

Tire Mark Striations: Sensitivity and Uncertainty Analysis

Gray Beauchamp, Dana Thornton, William Bortles, and Nathan Rose
Kineticorp LLC

ABSTRACT

Previous work demonstrated that the orientation of tire mark striations can be used to infer the braking actions of the driver [1]. An equation that related tire mark striation angle to longitudinal tire slip, the mathematical definition of braking, was presented. This equation can be used to quantify the driver's braking input based on the physical evidence. Braking input levels will affect the speed of a yawing vehicle and quantifying the amount of braking can increase the accuracy of a speed analysis. When using this technique in practice, it is helpful to understand the sensitivity and uncertainties of the equation. The sensitivity and uncertainty of the equation are explored and presented in this study. The results help to formulate guidelines for the practical application of the method and expected accuracy under specified conditions. A case study is included that demonstrates the analysis of tire mark striations deposited during a real-world accident.

CITATION: Beauchamp, G., Thornton, D., Bortles, W., and Rose, N., "Tire Mark Striations: Sensitivity and Uncertainty Analysis," *SAE Int. J. Trans. Safety* 4(1):2016, doi:10.4271/2016-01-1468.

INTRODUCTION

Tire marks often fall into one of two categories: skid marks or yaw marks. Skid marks are typically deposited when a driver applies the brakes aggressively. In response to the braking, the tires can slip and deposit rubber on the roadway. Yaw marks are deposited by tires that have generated a slip angle, or a discrepancy between their heading direction and velocity direction (Figure 1). As the tire slides sideways, rubber is deposited on the roadway.

Tire marks sometimes exhibit striations. In the absence of braking or partial braking, yawing tires are simultaneously rolling and sliding which creates striation marks that run at an angle to the direction of the tire mark. In the absence of braking, these striations are aligned at an angle perpendicular to the tires heading direction. In the case of full braking (lock-up) the striations are aligned with the tire mark, or parallel to the wheel hub velocity direction.¹ Because the striations are affected by both the heading angle of the tire and the amount of braking, these tire marks offer a glimpse into the actions of the driver when the tire marks were deposited. A full review of tire striations in the literature can be found in a forthcoming SAE publication [2]

In previous work, a theoretical model for determining longitudinal tire slip from striation marks was developed [1]. Equation 1 can be used to calculate the longitudinal slip, using the striation angle, θ , and the slip angle, α . The variables in Equation 1 are depicted in Figure 2. Full scale vehicle yaw testing was conducted to validate the equation. It was found that the model offered insight into the braking actions of drivers at the time the tire marks were being deposited.



Figure 1. Striated tire marks deposited by a yawing vehicle.

$$S = \frac{\tan \alpha}{\tan(90 - \kappa)} \quad (1)$$

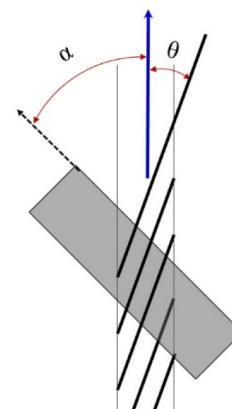


Figure 2. Tire depositing a yaw mark (not to scale).

1. Throughout this paper, the term "full braking" refers to the locking of the wheel, when its rotational velocity goes to zero. This condition would be consistent with full brake application in a vehicle that is not equipped with an antilock brake system (ABS).

EQUATION SENSITIVITY AND ERROR ANALYSIS

In order to analyze striations in practice, an understanding of the sensitivity of the equations and how error propagates through the analysis would be useful. In this section, the equation for longitudinal slip (Equation 1) will be studied.

Sensitivity Analysis

Application of the brakes has the effect of changing the angle of the striation marks [1,2,3,4]. Specifically, the marks change from a direction perpendicular to the tire heading with no braking, to a direction parallel to the wheel hub velocity (parallel to the tire mark) with full braking. The change in striation angle with braking is depicted in Figure 3. No braking, partial braking and full braking scenarios are depicted from left to right. In all scenarios the tire is at the same slip angle, α . The tires are moving from bottom to top on the page, as indicated by the blue arrow. The value κ is also introduced in Figure 3 which represents the angle between perpendicular to the tire and the striation direction. In image on the left of the figure, no braking is occurring. The striations (shown in bold lines) are perpendicular to the tire heading. Mathematically, this case can be described as $\alpha + \theta = 90$ and $\kappa = 0$. Partial braking is depicted in the middle image. The brakes have changed the direction of the striations an angle κ from perpendicular to the tire. In the case of partial braking, $\alpha + \theta + \kappa = 90$. On the right, the brakes are applied fully, locking the wheel. With full braking, the striations are parallel to the velocity direction of the wheel hub, which is parallel to the tire mark. Under the full braking condition, $\theta = 0$ and $\alpha + \kappa = 90$.

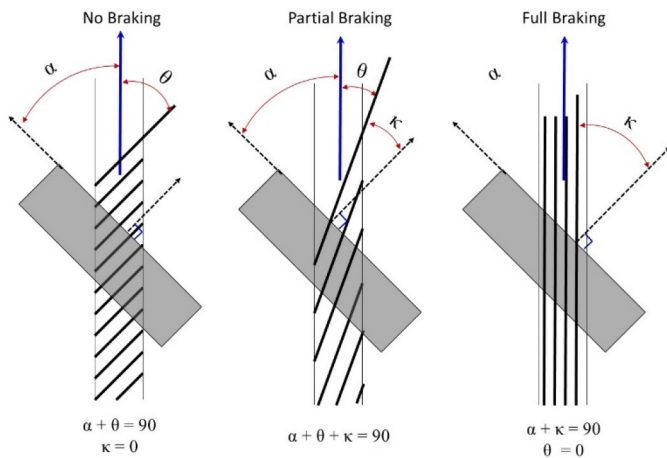


Figure 3. Transition in Striation Direction as a result of Braking (not to scale).

The tires in Figure 3 all have the same slip angle. Now consider the effect of changing the slip angle. Under full braking, the angle κ will be largest when the tire slip angle is small, and vice versa. In other words, when the slip angle is small, there is a relatively large angular difference in κ between no braking and full braking. When the slip angle is large,

there is a relatively small difference in κ between no braking and full braking. In Figure 4, full brake scenarios for slip angles of 10 and 80 degrees are depicted on the left and right, respectively.

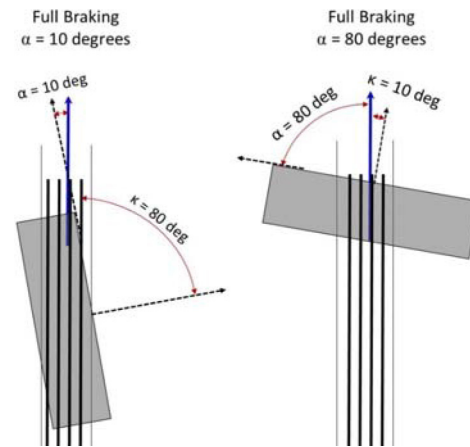


Figure 4. Full Braking, slip angle comparison (not to scale).

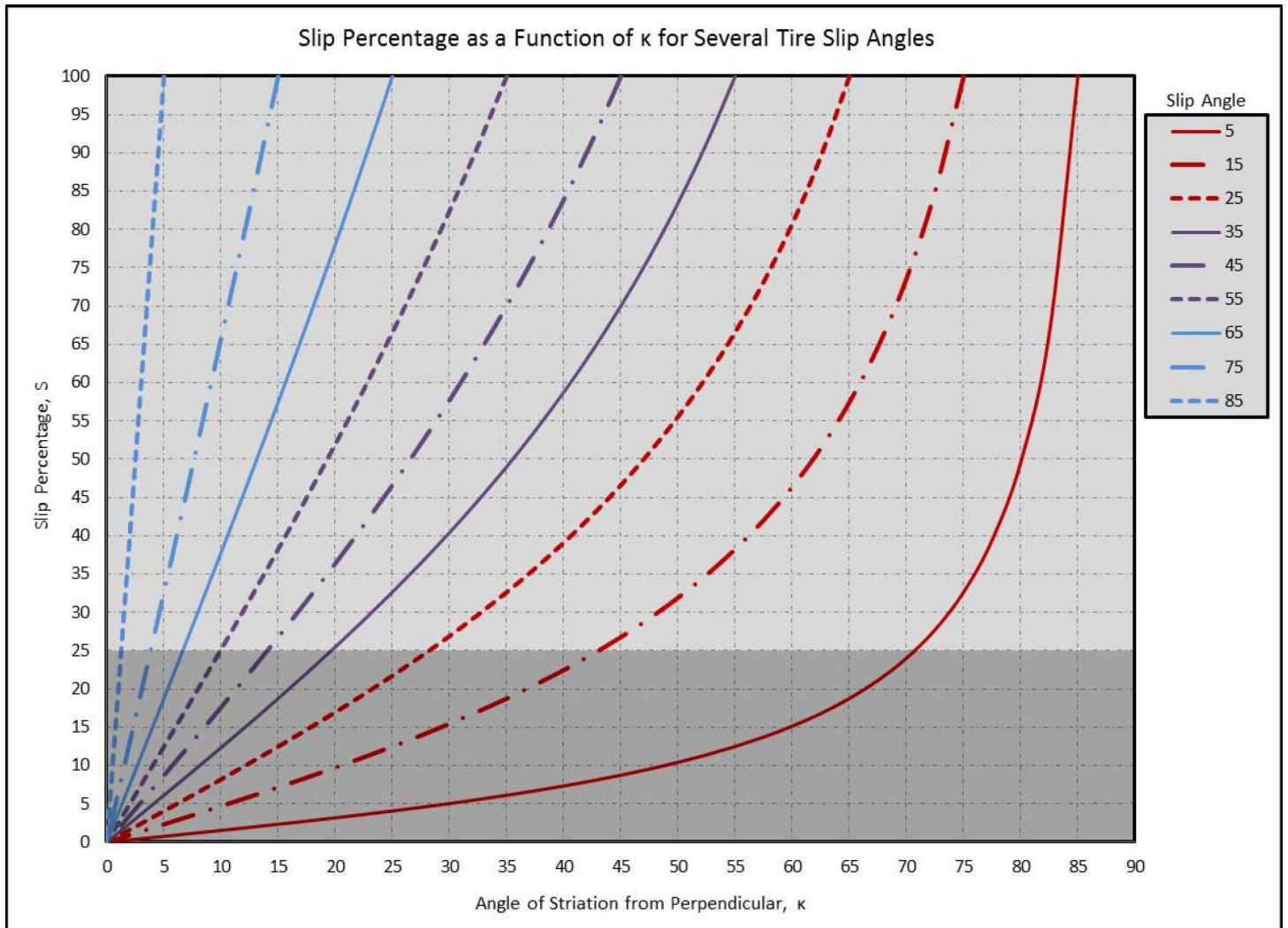
In practice, the angle of the striation marks will become more sensitive to braking as the slip angle increases. This sensitivity is illustrated in Figure 5. The longitudinal slip percentage is plotted as a function of the angle κ (Equation 2), for lines of constant slip angles. Maximum deceleration likely occurs at approximately 25 percent longitudinal slip for a typical passenger tire [1]. The build up to maximum braking is shaded in Figure 5. In general, the analysis of striations will be less sensitive to slip and striation angle measurement errors at lower slip angles. At a slip angle of 5 degrees, the striations will change over 70 degrees between no braking and maximum braking and braking will likely be easy to distinguish. At an 85 degree slip angle, less than 2 degrees separate no braking and maximum braking, and changes in striation angle from braking are unlikely to be detected.

$$S = \frac{\tan \alpha}{\tan(90 - \kappa)}$$

(2)

3.2. Uncertainty Analysis

An uncertainty analysis of Equation 1 was conducted. The heading angle of the tire, its velocity direction and the striation direction are needed in order to measure α and θ . The velocity direction is used in the measurement of both α and θ . Therefore, the uncertainties in α and θ are correlated. Further, an overestimation of α and will often be accompanied by and underestimation in θ , and vice versa. So, the uncertainties in α and θ have negative covariance [5]. In order to account for this, the slip function can be rewritten in a fixed coordinate system. On the left in Figure 6 are the angles α and θ as defined previously. On the right, those two angles are defined system by three measurements, A , B , and C , from a fixed coordinate.

Figure 5. Slip Percentage as a Function of κ for Several Tire Slip Angles.

$$S = \frac{\tan(B - A)}{\tan(C - A)} \quad (3)$$

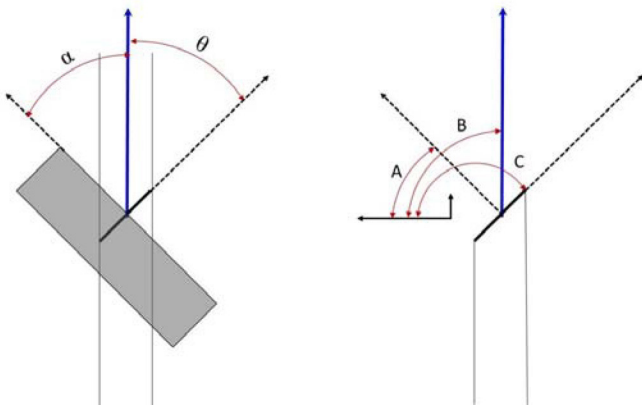


Figure 6. The variables of Equations 1 and 3 (not to scale).

The angles α and θ can then be redefined in terms of A , B , C , and the slip function can be rewritten as Equation 3.

By rewriting the striation function with the three independent quantities, A , B , and C , an uncertainty analysis can be conducted that accounts for the negative covariance between the angles α and θ . The uncertainties of three angles, δA , δB , and δC are considered [5].

$$\delta S = \sqrt{\left(\frac{\partial S}{\partial A} \delta A\right)^2 + \left(\frac{\partial S}{\partial B} \delta B\right)^2 + \left(\frac{\partial S}{\partial C} \delta C\right)^2} \quad (4)$$

The partial derivatives in Equation 4 are defined as follows:

$$\frac{\partial S}{\partial A} = \frac{\sec^2(C - A) \tan(B - A) - \sec^2(B - A) \tan(C - A)}{\tan^2(C - A)} \quad (5)$$