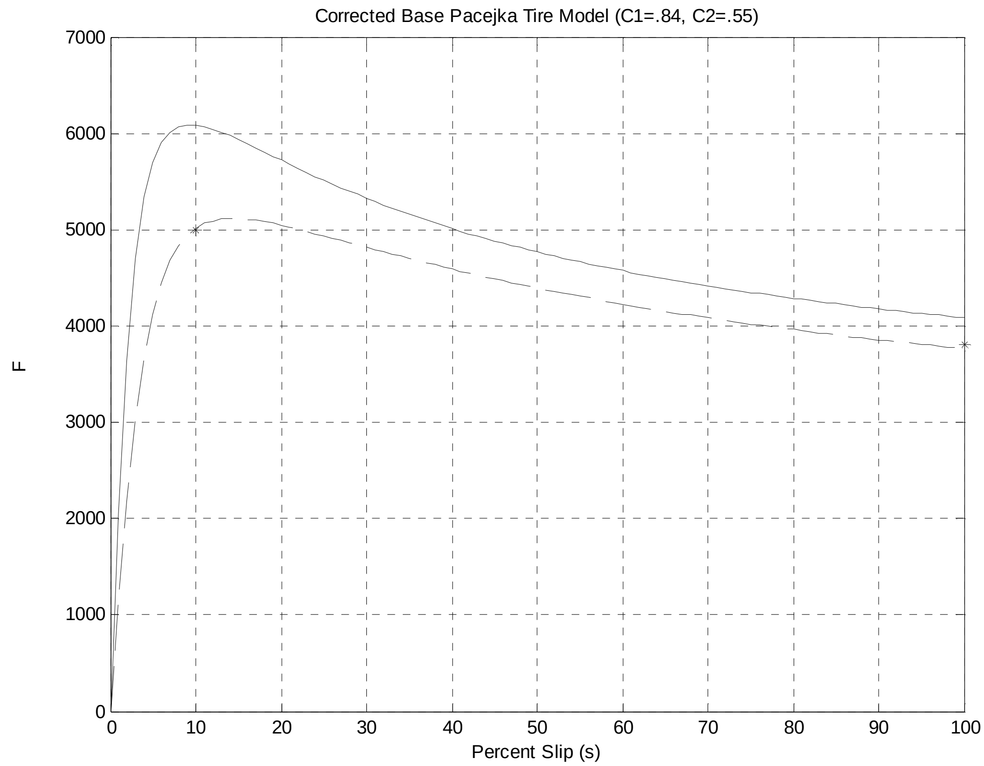


Figure C.1. Corrected Base Pacejka Brake Tire Model for Surface Scenario 2

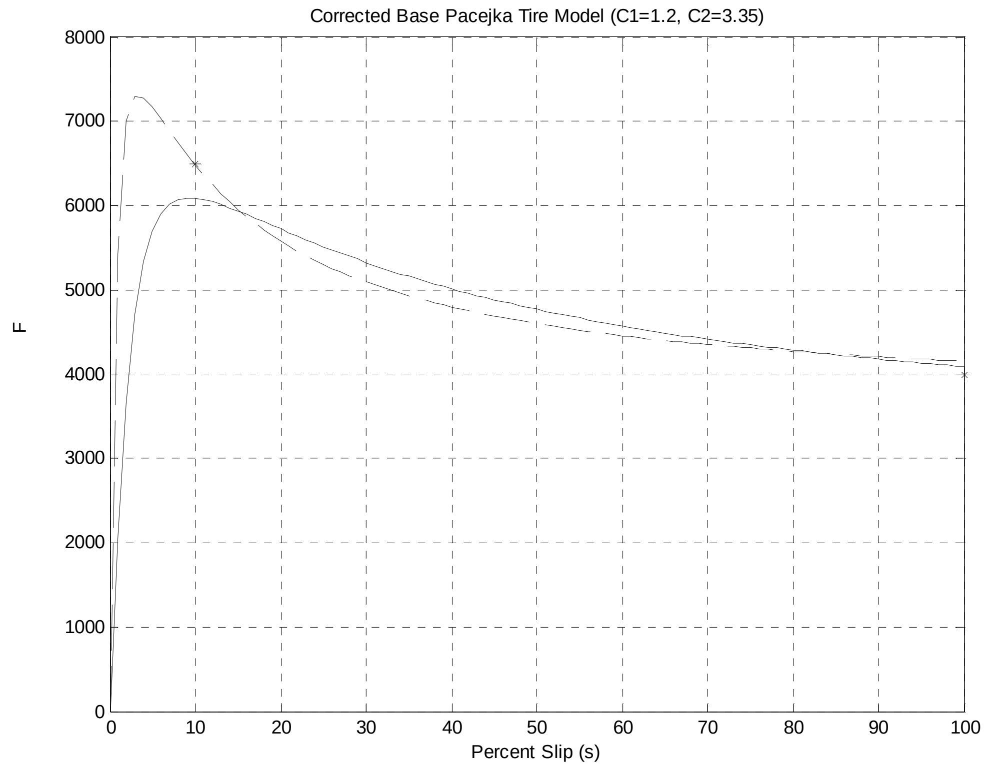


Figure C.2. Corrected Base Pacejka Brake Tire Model for Surface Scenario 3

```
clear all
c1 = 1.1;         %correction factor
c2 = 0.65;        %correction factor
B = 0.210;        %Stiffness factor
C = 1.67;          %Shape factor
D = 6090;         %Peak factor
E = 0.686;        %Curvature factor
Sh = 0;            %Horizontal Shift
Sv = 80.1;  %Vertical Shift
BCD = B*C*D;
Dnew = c1*D;
Bnew = c2*BCD/(C*Dnew);
BCDnew = c2 * BCD;
x = 0 : 1 : 100;
F = D * sin(C*atan(B*x - E*(B*x - atan(B*x))));
Fnew = Dnew * sin(C*atan(Bnew*x - E*(Bnew*x –
                  atan(Bnew*x))));

plot(x,F)
hold
plot(x,Fnew,'g')
plot(10.,6500.,'*')
plot(100.,5000.,'*')
xlabel('Percent Slip (s)')
ylabel('Brake Force (N)')
title('Corrected Base Pacejka Tire Model(C1=1.1, C2=.65)')
grid on
```

Figure C.1. Example Matlab Script Used to Generate Pacejka Brake Tire Model [4]

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Vita

Gilberto Lopez was born in El Paso, Texas on December 8, 1977. He was married to Christina Valadez June 2, 2002. He is the son of Gilberto I. Lopez, an architect living in New York City, and Concepcion H. Flores, an accountant living in San Antonio, Texas. Upon graduation from T. C. Clark High School, San Antonio, Texas, he entered Texas A&M University in College Station, Texas. His sophomore year he transferred to the University of Texas at Austin where he completed his Bachelor of Science Degree in Mechanical Engineering in December of 2000. During his undergraduate program of study he interned at Ford Motor Company and was awarded a scholarship to continue his academic work for a period of one semester in mechanical engineering at the Universidad Pontificia de Comillas in Madrid, Spain. In the spring of 2001, he entered The Graduate School at the University of Texas at Austin.

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