

The Relationship Between Tire Mark Striations and Tire Forces

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ABSTRACT

Tire mark striations are discussed often in the literature pertaining to accident reconstruction. The discussions in the literature contain many consistencies, but also contain disagreements. In this article, the literature is first summarized, and then the differences in the mechanism in which striations are deposited and interpretation of this evidence are explored.

In previous work, it was demonstrated that the specific characteristics of tire mark striations offer a glimpse into the steering and driving actions of the driver. An equation was developed that relates longitudinal tire slip (braking) to the angle of tire mark striations [1]. The longitudinal slip equation was derived from the classic equation for tire slip and also geometrically. In this study, the equation for longitudinal slip is re-derived from equations that model tire forces. Human Vehicle Environment (HVE), a common accident reconstruction and vehicle dynamics simulation software package, was then used to compare striation direction as predicted by the striation slip equation to tire force direction in the simulation.

This paper focuses on discussions about striations in the literature and the relationship between tire mark striations and tire forces. A companion paper, "Tire Mark Striations: Sensitivity and Uncertainty Analysis", focuses on the practical use of striation evidence for accident reconstruction purposes [2].

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INTRODUCTION

Pre-impact tire marks associated with a crash typically fall into one of two categories: skid marks or yaw marks. Skid marks are deposited by vehicles traveling straight that are braked aggressively. In response to the braking, the tires can slip longitudinally and deposit rubber on the roadway. Yaw marks can be generated when a vehicle develops a slip angle, or a discrepancy between their heading direction and velocity direction. As the tire slides sideways, rubber is deposited on the roadway.

Upon closer inspection of tire marks, it can often be seen that the marks contain a collection of smaller marks, called striations. In the case of no braking, yawing tires are simultaneously rolling and sliding and the striation marks created run at an angle to the tire mark. These striation marks are aligned at an angle perpendicular to the tires heading direction in the absence of braking (parallel to the rotational axis of the tire). In the case of full braking, or lock up, the striations are aligned with the tire mark, or parallel to the wheel hub velocity direction [1].¹ Discussions of tire mark striations appear in the technical literature dating back to at least 1980. This literature was reviewed and summarized in the first section below.

In previous work, theoretical models for tire slip angle and longitudinal slip were developed [1]. Equation 1 can be used to

calculate longitudinal slip, a mathematical description of braking, using tire mark striations. In Equation 1, α is the slip angle of the tire and θ is the angle of the striation mark, as illustrated in Figure 1.

$$S = \frac{\tan \alpha}{\tan(\theta + \alpha)}$$

(1)

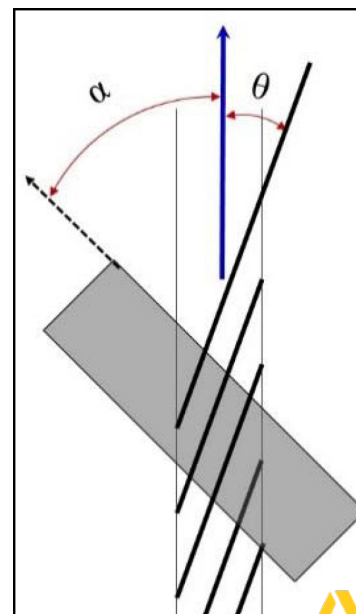


Figure 1. Tire depositing a yaw mark.

¹ Throughout this paper, the term "full braking" refers to wheel lockup, or when the rotational velocity goes to zero. This level of braking is consistent with full brake application in a non-ABS equipped vehicle.

Full scale vehicle yaw testing was conducted to validate this equation. It was found that the model could quantify the braking actions of the driver at the time the tire marks were being deposited. A full derivation of the equation and testing results were published with the Society of Automotive Engineers in 2009 [1].

The tires used in these tests were chosen specifically for their large shoulder block tread pattern, which are similar to tires that are regularly in use on SUV's and light trucks. Tires of this type produce tire mark striations that are easier to identify than tires with less aggressive shoulder patterns. It was found that the spacing of the striations was directly related to the spacing of the tread shoulder blocks. Specifically, the tire tested had 58 shoulder blocks around its circumference and the length of 58 striations was related to the circumference of the tire through the tires slip angle. The tread shoulder blocks also exhibited heavy wear consistent with leaving the marks. Figure 2 depicts the shoulder tread blocks as well as the shoulder wear on a tire as result of the testing. In these tests, the striations were created by the shoulder blocks of the tire.



Figure 2. Shoulder block wear as a result of yaw testing.

The striations indicate the path of individual portions of the tire. Since frictional forces act to oppose the direction of motion, the striations are also indicative of the direction of the frictional force acting on these portions of the tire. Assuming that the striation direction is equivalent to the force direction, an expression for the amount of longitudinal slip (braking) can be developed from equations that model tire forces. This derivation is developed in the second section of this publication. To further confirm the relationship between tire force and striation direction, a vehicle dynamics simulation software package, HVE, was used to compare simulated tire force direction with predicted striation direction. This comparison is the focus of the third section.

STRIATED TIRE MARKS IN THE LITERATURE

A review of the literature on the topic of striated tire marks was conducted. Striation marks are touched upon in many publications, most notably in the literature focused on the critical speed formula.

The literature review includes publications in which novel ideas regarding tire mark striations are introduced or tire mark striations are discussed to a significant degree. The literature reviewed is generally divided within two categories. The literature either examines the process by which the striations are deposited, or examines what striations tell us about driver steering, braking, and acceleration.

Within the literature, there are disagreements regarding the manner in which striations within tire marks are created as well as to what the striations indicate.

Two plausible theories have been proposed which describe how striations are deposited: In-plane buckling of radial tires [3,4,5,6], and point loading of the shoulder tread blocks [1,3,7,8,9,10]. It was shown that in-plane buckling can occur in the contact patch, especially when the tire has no tread pattern [4,5] or the tire pressure has been reduced to very low values [3]. The results by Yamazaki suggest that bias ply tires will not deposit striations because bias ply tires are not susceptible to in plane buckling [4,5]. However, Reveley successfully deposited striated tire marks using a bias ply tires [9]. Reveley's results are consistent with the tread shoulder blocks being involved in the creation of striated marks. Gardner's testing with large tread block tires also created striated marks. However the testing with highway tires without a defined tread block pattern did not create striation marks (unless the tire pressure was reduced substantially) [3].

These authors have had a similar experience in attempting to create striations. Testing involving tires with a more aggressive shoulder block pattern did deposit clear striations, tires without an aggressive shoulder block did not (unless the tire pressure was reduced substantially). A mathematical relationship between the striation marks and the shoulder tread blocks was also found by Beauchamp, further suggesting that the shoulder tread blocks made the marks [1]. The shoulder tread blocks from Beauchamp's testing also exhibited heavy wear, again consistent with the tread blocks depositing the striation evidence.

The research reviewed suggested that in-plane buckling can occur, but is more likely to be the source of striation marks if deposited by a tire with no tread pattern or an underinflated tire. Tires with more aggressive shoulder tread block patterns are more likely to deposit striated tire marks when properly inflated. Examination of wear to the tire can reveal whether in-plane buckling or the tread blocks deposited the marks (Figures 2 and 3). Figure 3 depicts wavy wear to the tire as a result of radial tire in-plane buckling from testing performed by Yamazaki [5].

The mechanism that created the striations can be important or of no consequence depending on which analysis technique is used. In 2009, Beauchamp introduced two methods for analyzing striations. The first called the longitudinal slip equation, used to determine braking, which will be explored in more detail in this study. The longitudinal slip equation considers the slip angle of the tire and angle of the striation. As will be discussed, the striation direction is consistent with the force direction. This is true whether the tread blocks, buckling or a combination of the two create the marks. Therefore, analysis of striations with the longitudinal slip equation is valid independent of

the mechanism that creates the marks. The second analysis method uses the slip angle equation to determine steering. The slip angle equation also considers the spacing between the striations and assumes that the striations are created by the tire shoulder blocks. In practice, the longitudinal slip equation has been found to be relatively easy to implement compared to the slip angle equation.

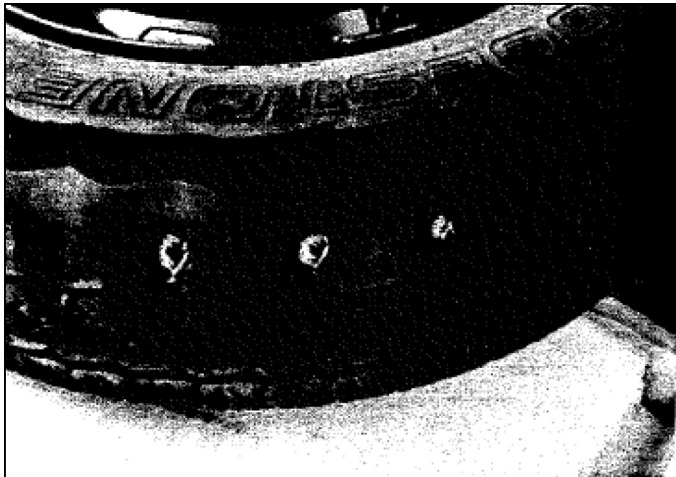


Figure 3. Tire wear to a radial tire as result of in-plane buckling. (Figure 25 from Yamazaki [5])

It is generally agreed upon that striation marks are angled away from the tire mark in the absence of braking and more in-line with the tire mark as the brakes are applied. However, there are several specific differences in the literature. These differences are primarily due to some researchers not considering the heading of the tire in their analysis. As will be discussed, the striation direction is indicative of the force direction on the tire. This being the case, the heading of the tire at the time the striations were deposited is an important consideration. Testing performed by Beauchamp et al. confirmed that striations are perpendicular to the tire heading in the absence of braking. Although this also turns out to be “angled” to the tire mark, the heading of the tire (defined by or the orientation of the vehicle on the tire marks for a rear tire) is required to determine whether the brakes are applied or not. In other words, the angle of the striation compared to the tire mark is by itself not enough to determine braking other than a full lockup up versus not full lockup generalization. The angle of the striation in relation to the tire heading and tire mark direction at the time it was deposited can allow for determination of braking or acceleration.

A full summary and discussion of the literature can be found in [Appendix A](#).

DERIVATION OF THE STRIATION LONGITUDINAL SLIP EQUATION - TIRE FORCE MODELING

When a vehicle yaws, the tires can both roll and slide sideways. Each tread block slides across the roadway depositing a striation mark on the pavement. This sliding of the tread blocks on the road creates friction, and it is the frictional force between the tires and the roadway that influences the vehicle dynamics. Since frictional forces oppose the direction of motion, the striations are indicative of the

direction of the tire forces. If the tire force direction and striation direction are equal, then expressions for longitudinal slip from striations can be derived from tire force modeling equations.

Tire Modeling

Pacejka introduced empirical equations to model the tire's longitudinal and lateral properties [11]. Equations 2 and 3 are the Pacejka equations for normalized longitudinal and lateral tire forces, respectively. The longitudinal force is a function of longitudinal slip, s . The lateral force is a function of slip angle, α . In the equations, B , C , D , and E are curve fitting coefficients, which are different for longitudinal and lateral forces. Table 1 depicts the values of these coefficients for a typical passenger car tire [12]. The variable K is a scaling parameter as is set to a value of 100 to convert the lateral and longitudinal slip ratios to percentages.

$$F_x(s) = D \sin\{C \tan^{-1}[B(1 - E)Ks + E \tan^{-1}(BKs)]\} \quad (2)$$

$$F_y(\alpha) = D \sin\{C \tan^{-1}[B(1 - E)K\alpha + E \tan^{-1}(BK\alpha)]\} \quad (3)$$

Table 1. Pacejka Parameters.

Parameter	Value for Longitudinal Tire Force Curve	Value for Lateral Tire Force Curve
B	0.118	0.093
C	1.398	1.498
D	1.152	1.124
E	-0.128	0.573
K	100	100

Equations 2 and 3 are plotted with the parameters in Table 1 in Figures 4 and 5, respectively [12]. Figure 4 is the normalized longitudinal force, plotted against longitudinal slip percentage, indicative of straight line braking. In Figure 5, the normalized lateral force is plotted against slip angle, indicative of a tire yawing without braking.

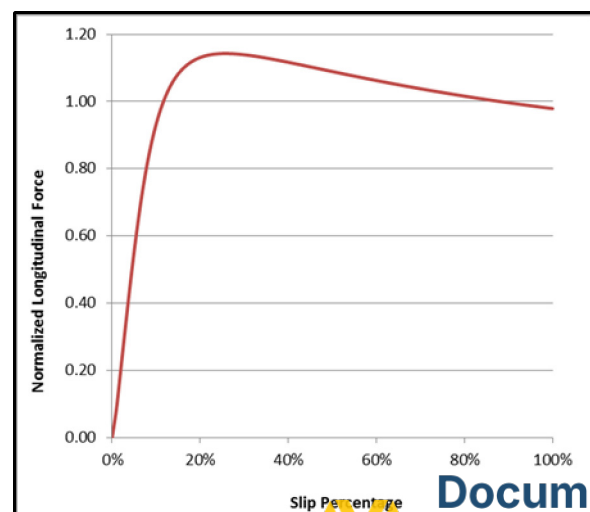


Figure 4. Typical passenger car tire longitudinal force curve.

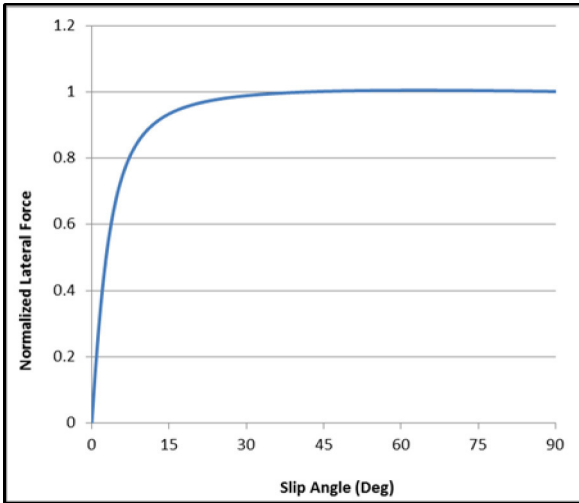


Figure 5. Typical passenger car tire longitudinal force curve.

The normalized tire plots are useful for accident reconstruction purposes. If the friction of the roadway/tire interface is known, then the deceleration of either a braking or yawing vehicle can be calculated. This deceleration can then be used to investigate vehicle speed during an accident. Brach proposed a method for using the lateral and longitudinal plots together in the combined braking and yawing scenario [13]. Equation 4 is the longitudinal force as a function of longitudinal slip and slip angle. Equation 5 is the lateral force, also as a function of longitudinal slip and slip angle. These equations are referred to as the Nicolas-Comstock-Brach (NCB) model in the literature.

$$Q_x = F_x(\alpha, s) = \frac{F_x(s)F_y(\alpha)s}{\sqrt{s^2(F_y(\alpha))^2 + (F_x(s))^2 (\tan \alpha)^2}} \quad (4)$$

$$Q_y = F_y(\alpha, s) = \frac{F_x(s)F_y(\alpha) \tan \alpha}{\sqrt{s^2(F_y(\alpha))^2 + (F_x(s))^2 (\tan \alpha)^2}} \quad (5)$$

Once again, s and α are the longitudinal slip and slip angle, respectively. $F_x(s)$ and $F_y(\alpha)$ are the Pacejka equations above, 4 and 5.

Striation Equation Derivation

Figure 6 depicts a tire in the midst of a yaw while braking. The tire is moving up the page as indicated by the blue arrow. In Figure 6, the longitudinal and lateral forces are indicated with Q_x and Q_y , respectively. The total force, Q , which acts at an angle δ from the tire heading, is also indicated. α is the tire's slip angle and θ is the angular difference between the tire hub's velocity direction and the force direction. Therefore, δ is equal to the sum of α and θ .

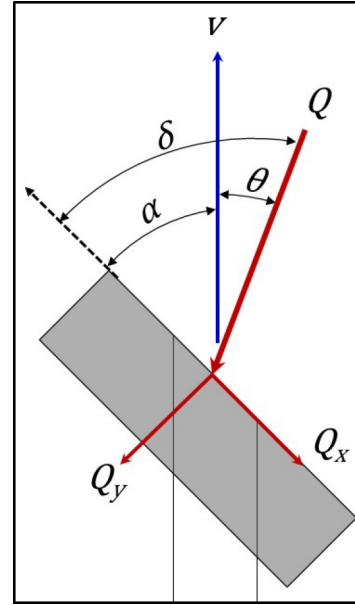


Figure 6. Tire in yaw with brakes applied.

Assume now that the tire force is aligned with the striation that was deposited by that yawing tire. The angle θ between the velocity direction and the force direction would also be the striation angle. Using Figure 6, the angle θ and the forces Q_x and Q_y are related as follows.

$$\delta = \alpha + \theta = \tan^{-1} \left(\frac{Q_y}{Q_x} \right) \quad (6)$$

The NCB expressions for Q_x and Q_y are then substituted, and the equation can be solved for longitudinal slip, s .

$$\alpha + \theta = \tan^{-1} \left(\frac{\frac{F_x(s)F_y(\alpha) \tan \alpha}{\sqrt{s^2(F_y(\alpha))^2 + (F_x(s))^2 (\tan \alpha)^2}}}{\frac{F_x(s)F_y(\alpha)s}{\sqrt{s^2(F_y(\alpha))^2 + (F_x(s))^2 (\tan \alpha)^2}}} \right) \quad (7)$$

$$\alpha + \theta = \tan^{-1} \left(\frac{\tan \alpha}{s} \right) \quad (8)$$

$$\tan(\theta + \alpha) = \frac{\tan \alpha}{s} \quad (9)$$

$$s = \frac{\tan \alpha}{\tan(\alpha + \theta)} \quad (10)$$

$$\theta = \tan^{-1} \left(\frac{\tan \alpha}{S} \right) \quad (12)$$

In examining Equation 12, it is apparent that imaginary values of θ will result when the longitudinal slip, s , is equal to zero. Initial simulations resulted in this zero slip condition within HVE outputs due to a lack of significant figures. Engineering Dynamics Corporation, the company that created HVE, was contacted and adjustments were made to the internal HVE software code to output more significant figures. This increase in significant figures resolved the near zero slip condition.

Figure 7 depicts the motion of the vehicle every 0.5 seconds. At the start of the simulation, the vehicle is traveling at 75 mph and a right steer input causes the vehicle to yaw clockwise.

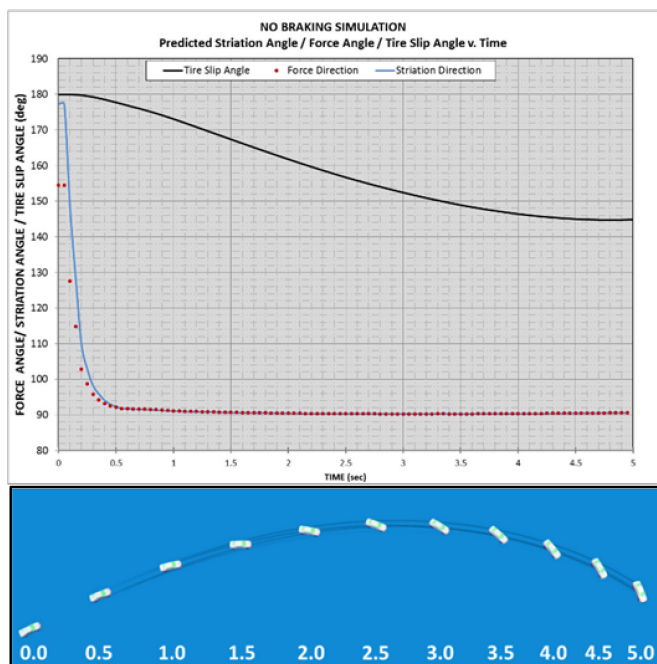


Figure 7. No braking simulation results. Force and Striation Direction for the Left Rear Tire.

The comparison between tire force direction and predicted striation direction for the rear left tire is also shown in Figure 7. During the first 0.5 seconds of simulation, the vehicle transitions into the yaw. During the yaw, the rear left tire develops a non-zero slip angle, or a discrepancy between its velocity direction and its heading direction. For graphical purposes, the supplementary angle to the slip angle of the rear left tire is plotted in black (Figure 7). For reference, a supplementary tire slip angle of 180 degrees indicates the car is traveling straight forwards. An angle of 90 degrees would result from the car sliding sideways, left side leading. The supplement of the slip angle was chosen in the plots because the force direction is opposite the velocity direction. Using the supplement of the slip angle is convenient for analyzing forces, as will become more apparent in the braking simulations. As a result of the steering input, the tire force direction, plotted in blue, becomes approximately lateral to the tire (90 degrees). This is expected, since the tire will experience lateral

loading in a yaw with no braking. During the yaw event, the predicted striation direction, depicted with the red circles in Figure 7, is also lateral to the tire (90 degrees).

During the transient phase, the first 0.5 seconds of the simulation, the tire reaches a slip angle of approximately 2 degrees and both the forces and striations approach 90 degrees. There is a difference of up to 23 degrees between the forces and striations early in the transient phase, as the initial yaw is developing. However, at small slip angles of under 2 degrees, it is unlikely that tire marks would be visible on the road so this difference would be undetectable. After 0.5 seconds, the tire forces and striations direction are approximately 90 degrees with negligible differences. In practice, the striations would be perpendicular to the tire heading direction in the absence of braking.

Yawing Vehicle Simulation - Full Braking (ABS Disabled)

For this simulation, The ABS was turned off. The vehicle's brakes were applied at approximately 3.0 seconds from 1 lb. of pedal force to 300 lb. of force in 0.2 seconds. Table 4 depicts the braking inputs and their associated times.

Table 4. Braking inputs for the full braking simulation.

Table: Pedal Force	
Pedal Force vs. time	
time (sec)	Pedal Force (lb)
0.0000	1.00
3.0000	1.00
3.2000	300.00

The steering input induced a clockwise yaw. The braking input, which occurred at approximately 3.0 seconds after the steering input began, slowed the rear left tire's rotational speed to the point of tire lock-up.

The vehicle motion and simulation results are depicted in Figure 8. Between 0.0 to 3.0 seconds, the predicted striation and force angle became saturated in a lateral direction (90 degrees). As the brakes were applied after 3.0 seconds, both the force direction and predicted striation direction align with the velocity direction of the tire hub or supplement of the slip angle.

Similar differences are noted during the initial transient phase. Once the vehicle had transitioned into the yaw (0.5 second), the striations and tire forces are aligned perpendicular to the tire, or 90 degrees, with negligible differences. As the brakes are applied, the striations and tire forces directions change towards the direction the tire is traveling (tire mark direction). In Figure 8, this transition can be seen as changing from 90 degrees to in line with the tire hub velocity direction (supplement of the slip angle). During the braking phase, the force and striation directions were within 2 degrees of one another.