Adhesion, Hysteresis and the Peak Longitudinal Tire Force

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INTRODUCTION

It is a well known phenomenon in vehicle tire mechanics that the braking force in the direction of wheel heading during wheel slip before lockup can exceed the force level achieved at lockup. The existence of a peak force forms part of the rationale of antilock braking systems. One hypothesis for the peak [1] is that as lockup is approached, the temperature of the tire at the interface rises causing lubrication and decreasing friction. Although temperature at the tire-road interface very likely has an effect on friction, because of the complexity of tire-road friction this mechanism has remained a hypothesis. This paper presents a different hypothesis to explain the phenomenon. This hypothesis attributes the higher friction force before lockup to the hysteresis in the tire material and the relationship of hysteresis to the tire's angular velocity.

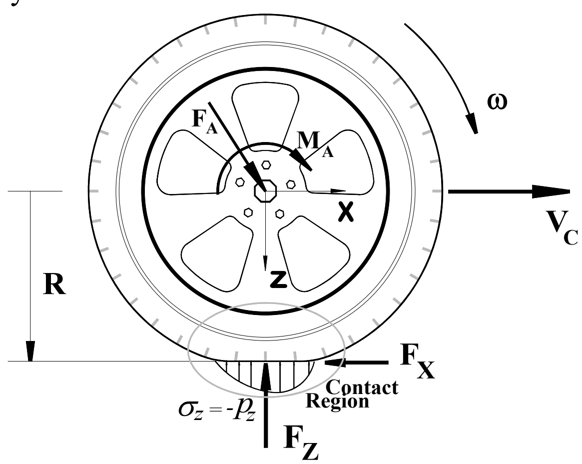

Figure 1. Rotating wheel.

In the context of vehicle tires and pavements, *friction* is the resistance to relative tangential motion during braking at the compressive contact interface between a tire and the road surface. In reference to Fig 1, the rolling radius is R, F_A and M_A represent a force system applied to the wheel, the normal force between the tire and the pavement is F_z, and the frictional force between the tire and the pavement is F_x. Note that F_x and F_z both are single equivalent point forces used to represent the effects of distributed forces over the contact area. The forces F_x and F_z are developed in reaction to the applied force system F_A and M_A. They, in turn, are related inertially to the vehicle's dynamics. When discussing the mechanics of longitudinal tire forces, that is, forces in the direction of the heading of the wheel, a distinction typically is made between wheel/tire "slipping" and "skidding". Figure 1 shows a wheel whose center is moving with speed V_C and which is rotating with angular velocity ω. The ratio of the tangential force, F_x, to the compressive force, F_z, is defined as the *coefficient of friction*, μ. In this work, the symbol μ_x for the tire-road friction coefficient is given a specific meaning. The symbol μ_x represents a *sliding* (locked wheel) coefficient where the subscript x indicates that the coefficient applies to motion along the heading, or x axis, of the wheel. In addition, the terms braking and acceleration are used here to indicate a force F_x that retards (decelerates) velocity of the wheel and increases (accelerates) the velocity of wheel, respectively. Although some of the information discussed and presented in the following has implications to side (cornering) forces developed by a rotating tire with sideslip, the paper is devoted primarily to the forces along the heading axis of a tire.

Wheel Slip and Longitudinal Tire Force When studying tire mechanics, it is common to define a kinematic variable, s, called wheel slip and to use it as an independent variable to express the traction force F_x, that is $F_x = F_x(s)$. For braking, wheel slip is defined as:

$$s_b = \frac{V_p}{V_c} = \frac{V_c - R\omega}{V_c} = 1 - \frac{R\omega}{V_c} \tag{1}$$

and for acceleration,

$$s_a = \frac{V_P}{R\omega} = \frac{V_C - R\omega}{R\omega} = \frac{V_C}{R\omega} - 1 \tag{2}$$

where V_C is the velocity of the wheel center, V_P is the kinematic velocity of the tire at the contact area and ω is the angular velocity of the wheel. Note that for braking, wheel slip takes on values $0 \le s_b \le 1$; for acceleration, $-1 \le s_a \le 0$. Note $s_b = 0$ and $s_a = 0$ represent a freely rolling wheel while $s_b = 1$ represents a locked wheel skid ($V_P \neq 0$ and $\omega = 0$) and $s_a = -1$ represents wheel spinning with the wheel center not moving ($\omega \neq 0$ and $V_C = 0$). All other values of s_b and s_a represent intermediate values of slip of the contact portion of the tire relative to the pavement surface. In reality, tangential contact shearing stresses and normal (perpendicular) contact pressures are nonuniform [2] as is the slip distribution over the contact area. Consequently the wheel slip s represents some sort of averaged value. Figure 2 shows a typical family of longitudinal tire force curves for different levels of sliding coefficients μ_x and fixed normal force F_z for both braking traction ($0 \le s_b \le 1$) and acceleration traction ($-1 \le s_a \le 0$). Acceleration forces usually do not reach the same level as braking typically because of vehicle engine torque limitations.

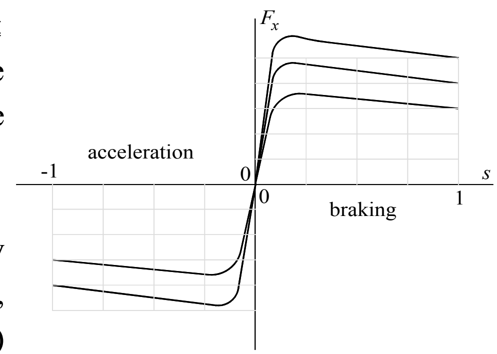

Figure 2. Typical longitudinal tire force curves as a function of wheel slip.

Note that curves such as those shown in Figure 2 typically are shown as symmetric with respect to slip, s, (for example, see [3, 4]). However, it can be noted (from Eq 1 and Eq 2) that they are not symmetric with respect to the wheel's angular velocity, ω.

Factors Affecting the Sliding Friction Coefficient Tire sliding friction depends to varying degrees on a large number of factors, many of which are interdependent. Factors that affect the sliding coefficient, μ_x include the items listed in the Table. The existence and interaction of these factors makes the full understanding, characterization and modeling of tire-pavement friction an enigmatic pursuit. None of these factors is taken into account explicitly in the following analysis, though all can play a role.

Because of vehicle aerodynamic drag, tire rolling resistance and other effects, torque must be transmitted to a vehicles's drive wheels in order to maintain a constant speed. This means that a traction force in the form of a shear stress over the tire at the contact area must exist even when a vehicle is traveling at constant speed on a level road.

Table: Factors that Affect the Sliding Friction Coefficient of Tires

1. vehicle
    - size, weight
    - static & dynamic weight distribution
    - normal force between the tire and the pavement
    - pressure and pressure distribution over the tire-pavement contact area
    - nominal contact area area, actual contact area
    - suspension system characteristics
    - kinematics
        - vehicle speed
        - wheel rotational speed, wheel slip ($0 \leq s \leq 1$)
        - vehicle acceleration
2. road surface
    - material
    - slope variations
    - roughness/texture
    - compliance
    - lubrication; wet, dry
    - contamination
    - consistency
3. temperature
    - ambient air
    - ambient tire
    - contact region
4. tire
    - construction materials
    - construction, radial/bias ply
    - chemical composition
    - elastomeric properties
    - hardness
    - tread depth - tire wear
    - age, condition
    - tread and sidewall design
    - tire inflation pressure

In an effort to relate the underlying causes of tire friction through consideration of the many forms of material interaction of a tire in contact with a rigid surface, Kummer [5] lists three sources of sliding resistance, adhesion losses, deformation losses and cohesion losses. Deformation losses are the result of energy losses in the form of hysteresis that accompany cyclic, normal (perpendicular) material deformation in the tire's elastomeric (viscoelastic) material. Adhesion losses are those associated with the attraction forces of the rubber and pavement over the contact area(s). Cohesion losses are only briefly mentioned and are summarily disregarded because of the differences in pavement and tire materials. Ultimately, Kummer's theory of tire friction is based on two sources or mechanisms of energy dissipation that are responsible for skid resistance, or what is referred to as tire "friction". These are adhesion and hysteresis.

It is argued here that adhesion plays no role in tire friction. It is also argued that hysteresis is related directly to the angular velocity of the tire. Based on these concepts, a somewhat different theory is proposed. The approach is phenomonological and leads to a simplified model of how the braking and acceleration forces behave rather than a theory of friction. Regardless, these concepts are proposed for the purposes of initiating discussion about how friction between tires and pavements acts, not a detailed, experimentally verified theory.

ADHESION:

The term "adhesion" is often misused particularly in the tire mechanics literature. In some cases adhesion is meant to describe an attraction force over the tire pavement contact area. In other cases it is intended to convey a condition of no slip or resistance to slip. More broadly, the scientific uses of the term are based on a concept of a tensile force developed over and due to physical effects at a contact interface. These lead to the concepts and terms such as pull-off force, stickiness, adhesive, etc. There are five forms of adhesion [6] which can be listed and described as follows.

1. *Mechanical Adhesion* is where two materials are mechanically interlocked. Sewing forms a mechanical bond, velcro forms another, and some textile adhesives form a third.
2. *Chemical Adhesion* is when two materials are joined by a compound. The strongest is where atoms of the materials swap (ionic bonding) or share (covalent bonding) outer electrons.
3. *Dispersive Adhesion*, also known as *Adsorption*, is where two materials may be held together by van der Waals forces and follows from molecular attraction (and repulsion) according to the Lenard-Jones potential. A van der Waals force is the attraction between molecules that have positive and negative polarity. Polarity may be a permanent property of a molecule or can occur in molecules as the random movement of electrons, as a temporary concentration of electrons at one end.
4. *Electrostatic Adhesion* is where materials may pass electrons to form a difference in electrical charge at the contact area. This results in a structure similar to a capacitor and creates an attractive electrostatic force between the materials.
5. *Diffusive Adhesion* is where some materials merge at the joint by diffusion. This may occur when the molecules of both materials are mobile and soluble in each other.

Of all of these forms of adhesion, the ones that could apply to dynamic contact between tires and pavement are dispersive adhesion and electrostatic adhesion. Although it is known that tires can gain electrostatic charges, Kummer [5] and others dismiss electrostatic adhesion as a significant factor since electrostaic forces tend to be very sensitive to relative humidity and the presence of liquids such as water. Humidity typically is not found to be significant factor for tire friction. This leaves dispersive adhesion. This type of adhesion has been found to form significant bonds for microparticles (particles in a nominal size range of 1 to 100 μm). However the force of adhesion for contact of large objects has been found to be insignificant [7]. For objects in contact [8] electrostatic forces are generally proportional to a characteristic size or diameter, d, or the diameter squared, d^2. Adhesion forces are proportional to d, and gravity forces are proportional to d^3. For microparticles, electrostatic and adhesion forces can be significant compared to gravitational forces. However, for objects as large as tires, gravitational forces (static and dynamic normal forces) are orders of magnitude greater than the others; electrostatic and adhesion forces are negligible. In addition, surface roughness, even at the micro level, can drastically reduce the effects of adhesion to where it is no longer significant [9]. In fact, Cheng, Brach and Dunn [9] show that surface roughness alone can reduce adhesion forces to nearly 1% of their smooth micro contact values. Grosch [1] and others state that adhesion plays a major role in rubber friction for smooth rubber specimens in contact with glass but that tire pavement friction process is based on a classic cyclic hysteresis mechanism. It is critical to note that dispersive adhesion is a self-induced force at the contact region (see Fig 1).

Another factor that plays a role in tire pavement friction is that of the lubrication effect of the "fluid film" that develops during sliding of a tire over a pavement. Under the conditions of severe sliding, Grosh and Sakai [1,10] discuss the heat generated over the contact surface and its lubricating effect. Such interface temperatures reach and exceed the softening temperature of asphalt (~ 95 C) and even well into the 100 C to 200 C range [10]. Under these conditions a film forms between the tire's surface and the asphalt surface which can cause softening, melting and material transfer. Such conditions would virtually destroy any ability for adhesion forces to develop and exist between the tire and road surface.

Consequently the concept and mechanism of adhesion is unlikely to play any significant role in the development of tire-pavement traction forces.

Tire materials are elastomers and it is well known that hysteresis is an important dynamic effect. The hypothesis presented here is that although the resistance to sliding between a tire and pavement is an extremely complex process, it can be viewed simply as a constant frictional force at the contact surface and that viscoelastic properties (and other effects) can enhance this resistance to sliding, that is, supplement friction. So the "sources" of friction itself are not investigated but rather a proposal is proffered as to how hysteresis enhances elastic friction. An approach similar to Kummer's [5] is followed where linear viscoelastic theory is used to relate an average force to the dissipative properties of the rubber.

CLASSICAL RIGID BODY FRICTION LAWS:

The classical laws of friction between planar surfaces of two rigid bodies in contact are well known. The laws typically are referred to as Coulomb's laws of friction. These also are referred to as the laws of dry friction to distinguish them from the mechanics of lubricated sliding. According to Coulomb's laws [11] the frictional force between contacting rigid bodies

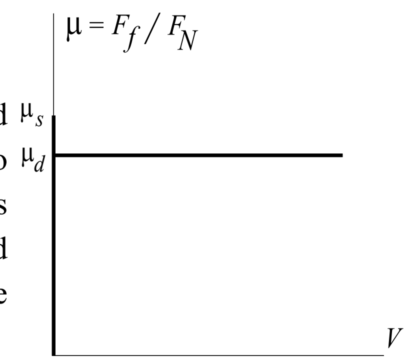

Figure 3. Idealized rigid body friction as a function of sliding velocity

1. is directly proportional to the force compressing the bodies (normal force),
2. is independent of the area of contact,
3. is largely independent of the relative velocity of sliding,
4. depends on the nature of the contact surfaces and the materials of the rigid bodies.

The ratio, F_f / F_N, of the frictional force, F_f, to the normal force, F_N, is called the coefficient of friction, μ. For given materials and surface conditions, the value of μ for impending motion often is found to be greater than the corresponding value of μ for established motion. Figure 3 illustrates the concepts of dry friction including the coefficient of static friction, μ_s, and the coefficient of sliding, or dynamic friction, μ_d. A frictional theory for dry friction of flexible belts on pulleys and cables wrapped over cylinders has been developed by extending Coulomb's rigid body laws.

TIRE FRICTION FOR ELASTIC CONTACT:

Bilinear Friction Model: An elastic law of friction, called elastic contact friction, is proposed here. It is for controlled sliding, or slip, of a wheel with a deformable tire over a relatively rigid surface. The model consists of two parts. The first combines the limiting aspect of the solid friction model with a finite initial slope to represent the effect of tangential elasticity of the tire. A second part represents the effect of hysteretic dissipation associated with cyclic/harmonic shear deformation in the tread in the region of contact with the pavement.

Figure 4 shows the proposed idealized elastic contact friction model that takes flexibility of the tire into account using a linear initial slope followed by a constant limiting force corresponding to a sliding friction coefficient, μ_x, times the normal force, F_z. This is a bilinear model whose equation can be written as:

$$F_x = \begin{cases} C_s' s, & 0 \le s \le s_0 \\ \mu_x F_z, & s_0 \le s \le 1 \end{cases} \qquad (3)$$

where C_s' is an experimentally determined stiffness coefficient equal to $\mu_x F_z / s_0$.

The concept of static friction does not have a place in tire-road forces, with the possible exception of a vehicle at rest vehicle (with locked wheels) being put in motion by an external towing force. At the road contact area, the tire's chord length is always shorter than the original, undeformed arc length of a rolling tire. So for a moving vehicle there is relative dynamic slipping or relative tangential motion (along and across the contact interface) even when braking or acceleration forces are not applied [12].

Hysteresis: Hysteresis is claimed to be an important contributor to frictional drag [1,5]. Hysteresis in general has been studied and observed as a process associated directly with friction [13]. The source of the hysteresis in tires can be from one or more of the following: 1) local, normal (perpendicular) deformation due to elastomeric compliance to pavement asperities and surface texture at the contact area, 2) to random cyclic stick-slip frictional phenomenon over the contact area and over asperities, 3) to elastomeric shearing deformation as

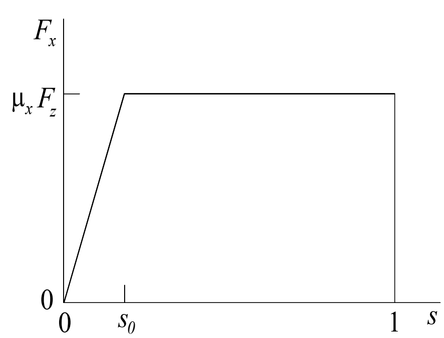

Figure 4. Proposed idealized frictional force for an elastic solid sliding over a rigid surface.

portions of a rotating tire continually and cyclically pass through the contact area and 4) through irregular interaction with transverse tread grooves, wear bars, ply geometry, etc. and coupling with brake pad-disc stick-slip vibrations.

For both a steady state rolling and a sliding tire, a normal pressure distribution, p_z, exists over the contact surface (see Fig 1) and typically is represented by a single equivalent point force, F_z. A similar, tangential pressure distribution exists in the x direction (see, for example [14]) and is represented by the single equivalent point force F_x. The pressures are equivalent to applied stresses over the contact interface. In turn, these applied stresses develop stresses internal to the rubber tread (see Fig 5). According to the theory of deformable bodies, changes in normal stresses are accompanied by shearing stresses, that is, $\sigma_z = - p_z$. Consequently, the applied tangential shearing stresses in the x direction due to friction as well as the change in normal stresses, $\partial\sigma_z/\partial z$ develop a shearing stress distribution throughout the tread in the region of contact. These shearing stresses are dynamic and cyclic (with a variety of frequencies) and are associated here with hysteresis.

For locked wheel skidding, any cyclic stresses are associated with stick-slip oscillations over the local contact area and with compliance to asperities. In fact, it has been demonstrated [15] that the frictional process itself induces harmonic waves in the region of the sliding contacting surfaces. Compressive, cyclic stresses normal to the pavement surface occur in the contact region (including compliance over asperities) during brake-free motion likely are small (because of low contact pressure values and also because of side wall compliance). Despite being small, these do contribute to rolling resistance. Finally, as a matter of interest, note that the shearing stresses, τ_{xz}, that act over the sliding interface on a skidding vehicle are of the same order of magnitude as the normal stresses, $\sigma_z = - p_z$.

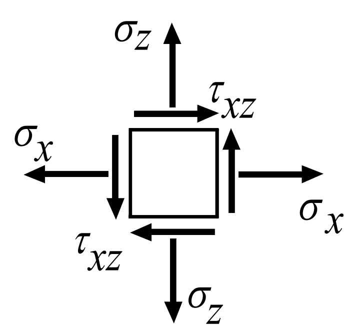

Figure 5. Stresses acting on a typical internal element of tread.

At this point attention is devoted to the cyclic shearing deformation that occurs in the tire at the contact region (see Fig 1) during braking due to the sources of hysteresis listed above. The frequencies (fundamental and harmonics) of such elastic shearing deformation in the rubber are proportional to some multiple of the rotational velocity, ω, of the tire. That is, $\omega_s = N\omega$ where ω_s corresponds to each of the many frequencies of harmonic shearing deformation in the tire in the contact region and N is a constant greater than 1. For example, Breuer, et al., [16] show that the tread element deformation as a function of time in the direction of heading of the tire changes from a near sinusoidal form at zero slip to a near constant with a significant amount of relatively high frequency random variations when a slip of $s = 1$ is reached.

A Kelvin-Voight viscoelastic model is used to model the hysteresis as done by Kummer [5]. The viscoelastic energy dissipated per cycle, W_d, when undergoing a damped harmonic oscillation is given by [17]

$$W_d = \pi D \omega_s X^2 \qquad (4)$$

where D is the damping coefficient, ω_s is a forcing frequency and X is the amplitude of the oscillation. The amplitude X is a function of the magnitude of the applied force, $X(F_0)$. An average force, F_h, corresponding to the work associated with the energy loss per cycle is

$$F_h = \pi D \omega_s X / 2 \qquad (5)$$

An important feature of this force is that it acts tangent to the tire-road interface and interacts with the frictional force. Obviously, if there is zero friction, $\mu_x = 0$, then F_h must also be zero. This implies that F_h is directly related to $\mu_x F_z$ and further implies that in its simplest form

$$F_h = K \omega_s F_x \qquad (6)$$

where K is some constant and F_x is from Eq 3. **That is, the retarding force, F_h, due to hysteresis is proportional to the frequencies of elastic shearing deformations and to the steady value of the elastic frictional force (Fig 4)**. The total force is the combination of the hysteresis force, Eq 6, added to the bilinear friction force (Eq 3). The result is shown in Figure 6 where for illustration purposes the constant K is chosen to produce a maximum force approximately 20% higher than $\mu_x F_z$. The actual values of K for various factors must be determined experimentally.

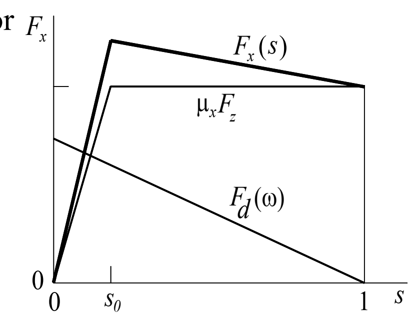

Figure 6. Idealized braking friction force.

Note that from Eq 1, it is easy to show that for braking

$$R\omega / V_C = 1 - s_b \qquad (7)$$

For acceleration

$$R\omega / V_C = \frac{1}{1 + s_a} \qquad (8)$$

In both cases ω is a function of the wheel slip and the forward speed of the wheel.

Since the sources of the vibrations induced in the tire tread in the contact region are multiple and varied, they possess a pseudo random nature. Note that according to the proposed mechanism, the hysteretic component of F_x is directly related to the tire rotation speed, ω, where $\omega = V_P/R$. Consequently F_x depends on ω since $\omega_s = N\omega$ and the vehicle speed. This implies that the initial slope (tire stiffness) is increased by the hysteresis. If the BNP model [18] is used to replace the idealized bilinear elastic friction force, the hysteresis is then added and the curves normalized, the result is shown in Figure 7. Figure 7 also illustrates (dashed curve) how additional energy loss mechanisms such as proposed by Grosch [1] due to interface temperature effects will additionally decrease the force.

The lack of symmetry with respect to ω (and V_C) displayed by Eq 7 and Eq 8, is illustrated in Fig 8. If hysteresis plays an important role in longitudinal tire forces and hysteresis is directly related to ω and V_C, then symmetry as depicted in Fig 2 should not be expected. Perhaps what is perceived as symmetry is due more to the nature of the measurements. Canudas-de-Wit [14] points out that the dependence of static plots of force-slip curves (F_x) on vehicle velocity (and ω) are found in the literature and that it is impossible for V_C and ω to be controlled independently during normal driving conditions. For this reason, and since braking and acceleration longitudinal traction forces depend differently on ω, hysteresis could affect braking and acceleration traction forces differently. This could explain why (anecdotally) acceleration marks often appear darker than braking tire marks. For most vehicles traveling at highway speeds (> 60 kph) it should be kept in mind that both acceleration and braking take place on the initial, linear portion of the F_x curves. Under such conditions, the major influence of hysteresis is an increase in the initial slopes of the F_x curves.

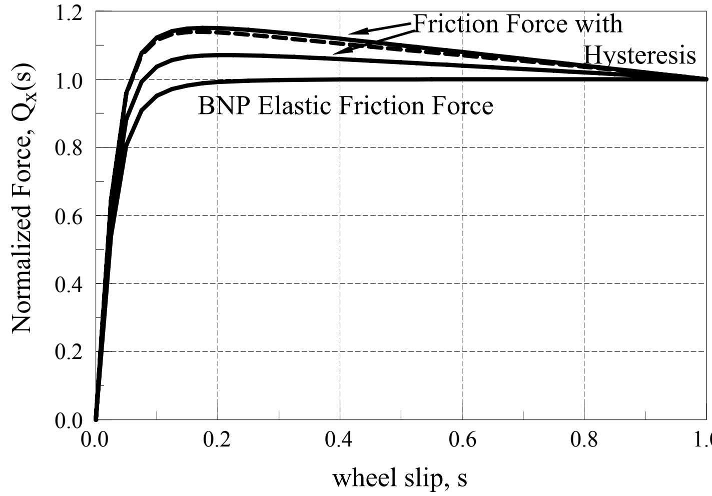

Figure 7. Hysteresis added to the elastic contact friction model represented using the BNP model (dashed curve simulates additional temperature effects during hard braking)

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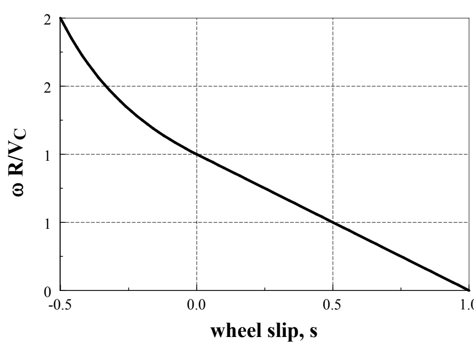

Figure 8. Relationship of wheel rotational speed, ω, and wheel slip, *s*.

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