

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)

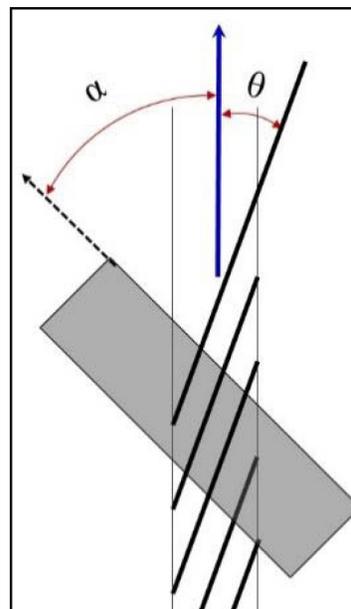


Figure 1. Tire depositing a yaw mark.

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.

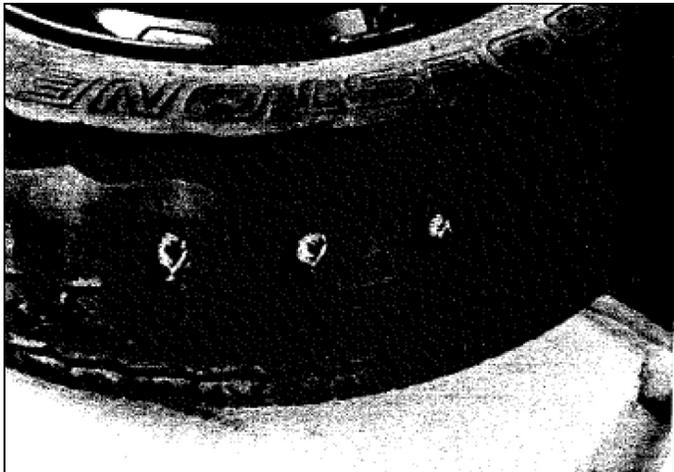


Figure 3. Tire wear to a radial tire as result of in-plane buckling. (Figure 25 from Yamazaki [5])

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.

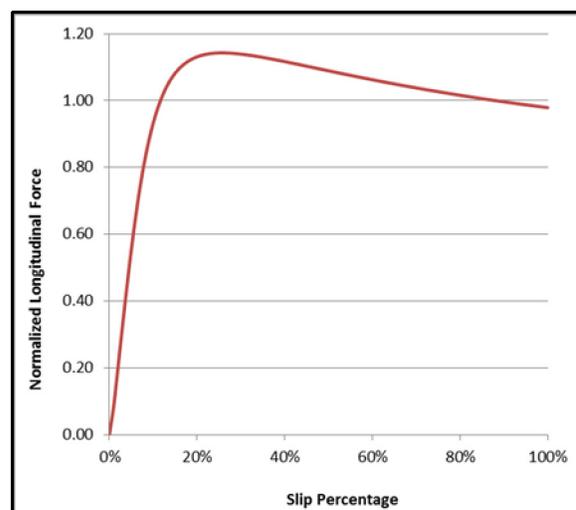


Figure 4. Typical passenger car tire longitudinal force curve.

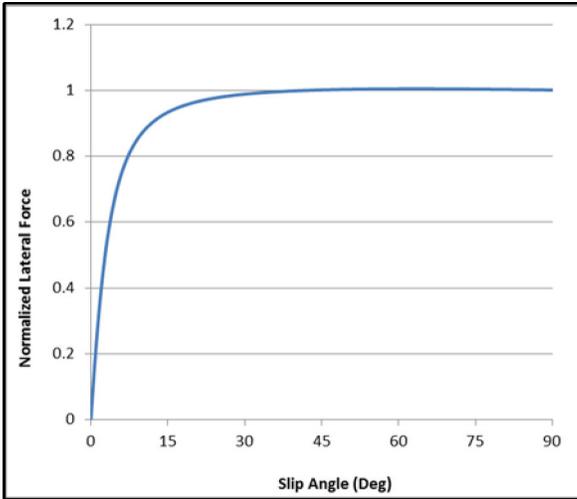


Figure 5. Typical passenger car tire longitudinal force curve.

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 theta 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 .

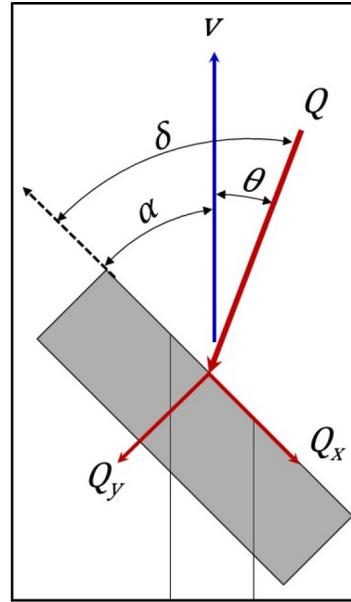


Figure 6. Tire in yaw with brakes applied.

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 .

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

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

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

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

Equation 10 is equivalent to the equation derived previously from the classic definition of longitudinal slip (Equation 1).

A COMPARISON OF STRIATION DIRECTION AND FORCE DIRECTION

In the previous section, it was demonstrated that the striation equation for braking could be derived from tire modeling equations. Next, an examination of tire force and striation direction was conducted. There are difficulties in designing a physical test where both tire forces and striation marks can be quantified. Therefore, the vehicle dynamics software package HVE was used for the comparison. Lateral and longitudinal tire forces, which give force direction, are outputs of HVE. Equation 10 can be solved for striation direction as a function of slip angle and longitudinal slip percentage. The inputs necessary to compute striation direction, longitudinal slip percentage and slip angle, are also outputs of HVE. HVE simulations can then be used to compare tire force direction and predicted striation direction.

Description of HVE

Human-Vehicle-Environment (HVE) is a computer software package designed specifically to simulate three dimensional vehicle dynamics. Within HVE the software allows the user to input roadway and vehicle geometry as well as individual vehicle characteristics. Of HVE's numerous modules, Simulation Model Non-Linear (SIMON) embodies the most sophisticated mathematical tire models and, thus, the most advanced vehicle dynamics models. Specifically, SIMON utilizes the Highway Safety Research Institute (HSRI) tire model developed by the Michigan Transportation Research Institute. Validation studies on HVE and SIMON are available in the literature [14,15,16,17].

Description of Vehicle and Scene

For this simulation study, a midsize car was chosen. Table 2 gives the vehicle dimensions. For the most part, default settings for this vehicle were used. In some runs, ABS was disabled.

Table 2. Vehicle parameters used in the simulation.

Vehicle Parameters	
Weight (lbs.)	3770
Length (in.)	191.8
Width (in.)	70.3
Height (in.)	57.1
CG from Front Axle (in.)	47.0
CG Height (in.)	21.9
Front Overhang (in.)	38.0
Wheelbase (in.)	112.3
Tire Radius (in.)	13.3
Tire Width (in.)	8.9
Front Track Width (in.)	59.6
Rear Track Width (in.)	60.0

HVE is equipped with several default road surfaces. For this study, a flat asphalt surface was chosen.

Yawing Vehicle Simulations

The vehicle was simulated traveling at an initial speed of 75 miles per hour. An abrupt right steer followed by progressively straightening the steering wheel was used to generate vehicle yaw. Table 3 depicts the steering inputs, which were used in all simulations. During the simulations, a small brake pedal pressure of 1 lb was used for purpose maintaining a rearward force on the tires. This created a longitudinal force of approximately 4 lb at the tire contact patch. Without the small braking input, lateral tire forces can periodically change between very small forward and very small rearward angles in the simulations. These changes created 180 degree phase shifts in the plots that will be presented later in the paper. The small brake force prevented the phase shifts and had a negligible effect on vehicle dynamics. The small brake force also did not change any relationships that will be discussed below, but made the plots more comprehensible. Additional braking was added in subsequent simulations, but for the purposes of discussion, no braking includes 1 lb of brake pedal force in the simulations below.

Table 3. Steering inputs in the no braking simulation.

time (sec)	Steering Angle (deg)
0.0000	0.00
1.0000	90.00
2.0000	70.00
3.0000	60.00
4.0000	50.00

Yawing Vehicle Simulation - No Braking

Within the no braking simulation, driver steering inputs are shown in Table 3 above. After the simulation was run, the tire force direction and predicted striation directions of the rear left tire were compared. This comparison was made by examining several outputs from the simulation every 0.05 seconds. The tire force direction in the tire reference frame was calculated at each time step from the longitudinal and lateral tire forces. The predicted striation direction was calculated using Equation 12, which is the equation for longitudinal slip (Equation 11) solved for striation angle in the tire's reference coordinate system. Both the longitudinal slip of the left rear tire, S , and the left rear tire slip angle, α , were outputs from the HVE simulation.

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

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

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.

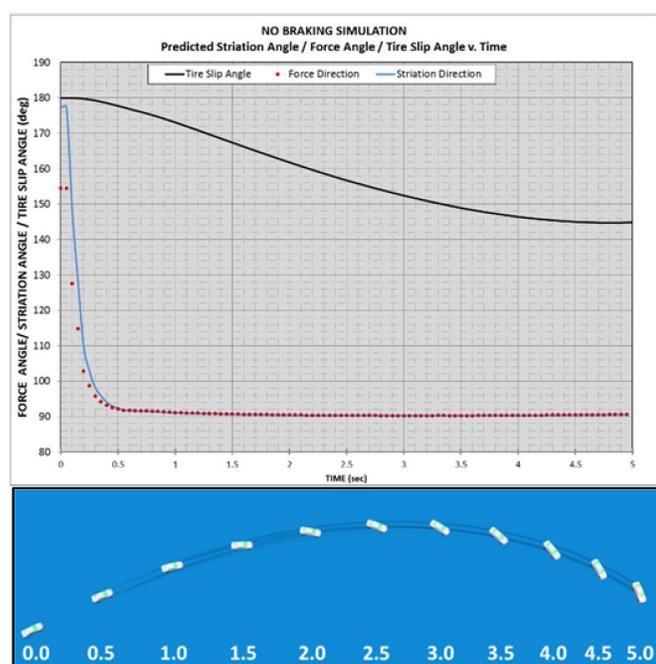


Figure 7. No braking simulation results. Force and Striation Direction for the Left Rear Tire.

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.

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.

In practice, the striations would be perpendicular to the tire heading in the absence of braking. When the brakes locked the wheels, the striations would transition to a direction parallel to the tire mark direction.

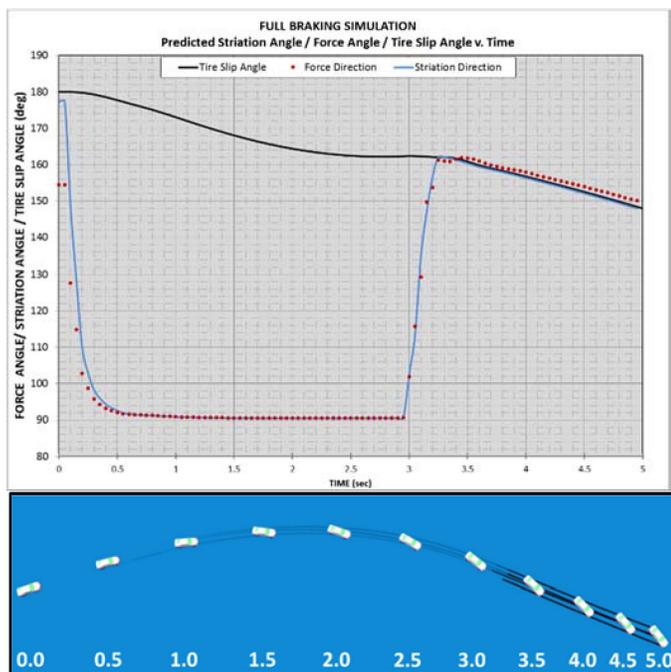


Figure 8. Full Braking simulation results (ABS Disabled). Force and Striation Direction for the Left Rear Tire.

Yawing Vehicle Simulation - Full Braking (ABS Active)

For this simulation, The ABS was turned on. The vehicle's brakes were again applied at approximately 3.0 seconds from 1 lb. of pedal force to 300 lb. of force in 0.2 seconds as described in Table 4.

The vehicle motion and simulation results are depicted in Figure 9. Between 0.0 to 3.0 seconds, the predicted striation and force angle became saturated in a lateral direction (90 degrees). The differences in the initial transient phase are again visible in Figure 9. During the yaw phase, there were negligible differences between force and striation directions. As the brakes were applied after 3.0 seconds, both the force direction and predicted striation direction start to change. The ABS then begins cycling the brakes at approximately 3.25 seconds. Both the force and predicted striation angle cycle over approximately a 10 degree range while the ABS is functioning. The force and striation directions are within 2.5 degrees of one another during this cycling.

In practice, the striation marks would be perpendicular to the tire in the absence of braking. When the brakes are applied aggressively, the striations will change to a direction more in line with the tire marks but ABS would prevent the tires from locking. The striations produced would be at an angle in between perpendicular to the tire and in line with the tire mark. Variations in the angle of the striations may be visible in the tire mark, consistent with the observations of Daily [18].

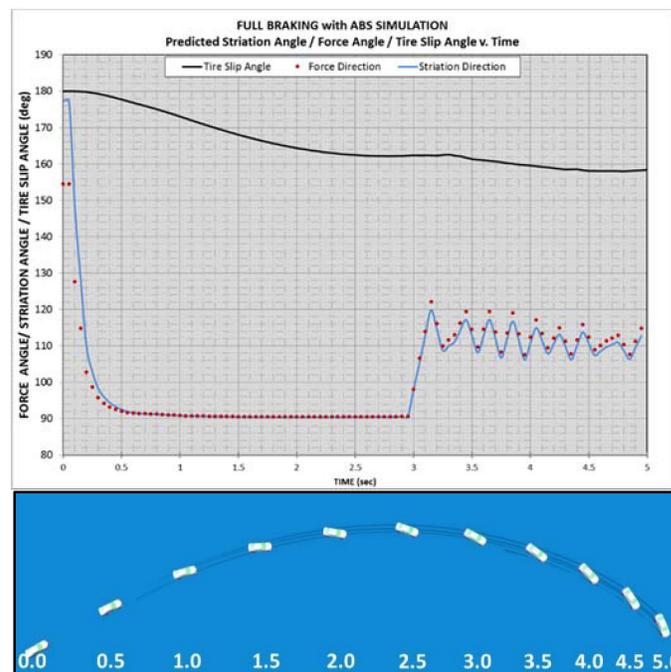


Figure 9. Full Braking simulation results (ABS Active). Force and Striation Direction for the Left Rear Tire.

Yawing Vehicle Simulation - With Partial Braking

The ABS was turned off for this simulation. During the right steer maneuver, the vehicle's brakes were gradually applied after approximately 3.0 seconds. Table 5 depicts the braking inputs and their associated times. In this simulation, the brake pedal force was increased to 60 pounds over a 2 second period.

Table 5. Braking inputs in the partial braking simulation.

Pedal Force vs. time	
time (sec)	Pedal Force (lb)
0.0000	1.00
3.0000	1.00
5.0000	60.00

The braking input, which started at approximately 3.0 seconds, slowed the rear left tire's rotational speed but did not produce full lock-up. The motion of the vehicle every 0.5 seconds is depicted below in Figure 10.

The vehicle's motion and simulation results are depicted in Figure 10. Between 0.0 to 3.0 seconds, the predicted striation and force angle became saturated in a lateral direction (90 degrees). Transient differences are again present in the first 0.5 seconds. Differences were again negligible during the pure yaw phase. As the brakes were applied after 3.0 seconds, both the force direction and predicted striation direction began change, aligning more with the tire's velocity direction. Since the tire did not lock up, the force and

striation direction never become equivalent to the tire hub direction. The force direction and striation direction were within 1.5 degrees during the braking phase.

In practice, the striation marks would be perpendicular to the tire in the absence of braking. When the brakes are applied, the striations would change to a direction more in line with the tire marks. However, there was insufficient braking to lock the tires. The striations produced after 3 seconds would be at an angle in between perpendicular to the tire and in line with the tire mark.

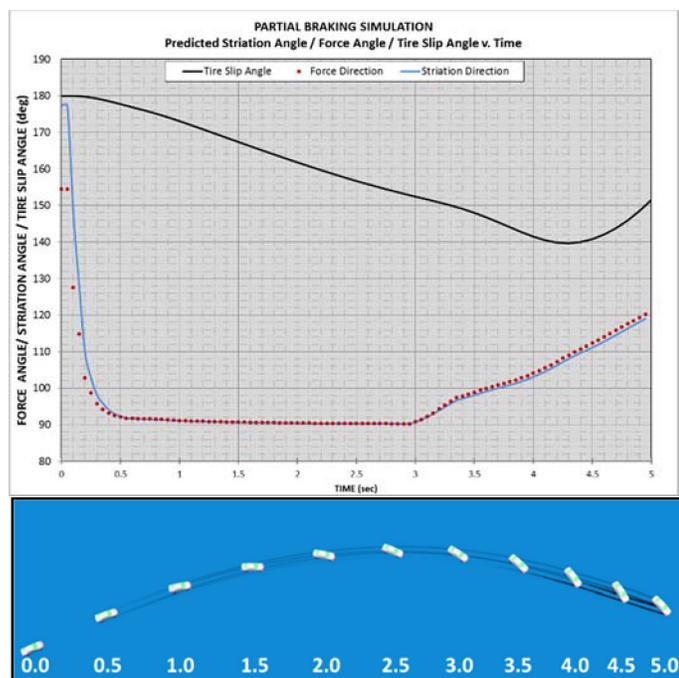


Figure 10. Partial braking simulation results. Force and Striation Direction for the Left Rear Tire.

To summarize, the striation and force direction is perpendicular to the tire in the absence of braking and transitions towards the direction of the tire mark as the brakes are applied. The trend is depicted graphically in Figure 11. The tires in Figure 11 are moving up the page as indicated by the blue arrow. The longitudinal slip can be quantified using Equation 1.

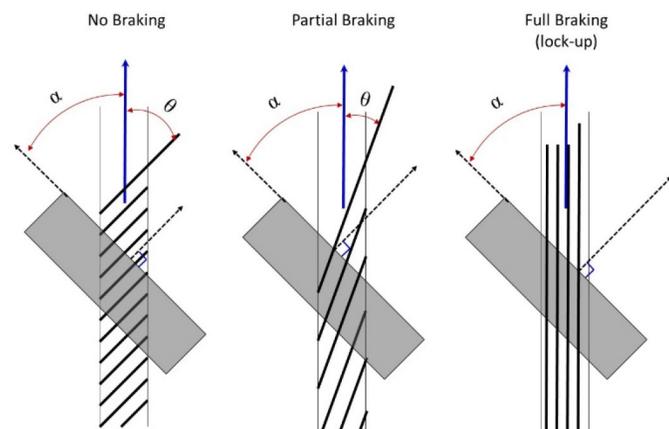


Figure 11. The effect of braking on striation direction.

Although the simulated tire force and striation directions are generally consistent, there are small differences between them, particularly when the brakes are applied or the forces are rapidly changing when ABS is active. It is likely that these differences were due in part to camber thrust forces which are included in the HVE model, but not in the striation modeling. In the case of no braking, the camber thrust forces and tire forces generated by way of the slip angle are aligned to one another, namely, they are both lateral to the tire. Under braking, the camber thrust forces are still lateral, but the braking component is applied longitudinal to the tire creating a small difference in direction between the HVE tire forces and predicted striation direction. The difference was small, consistent with the small contribution of camber thrust to the overall tire forces in radial tires [19].

CONCLUSIONS

Two plausible mechanisms for the creation of tire mark striations are discussed in the literature; point loading of the tread should blocks or in-plane buckling. Tires with aggressive shoulder blocks typically deposit clearer striations and the shoulder blocks are likely the cause of the marks. Tires with very low tire pressure or tires without a tread pattern are more likely to buckle and deposit striations in that manner. Wear evidence on the tire may allow the analyst to distinguish between the two mechanisms.

The striation equation for longitudinal slip was re-derived from a commonly used tire force model. The vehicle dynamics simulation software package, HVE, was then used to compare predicted striation direction with tire force direction for the left rear tire. Excluding the transient phase when tire marks would not be expected to be visible, the predicted striation directions and tire force directions showed good agreement. Specifically, the tire force and striation directions showed negligible differences during pure yaw and were within 2.5 degrees during combined yawing and braking. This good agreement is consistent with the fact that the striations are indicative of the path of individual portions of the tire. Since frictional forces oppose the velocity direction it was expected that the striations were indicative of force direction. Further, striations are expected to be indicative of force direction regardless of whether they are created by tread shoulder blocks, in-plane buckling or a combination of both mechanisms.

The striation and force direction is perpendicular to the tire in the absence of braking and transitions towards the direction of the tire mark as the brakes are applied.

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APPENDIX

APPENDIX A - STRIATED TIRE MARKS IN THE LITERATURE: SUMMARY AND DISCUSSION

In Baker's text, Traffic Collision Investigation, the manner in which striated tire marks are created is discussed [7]. Striations are said to be created from either gritty particles entrapped in the contact patch (between the road and the tire), or from the shoulder tread blocks (sidewall ribs). Through the progression of an individual tire mark, striations are described as nearly crosswise at the beginning, progressing into oblique marks, then becoming parallel to the mark at crossover when the tires stop rotating momentarily.

Fricke includes a discussion of tire mark striations in Volume 2 of the Traffic Accident Reconstruction Manual during an examination of the estimation of vehicle sideslip velocity [20]. Most notably, the effects of acceleration and braking on the appearance of striations were discussed and illustrated graphically. In the absence of braking, Fricke described the striation marks as being parallel to the axle of the tire that deposited the marks. It was described that braking had the effect of angling the striations more towards the tire mark. Acceleration, on the other hand, angles the striations in the opposite direction as braking, typically making them more perpendicular to the tire mark. Steering, it was said, has no effect on the angle of the striation marks. Figure A1, Exhibit 60a in Fricke, depicts the striation marks for a free rolling tire to be parallel to the axle, independent on the steer angle of the tire.

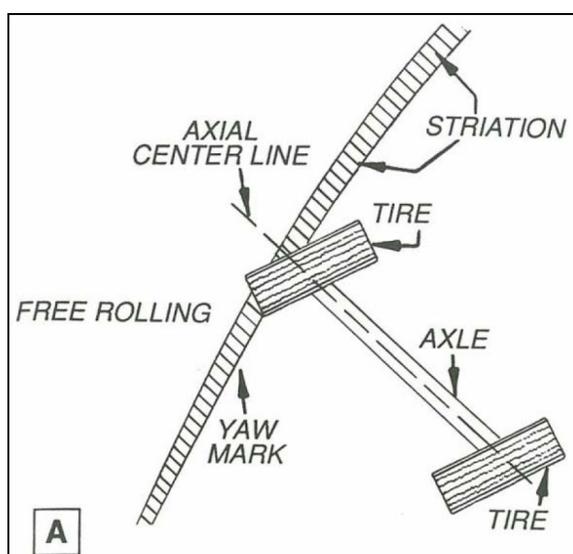


Figure A1. Exhibit 60a from Fricke, used with permission from Northwestern University. A free rolling tire depositing a striated tire mark. Note the striations are drawn at an angle parallel to the axle, independent of the steer angle. [20]

In Fricke's discussion of the striations, he reached the finding that the striations are parallel to the axle in the absence of braking and that steering does not affect striation angles. This description by Fricke holds true for small steering inputs. However, other researchers have found that striations are actually parallel to the tire axis of rotation (perpendicular to the tire heading direction) rather than parallel to the axle in the absence of braking [1, 8]. For rear tires the axis of rotation and axle are of the same direction. For front tires, the axis of rotation and axle are approximately the same for low steering angles, but diverge at larger steering angles. At low steering angles, differences in striation angle as a result of steering may not be detected. At larger steer angles, like that depicted in Figure A1 for example, the effects of steering would be more pronounced.

In 1980, Gardner et al. conducted an examination of the tire marks deposited by radial tires during three different modes; acceleration, braking and yawing [3]. Using a 1979 Chevrolet Impala, Gardner conducted swerve tests using tires with different tire tread patterns while varying the tire inflation pressure. He also utilized a "skid trailer" which allowed them to specify the normal load and slip angle of the tire while varying tread pattern and inflation pressure. Figure A2, which appears as Figure 1 in Gardner et al.'s publication, depicts the tires from the tests. Three different tires were used in the study, including one with highway tread (right), another with all-weather tread (middle) and third with a mud and snow tread (left).

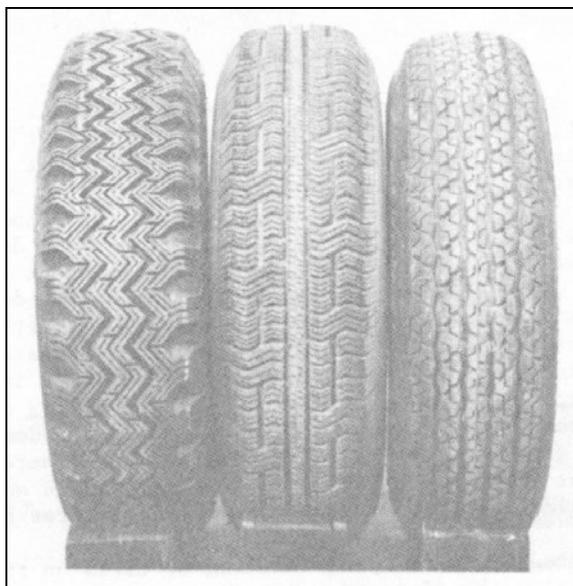


Figure A2. Figure 1 from Gardner et al. illustrating the tires used in their yaw mark testing. [3]

The mud and snow tire, on the left, had aggressive shoulder blocks. The all-weather tire, the center tire, had shoulder blocks that ran roughly lateral to the tire, but were small in size and tightly spaced. The highway tires, on the right, had a less regular tread pattern and no distinct shoulder blocks. Under normal inflation pressure, angled friction marks can be seen in the marks deposited by the highway and all-weather tires, but only the mud and snow tires appeared to deposit obvious striation marks. Gardner noted that it was the lugs on the shoulder of the mud and snow tire that were responsible for depositing the striation marks on the roadway.

Using the skid trailer, 7 tests of the highway tires were performed at varying inflation pressures. For all the tests, the slip angle and normal load were kept constant, 15 degrees and 800 lb respectively. Figure A3, which appears as Figure 20 in Gardner's publication, depicts the tire marks from each of the test. Starting from the left, the inflation pressures were 32 psi, 26 psi, 15 psi, 10 psi, 5 psi, 0 psi and 0 psi.

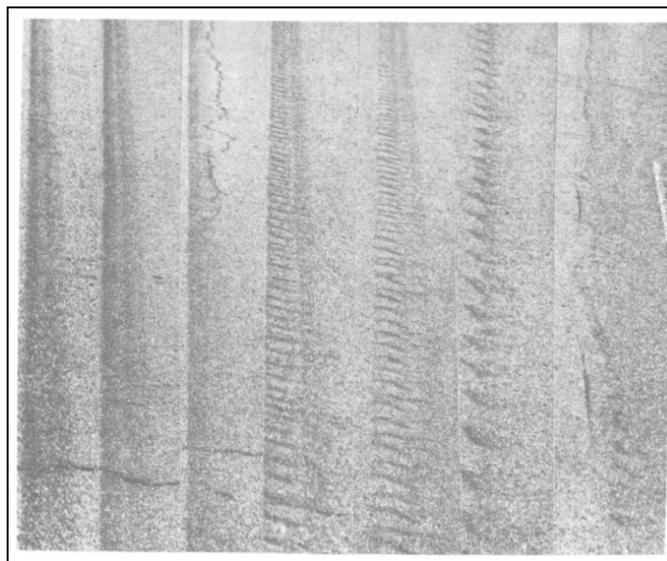


Figure A3. Figure 20 from Gardner et al. The tire mark evidence deposited on the roadway from 7 highway tire tests with varying inflation pressure. [3]

As is seen from Figure A3, the tires tested at inflation pressures of 15 psi and higher did not deposit distinct striation patterns. At pressures of 10 psi or less, however, obvious striation marks appear. Gardner concludes that these striation marks were deposited because tire deflection allowed buckling of the tire upper sidewall and shoulder area. He went on to compare these under inflated tire striations to those deposited by the mud and snow tire at regular inflation pressure, explaining that they are similar, but the spacing of the under inflated tire striations were greater. Gardner also tested a tire after removing the tread layer. The tire mark produced by this tire did not contain obvious striations.

In 1985, Ishikawa presented the JARI 2 Dimensional Automobile Collision Simulator (J2DACS), which included a discussion of striated tire marks [8]. JSDACS is a computer simulation program that considers both vehicle and occupant motion, and includes the incorporation of Sakai's tire model [21]. For a braking or free rolling tire, the yawmark angle is defined by Equation A1, which appears as Equation 30 in Ishikawa's paper.

$$\phi = \frac{\sin^2 \zeta + s \cdot \cos^2 \zeta}{\sqrt{\sin^2 \zeta + s^2 \cdot \cos^2 \zeta}} \quad (\text{A1})$$

In Equation A1, ϕ is the yawmark angle (striation angle), ζ is the slip angle, and s is the slip ratio. This equation was found to be mathematically equivalent to Equation 1, presented by Beauchamp. Ishikawa considers the heading direction of the tire and his interpretation of striation direction is consistent with Beauchamp [1].

JSDACS uses the preceding equations to "show the trace of ground contact per rubber block of tires for each step of numerical simulation." [8] Ishikawa found good agreement between the yaw mark angles in the simulation and those in the actual test. Ishikawa indicates that the striations will be perpendicular to the tire heading in the absence of braking. Braking has the effect of making the striations more angled forward, or more in line with the tire mark. Acceleration, on the other hand, angles the striations rearward, or further away from the tire mark direction.

In 1988, and again in 1998, Yamazaki et al. conducted research on the topic of in-plane buckling within the contact patch of tires subjected to lateral forces [4,5]. The study included physical testing of tires, both yaw testing of vehicles and testing of tires on a tire testing apparatus. The testing revealed that as a result of lateral forces, radial tires exhibit in-plane buckling deformation within the contact patch that allow regions of the patch to be in contact with the ground, while prohibiting others. Figure A4, which is Figure 28a in Yamazaki's 1998 publication, depicts a photograph of a radial tire with no tread pattern in the midst of being tested at a significant slip angle on a tire testing apparatus. The photograph is taken from below the tire, such that the contact patch is visible. The area in white are portions of the tire in contact with the test surface while the black areas are not.

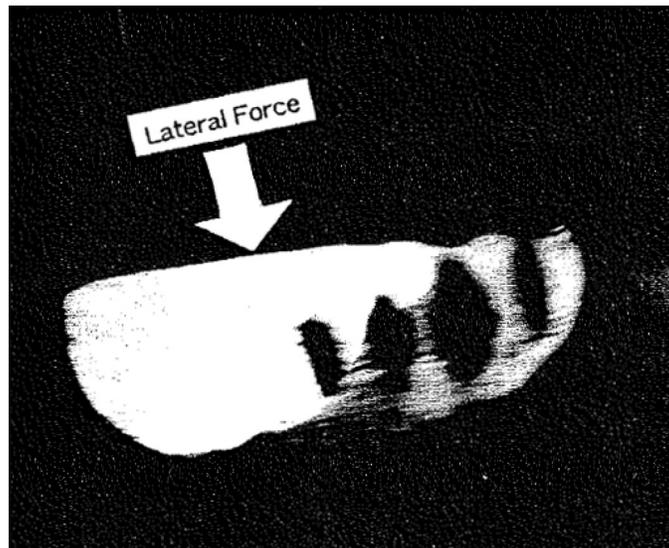


Figure A4. Buckling in the contact patch of a radial tire with no tread pattern during testing performed by Yamazaki. (Figure 28a from Yamazaki [5])

By comparison, the buckling behavior that occurs in the contact patch of a radial tire does not occur in a bias ply tire. Figure A5, which is Figure 28b in Yamazaki's 1998 publication, depicts a bias ply tire being loaded laterally. Again, the white areas are in contact with the test surface, and the black area are not. The buckling is longitudinal instead of lateral in a bias ply tire.

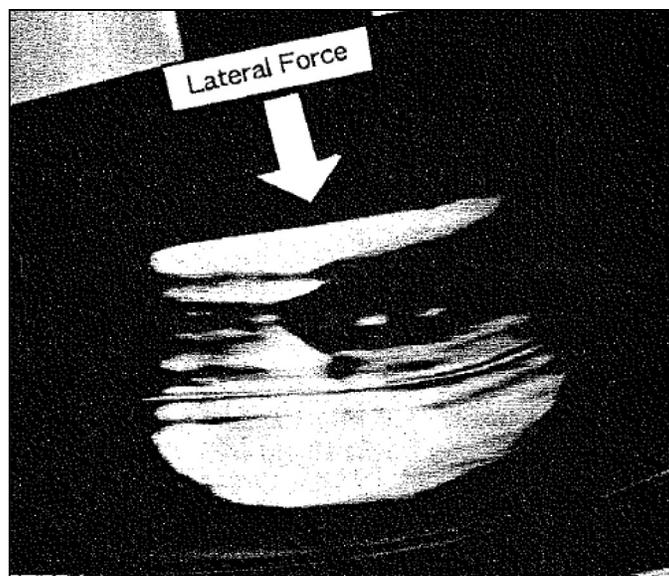


Figure A5. Buckling in the contact patch of a bias ply tire with no tread pattern during testing performed by Yamazaki. (Figure 28b from Yamazaki [5])

Yamazaki also conducted on-vehicle yaw testing of radial and bias ply tires. The radial tires tested had a patternless tread and deposited tire marks that contained striations that were angled away from the tire mark direction. Bias ply tires, by contrast, deposited tire marks that did not contain angled striations. The publications did not state the tread pattern of the bias ply tires that were tested. Figure A6, which is Figure 30 in Yamazaki's 1998 publication, depicts yaw marks deposited by a radial tire during his testing. No photographs of the tire marks from the bias ply tire testing appeared in the publications.

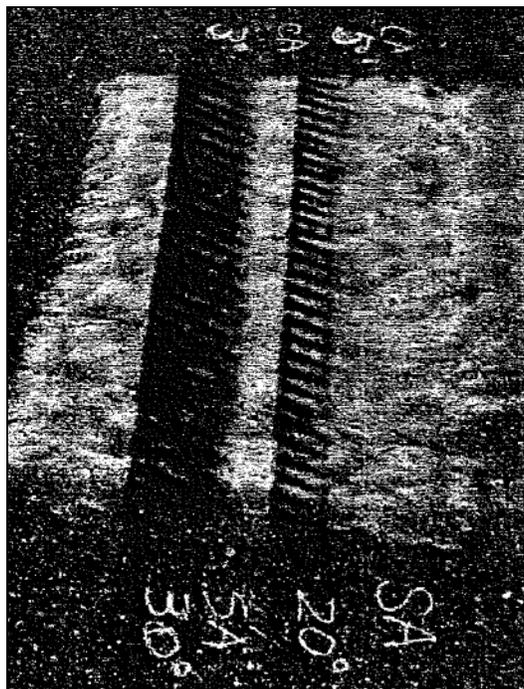


Figure A6. Tire marks deposited in testing of radial tires performed by Yamazaki. (Figure 30 from Yamazaki [5])

Yamazaki noted that the frequency of the radial tire striations was regular while the tread patterns of modern passenger cars are irregular. Based on the results of this testing, Yamazaki concluded that tire mark striations are created by the buckling behavior of radial tires. Yamazaki also notes that the buckling, and subsequent depositing of striations, resulted in a wavy wear pattern around the shoulder of the tire. Yamazaki included an image of this tire wear in his Figure 25, shown below in Figure A7.

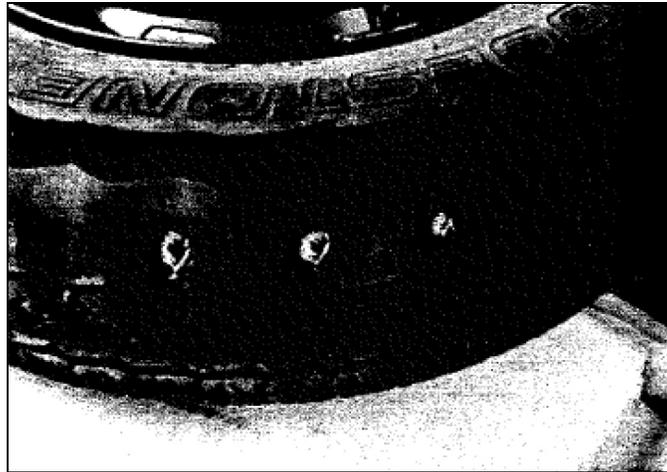


Figure A7. Tire wear to a radial tire as result of in-plane buckling. (Figure 25 from Yamazaki [5])

It should be noted that in-plane buckling does not prevent the shoulder blocks on the leading edge from being point loaded into the ground. Consider again [Figure A4](#) above from Yamazaki. In this image of the contact patch of a cornering tire, the tire is moving up relative to the page. Areas in white are in contact with the ground, and areas in black are not in contact. This tire reportedly had no tread pattern, however, many tires on the road do have an aggressive shoulder block tread pattern. Nearly the entire leading edge (top edge) of the contact patch is in contact with the ground. If this test tire had a tread pattern with shoulder blocks, it is likely that the blocks would have been loaded during the Yamazaki's testing.

In 1989, Reveley et al. conducted a comparison study between skid and yaw marks, noting the differing characteristics between the two cases [9]. Reveley conducted in line braking tests as well as yaw tests with both radial and bias ply tires. It was noted during the in line braking tests that striation marks were deposited that ran parallel to the tire marks. Striation marks deposited by a yawing vehicle without the brakes applied were described as being lateral to the tire mark direction. As a vehicle yawed past a slip angle of 90 degrees, striations within the tire marks were observed to change form "lateral to parallel and back to lateral" [9]. It was also observed that steering had an effect on the appearance of tire mark striations. Specifically, steering changed the striations from "lateral to between lateral and parallel to the path of the tire mark." [9] Similarly, Reveley noted that braking had the effect of changing striations from lateral to parallel to the tire mark direction. Their observations of the effects of braking led him to conclude that striations parallel to the tire mark are indicative of braking occurring, and, striations lateral to the tire mark are indicative of no braking. The yaw testing performed with bias ply tires resulted in striated tire marks being deposited. [Figure A8](#), which appears as [Figure 11](#) in Reveley, et al.'s, 1989 publication, depicted striated tire marks deposited with bias ply tires.



Figure A8. Striated tire marks deposited with bias ply tires during testing performed by Reveley et al. (Figure 11 from Reveley [9])

In 1989, Lambourn discussed striations within his analysis of vehicle speed from curved tire marks [6]. Lambourn included a literature review in this publication, some of which are included in this section. During his review, Lambourn considered two different methods in which striations are created; striations are a result of tire tread patterns or striations are the result of in-plane buckling of the contact patch in radial tires, as proposed by Yamazaki. Lambourn also conducted vehicle yaw testing with radial and bias ply tires in which special attention was given to the tire mark striations that were deposited. Lambourn observed that the striations were, “readily distinguishable from tread pattern prints.” [6] Specifically, the striation frequency was not consistent with any of the tread patterns. The radial tires deposited more defined striations than the bias ply tires. The data collected in these tests was said to be consistent with the findings of Yamazaki, or in other words, the striations in these tests were formed due to buckling in the contact patch of the radial tires. It was also noted that factors such as, tire size, tire construction, tread pattern, and road surface construction affect the clarity of the marks.

In 1997, Hague et al. published two critical speed studies which discussed striated tire marks [22,23]. Numerous vehicle yaw tests in which the vehicle accelerated, braked, or coasted were presented in these studies, and a correlation between the angle of the striation marks and the actions of the driver were examined. In general, it was found that braking had the effect of bring the striations closer to in line with the tangent to the tire mark, or making them steeper than in the unbraked tests. In the acceleration tests, the powered tires deposited striations that were angled further away from in line with the tangent to the tire mark, often beyond perpendicular to the tire mark. The ABS also had the effect of changing the angle of the striation marks. Specifically, ABS application made the striations steeper, or more in line with the tire marks. Striation angles were given in the study, but the position of the tire when the marks were deposited was not considered.

In a related study by Hague, the test vehicles were instrumented with longitudinal and lateral accelerometers, so that the angle of the tire marks striations could be compared to the net force acting on the vehicle. It was hypothesized that the net force on the vehicle is equal to the weighted average, by vertical load, of the striation angles of the four tires. Hague was not able to prove this equality directly with these tests as a result of measurement challenges as well as vehicle specific hurdles, such as ABS braking in some tests. Hague does maintain, however, that the angle of tire mark striations do indicate the angle of the force on that tire.

Bellion conducted yaw test in his examination of critical speed analysis in 1997 [24]. With regard to the tire mark striations, Bellion noted that the angle and spacing of the marks were indicative of the actions of the driver. During acceleration, the tire mark striations were described as, “closely spaced and angle out rearwards. Braking, on the other hand, created striations that were “more spread out and angle forwards.” [24] Also, when a tire was locked completely, striation marks transitioned from an angle to the tire mark, to a direction parallel to the tire mark.

In 2001, Van Kirk commented on striated tire marks [25]. With regard to tire marks deposited by a vehicle in a yaw, Van Kirk claims that both the width of the tire marks and the angle of the striations within are “heavily dependent on the speed of the vehicle.”

Van Kirk’s observation that tire mark striation angles are “heavily dependent” on vehicle speed is inconsistent with the work of these authors. The striations are expected to be perpendicular to the tire’s heading (in line with the force direction) in the absence of braking at any speed. Vehicle dynamics differences between high and low speed maneuvers may change the overall appearance of the tire marks, but the relationship between striation angle, tire longitudinal slip and tire slip angle is not speed dependent.

In 2005, Fischer concluded that striations are caused by, “collapsed sidewalls of tires that lose lateral traction and begin to sideslip through a turn.” [26] Fischer goes on to state that, “It is the sidewall contacting the pavement, not the tire tread, that causes the unique striations in the yaw marks.” Fischer includes [Figure A9](#) (Exhibit 15 in his paper, originally a figure found within the Traffic Crash Investigation manual published by Northwestern University) to communicate his sidewall collapse theory.

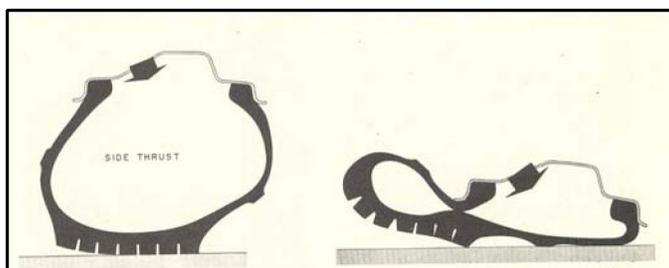


Figure A9. Exhibit 15 from Fischer’s study [26], used here with permission from Northwestern University

Fischer’s observation that striations are caused by the tire side wall contacting the ground after the tire has collapsed has similarities to point loading of the shoulder of the tire. In fact, the shoulder is point loaded on the left side graphic in [Figure A9](#). However, in these authors experience full tire collapse and contact with the sidewall is not necessary to create striation marks. Yaw testing in the literature depicts wear evidence to the shoulder tread blocks on a tire with tread [1] or shoulder and bottom of the contact patch on a treadless tire [4,5] inconsistent with the sidewall creating the marks as Fischer has proposed. Collapsing of the tire would be expected to create irregular marks, like those created during Gardner’s flat tire testing. Tire de-beading and rim gouging would also likely occur if the tire collapsed as Fischer illustrated on the right in [Figure A9](#). [Figure A9](#) (right) originally appears in the Northwestern manual accompanied by the following description, “If the downward and sideward thrust is great enough and the pressure in the tire is low, the tire may flatten. Sidewall wears through quickly if it slides on the roadway. Bead may be pulled from rim releasing air.” [7]

In their 2006 text, Daily, et al., offered a correlation between the angle of tire mark striations, and the braking actions of the driver [18]. Specifically, when no braking occurs striations are expected to be nearly perpendicular to the tire mark. Braking has the result of angling the striation marks towards the direction of travel, or towards a direction tangent to the tire mark. Daily also noted that ABS, “showed itself as variations in the angle of the diagonal striations” [18].

Daily’s observation that striations are nearly perpendicular to the tire mark without braking is approximately true at low slip angles. Again, the angle of the tire at the time the mark was deposited is necessary to determine braking. In the absence of braking, the striations are perpendicular to the tire, not perpendicular the tire mark. At low slip angles, these two directions are nearly the same. However, as the slip angle increases, a direction perpendicular to the tire diverges from a direction perpendicular to the tire mark. This is most obvious when a tire is sliding sideways, creating striations that are perpendicular to the tire and in line with the tire mark (90 degree difference).

In 2007, Lambourn, et al., studied tire mark striations deposited by vehicles equipped with Electronic Stability Control systems (ESC) [27]. ESC applies braking to individual tires in order alter vehicle yaw response in some situations. Lambourn states that striations should run across the tire mark at 90 degrees under cornering without braking (pure side force). However, it was generally found that the angle was less, on the order of 90 degrees to 45 degrees). He goes on to state that the angle appears to be related to the amount of longitudinal force applied through braking or accelerating.

Lambourn performed several yaw tests with different steering and throttle combinations. The striation angles, if visible, were documented with a protractor. The angle of the tire when the striations were deposited was not considered.

Lambourn found no clear characteristics in the tire marks to indicate that ESC was enabled. They did note that the striations were deposited at a lesser angle, or more in line with the tire mark, when ESC applied the brakes. However, without the knowledge that ESC had engaged they would have been unable to distinguish whether the lesser striation angles were caused from ESC or other driver actions.

In Lambourn's ESC testing, the ESC had the effect of lessening the striation angles. ESC applies the brakes to individual tires, and the trend of braking making the striations more in line with the tire marks is consistent with the findings of Beauchamp [1]. Although the trends are generally correct, the tire angle should be considered when determining braking, or in this case ESC.

In 2009, Amirault, et al., performed 29 yaw tests for an examination of the critical speed formula [28]. Included in this study was an examination of how the angles of the striation marks were affected by the level of braking. Following a yaw test, Amirault placed a protractor on the tire mark 5 to 15 meters after the front and rear tire marks separated and measured the angle of a striation mark. An angle of 90 degrees corresponded to striation marks that were perpendicular to the tire mark, and an angle of 0 degrees corresponded to striations that were in line with the tire mark. Amirault identified a trend within the striation angles, namely, braking tended to decrease the angle of the striations, or bring the striations more in line with the tire mark direction. In their conclusions, it was recommended that striations be measured as close to tire mark separation as possible. Striation angles of less than 50 degrees indicated braking and angles of higher than 60 degrees indicated no braking. If the angle was between 50 and 60 degrees, the level of braking was undetermined.

Amirault analyzed the striations by placing a protractor on the tire marks to measure the striation angle. Depending on the angle of the striations, a determination was made whether the brakes were applied. The trend that Amirault found, that braking causes the striations to be more in line with the tire mark direction, is generally correct. However, due to the fact that Amirault's method does not consider the angle of the tire when the marks are deposited, caution is warranted if applying this technique. Amirault's conclusions are likely limited to the specific tests presented in his paper and may not generalize to different vehicle dynamics or different vehicle positions during the progression of yaw maneuver.

Striations are discussed in Fricke's 2010 Traffic Crash Reconstruction text [10]. Oblique striations in yaw marks are said to be caused by "the outside tire tread edge." The affects of braking and acceleration on tire mark striation angle are consistent with Fricke's 1990 publication.