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Determining Vehicle Steering and Braking from Yaw Mark Striations

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ABSTRACT

This paper presents equations that relate the orientation and spacing of yaw mark striations to the vehicle braking and steering levels present at the time the striations were deposited. These equations, thus, provide a link between physical evidence deposited on a roadway during a crash (the tire mark striations) and actions taken by the driver during that crash (steering and braking inputs). This paper also presents physical yaw tests during which striated yaw marks were deposited. Analysis of these tests is conducted to address the degree to which the presented equations can be used to determine a driver's actual steering and braking inputs. As a result of this testing and analysis, it was concluded that striated tire marks can offer a meaningful glimpse into the steering and braking behavior of the driver of a yawing vehicle. It was also found that consideration of yaw striations allows for the reconstruction of a vehicle's post-impact yaw motion from a single tire mark.

INTRODUCTION

Braking and steering will both affect the characteristics of the striations that are sometimes present in the tire marks that a yawing vehicle deposits. As an example, consider Figure 1, which is a photograph from testing conducted by Daily [1] that depicts a yaw mark deposited by a vehicle during a counter-clockwise yaw. The vehicle that deposited this tire mark was traveling into the page. Initially, the vehicle was unbraked, then, the brakes were applied. As a result of this changing braking level, the striations in the tire mark undergo a change in direction.

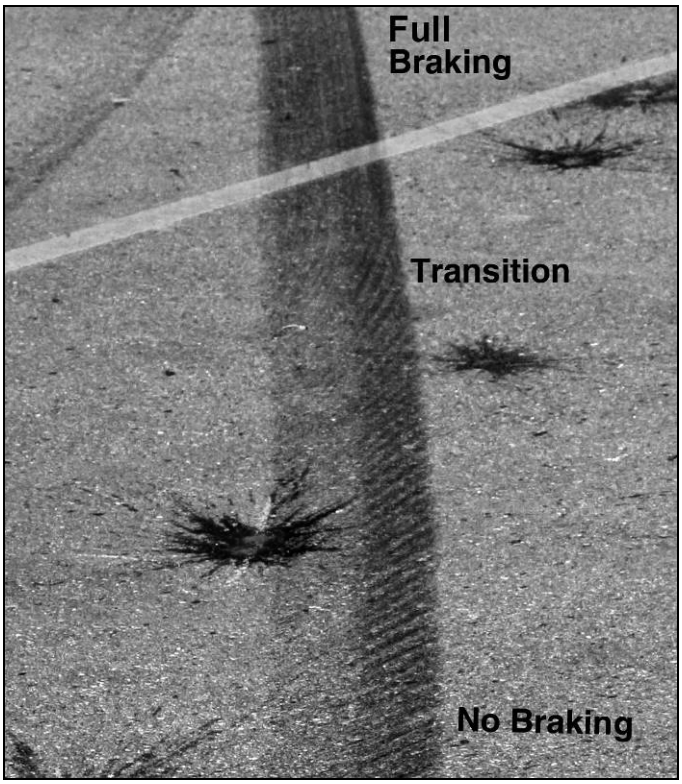

Figure 1 – A yaw mark deposited during testing performed by Daily et al.

As will be explained in greater detail later, the striations in a yaw mark indicate the travel direction of tire shoulder blocks during the yaw. Since frictional forces act to oppose the direction of motion, these striations are also indicative of the direction of the frictional force acting on these portions of the tire. In the case of increasing

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braking depicted in Figure 1, the direction of the forces on the tire, and thus, the direction of the striations, transition from a direction perpendicular to the heading of the tire to a direction parallel to the velocity direction of that tire hub (tangent to the path of the tire mark). In other words, the no braking case references the angle of the tire and the full braking case references the general direction of the tiremark. Thus, the analysis of striations includes consideration of the vehicle and the tire mark evidence. In most cases, the tire mark evidence by itself is insufficient to determine the amount of braking or steering that was occurring.

Of course, even in the absence of braking, tire mark striations could make a similar transition to that shown in Figure 1. In the absence of braking, the tire forces will be oriented perpendicular to the tire heading, and thus, the striations will also be oriented perpendicular to the tire heading. In the case of steadily increasing slip angle, the striations in a tire mark would transition in a manner similar to that shown in Figure 1. The striations would become parallel with the direction of the tire mark when the slip angle reached 90 degrees. To take this a step further, it should be noted that steering will influence a tires slip angle, and thus, will also influence the orientation of striations deposited by an unbraked tire.

The tire slip angle and braking level will both influence the characteristics of the striations in a yaw mark. If one considers only the orientation of the striations, then these various influences will be indistinguishable. However, it will be shown below that consideration of both the orientation and the spacing of the striations will allow the effects of slip angle and braking to be distinguished and parsed out.

Thus, a relationship exists between the actions of a driver and the characteristics of the tire marks their vehicle deposits during a yaw. Formalizing this relationship can enable reconstruction of a driver's actions during a crash based on physical evidence. The remainder of this paper presents and tests equations that relate the striation characteristics (direction and spacing) to both the percentage of braking slip and the slip angle of the tire at the time a yaw mark was deposited.

YAW MARKS

When a vehicle yaws, its velocity direction deviates from its heading direction. This difference can result in tire marks being deposited on the roadway, within which striation marks are often visible, as discussed above. Tire mark striations are direct physical evidence of the direction of the force that was applied to the tire at the time the mark was deposited. Without braking, the tire force is perpendicular to the tire heading, and thus, the striations produced are perpendicular to the tire heading. When a yawing vehicle locks its brakes, the resultant tire force is in line with velocity direction of the tire hub, hence the direction of the striations becomes in line with that velocity direction.

Except for in the cases of full lockup or 90-degree tire slip angle, a tire rolls and slides as it deposits striations. This sliding results in forces that deform the tire carcass laterally and load the leading shoulder of the tire (the shoulder is the area where the tread or bottom of the tire and the tire sidewall meet). An extreme case of such shoulder loading is shown in Figure 2 [2]. When distinct striations are visible in a yaw mark (Figure 1), it is the individual tread blocks on the shoulder of the tire that are responsible for the darker striations. The fact that the shoulder tread blocks create distinct striations is fundamental to the modeling presented below.

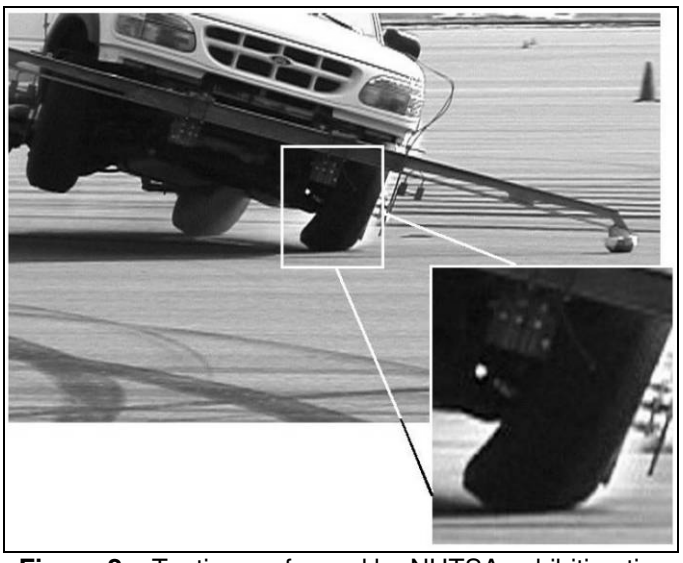

Figure 2 – Testing performed by NHTSA exhibiting tire deformation

Figure 3 is a schematic depicting the alignment of a tire relative to a yaw mark that it is depositing. In Figure 3, the contact patch, or portion of the tire in contact with the roadway surface, has been identified with a dark grey box. The tire mark is divided, with darker striations on the right being deposited by the shoulder blocks and lighter striations on the left being deposited by the tread. Such a division in the darkness of the striations from left to right is visible in the tire mark in Figure 1. In Figure 3, the striations are neither perpendicular to the tire heading or parallel to the velocity direction, indicating that partial braking is occurring. The dark striations from the shoulder blocks will be the focus of the model to be presented below. The slip angle, α, is labeled in Figure 3.[1]

THEORY

In this section, mathematical equations are presented that relate braking and steering to the orientation and spacing of striations deposited on the roadway. This theory assumes that the tire is rigid, which as shown in Figure 2, is obviously not the case. Later in this paper, the implications of this rigid tire assumption are

1 A full listing and description of the variables used in this paper can be found in Appendix A.

discussed. The equations below also don't consider the fact that both the size of the shoulder tread blocks and the spacing between them are variable around an actual tire's circumference. This is an important characteristic of tires to consider in practice and is discussed later.

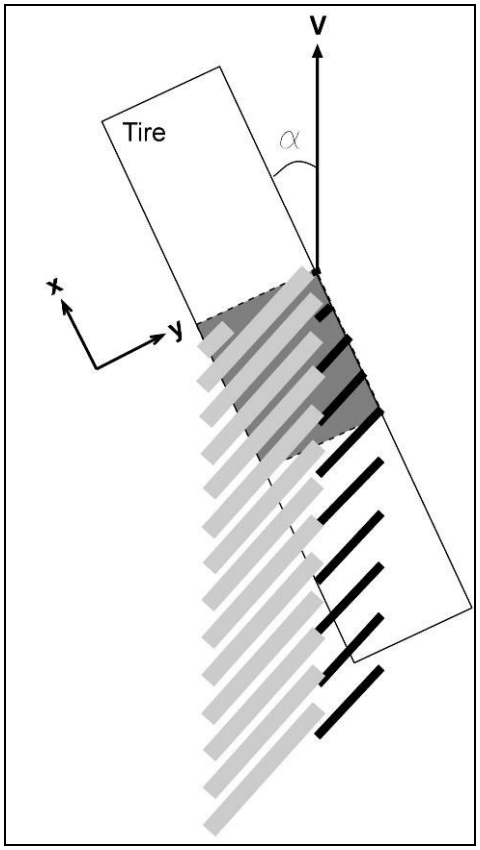

Figure 3 – Tire depositing a striated tire mark.

TIRE SLIP ANGLE – Figure 4 depicts the same yawing tire as Figure 3. It is the dark striations deposited by the shoulder of the tire that form the foundation of the modeling below, thus, these striations have been singled out in Figure 4. The coordinate system depicted in Figure 4 is consistent with the SAE tire axis system. It is right-handed, with the z-axis pointing into the page, and the x-axis aligned with the tire's heading. The angle α is the tire's slip angle, which is the angle between the tire's heading and the tire's velocity direction. The dark black lines represent the striations in the tire mark, deposited by the shoulder treads of the tire, and they are oriented an angle Ψ from the tire's heading. As drawn in Figure 4, both α and Ψ are positive. The angle θ is the angle between the tire's velocity direction and the direction of a striation. The striations are a distance of SD apart in the direction of the tire mark, or tire velocity direction.

In the lower portion of Figure 4, a zoomed in view of two right triangles is shown. One side of both triangles is formed by a line connecting two adjacent striations in a direction perpendicular to the striations. The hypotenuse of the larger triangle is SD. The second right triangle has a hypotenuse of length TD and is denoted by a dashed line. TD has a length equivalent to the spacing between the tread blocks on the tire and is oriented such that it connects two adjacent striations. This alignment orients the line TD parallel to the tire heading. Both triangles are completed by lines along the striation mark, as depicted. The striation angle, θ, is shown on the triangle. Because TD is parallel to the tire heading, the angle Ψ is created in the second triangle. In practice, the angle θ and the distance SD can be measured from a striated tire mark. The tread block spacing distance, TD, is a measurement taken from the tire. Measurement techniques for θ, SD and TD are discussed later.

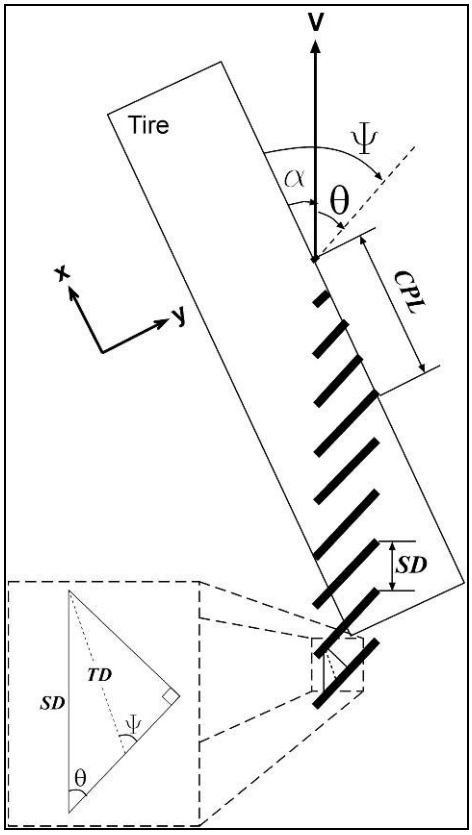

Figure 4 - Top view of a yawing tire depositing a striated tire mark.

The triangles to the lower left of Figure 4 can be geometrically related to obtain an expression for Ψ, given by Equation (1) below.

$$\Psi = \sin^{-1}\left(\frac{SD\sin\theta}{TD}\right) \tag{1}$$

Using Equation (1) along with geometric relationships between Ψ, α and θ, an expression for the slip angle, or the angle of the tire relative to the tire velocity, can be obtained, given below in Equation (2). All of the variables in Equation (2) can be measured from either a tire or a tire mark.

$$\alpha = \sin^{-1}\left(\frac{SD\sin\theta}{TD}\right) - \theta \tag{2}$$

When multiple tire marks are deposited on the roadway, vehicle yaw angles can be determined by aligning a vehicle with its tire marks. Using the equations above, the slip angles of each tire can also be determined. Rear tire slip angles are equal to the slip angle of the vehicle in the absence of tire misalignment or toe in/out design differences. The difference between the heading direction of the front tires and the heading direction of the vehicle is the steering angle at the front tires. The angle of the steering wheel can then be calculated through the steering ratio.

BRAKING/SLIP PERCENTAGE – Along with the orientation of the tire, the amount of braking of a yawing tire is often of interest. Braking can be discussed in terms of slip percentage, which can be calculated using some of the parameters that appear in Figure 4. As will be shown, slip percentage is dependant on fewer variables than slip angle. This is important because in some cases, slip percentage can be calculated when the slip angle cannot.

Our discussion of slip will begin with the classic definition of braking slip, which appears in several vehicle dynamics texts. For instance, Gillespie states: "Slip of the tire is defined by the ratio of slip velocity in the contact patch to forward velocity" [3]. Mathematically, this is shown in Equation (3) for the case of in-line braking.

$$S = \frac{V - \omega r}{V} \tag{3}$$

In Equation (3), V is the velocity of a wheel hub, ω and r are the rotational speed and radius of its tire, respectively. The quantity ωr will be equal to V when the tire is free rolling so the slip will be 0. Comparatively, at full wheel lockup when ω is equal to 0, slip will be equal to 1.

Equation (3) assumes a tire that has its heading and its travel direction aligned. For a yawing vehicle, it is the velocity of the tire along its heading direction that is of interest. The velocity of the tire along its heading, V_T, is the actual velocity multiplied by the cosine of the slip angle of the tire. Thus, Equation (5) gives braking slip for a tire in a yaw.

$$S = \frac{V_T - \omega r}{V_T} \tag{4}$$

$$S = \frac{V\cos\alpha - \omega r}{V\cos\alpha} \tag{5}$$

Now consider Figure 5. While the shoulder tread block of a yawing tire deposits the striation mark indicated by the bold line, it moves from Position 1 to Position 2 up the page. The two images on the right depict a side view of the tire at Positions 1 and 2. Between Positions 1 and 2, the tire rotates β radians. While the tire travels from Position 1 to 2, it deposits a striation of length LS, depicted by the bold line in the top view image on the left. The tire mark has a width w. The tire slip angle and the striation angle are indicated by α and θ respectively. The contact patch length is also indicated on the diagram by the dashed line.

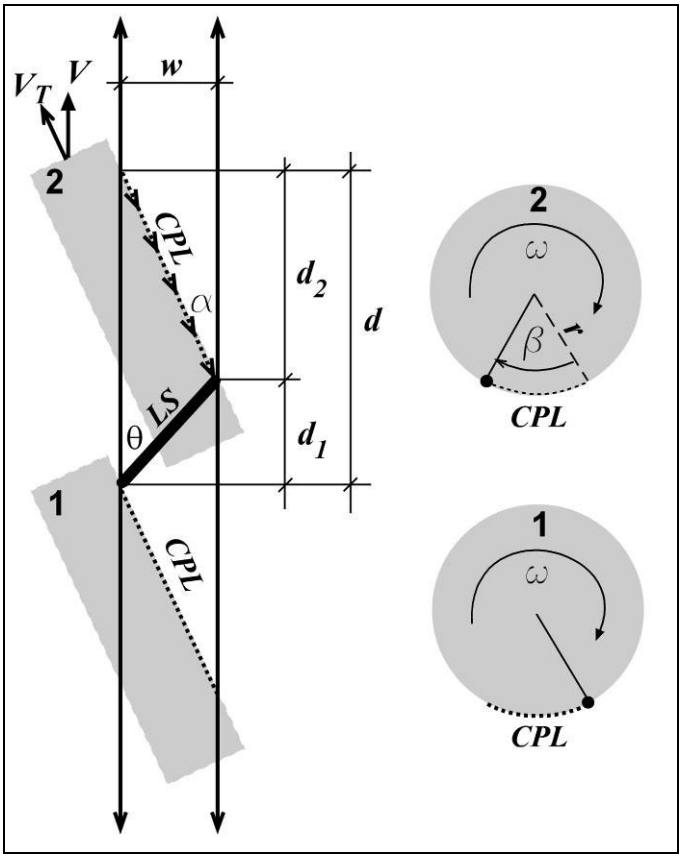

Figure 5 - Depositing of one striation mark. On the left, a top down view. On the right, a right side view.

Physically, the contact patch length, CPL, is the length of the portion of the tire that is in contact with the ground. Figure 5 depicts the contact patch length. In Position 1, a point on the circumference of the tire marked with a black dot has just come into contact with the ground at the front of the contact patch. While the striation is being deposited, the tire rotates and that point on the tire moves towards the rear of the contact patch before lifting away form the ground at Position 2. All of the parameters that appear in Equation (5), V, α, ω, and r are visible in Figure 5.

The time it takes to deposit one striation mark, t, will now be explored. Equation (5) can be rewritten as a function of this time, t, to yield Equation (6). Time is equal in all terms of Equation (6) and cancels out. Rearranging results in Equation (7).

$$S = \frac{\frac{d}{t}\cos\alpha - \frac{\beta r}{t}}{\frac{d}{t}\cos\alpha} \quad (6)$$

$$S = 1 - \frac{\beta r}{d\cos\alpha} \quad (7)$$

Two different triangles can be used to equate the tire mark width, as shown in Equation (8). The contact patch length can then be determined using Equation (9). The images on the left of Figure 5 reveal that the contact patch length is equal to βr. It should be noted that this contact patch length calculated is theoretical because only the shoulder blocks are assumed to be leaving marks on the road. In actuality, the bottom tread of the tire also leaves marks and the contact patch length is not so readily determined. For the modeling that follows, the triangles would be of different proportions if the actual contact patch length were utilized. As will be shown, all the triangle side lengths fall out of the analysis leaving the trigonometric relationships which are unaffected by the shoulder tread block assumption.

$$CPL\sin\alpha = w = LS\sin\theta \quad (8)$$

$$\beta r = CPL = \frac{LS\sin\theta}{\sin\alpha} \quad (9)$$

As is seen in Figure 5, d is equal to the summation of d_1 and d_2 which can be determined geometrically, as follows:

$$d_1 = LS\cos\theta \quad (10)$$

$$d_2 = CPL\cos\alpha = \frac{LS\sin\theta\cos\alpha}{\sin\alpha} \quad (11)$$

$$d = d_1 + d_2 = LS\cos\theta + \frac{LS\sin\theta\cos\alpha}{\sin\alpha} \quad (12)$$

Equation (9) and Equation (12) can then be substituted into Equation (7) yielding Equation (13).

$$S = 1 - \frac{\left(\frac{LS\sin\theta}{\sin\alpha}\right)}{\left(LS\cos\theta + \frac{LS\sin\theta\cos\alpha}{\sin\alpha}\right)\cos\alpha} \quad (13)$$

Equation (13) can then be simplified through the following series of equations to obtain Equation (20).

$$S = 1 - \frac{\sin\theta}{(\cos\theta\sin\alpha + \sin\theta\cos\alpha)\cos\alpha} \quad (14)$$

$$S = 1 - \frac{\sin\theta}{\sin(\theta+\alpha)\cos\alpha} \quad (15)$$

$$S = 1 - \frac{\sin\theta}{\sin\psi\cos\alpha} \quad (16)$$

$$S = 1 - \frac{\sin(\psi-\alpha)}{\sin\psi\cos\alpha} \quad (17)$$

$$S = 1 - \left(\frac{\sin\psi\cos\alpha - \cos\psi\sin\alpha}{\sin\psi\cos\alpha}\right) \quad (18)$$

$$S = 1 - 1 + \frac{\cos\psi\sin\alpha}{\sin\psi\cos\alpha} \quad (19)$$

$$S\% = \frac{\tan\alpha}{\tan(\theta+\alpha)} \times 100 \quad (20)$$

Equation (20) is multiplied by 100 giving slip percentage, $S\%$. Equation (20) is mathematically equivalent to the classic equation of slip during yaw, Equation (5). Equation (20) demonstrates that the slip percentage of a tire during the depositing of a striation mark can be calculated if the angle of that striation and the slip angle of the tire are known.

Next, consider the effects of braking on tire mark/tire geometry. Figure 6 depicts three scenarios; a free rolling tire on the left, partial braking in the center and full wheel lockup on the right. The vertical line in each scenario, which is aligned to the tires velocity direction, has a dimensionless length of 1. From the bottom end of this vertical line, two lines are drawn, one along the heading direction of the tire, an angle α from the velocity direction, and the other along the direction of the striation, θ from the tire velocity. Two lines are then drawn from the top end of the vertical line that intersect perpendicularly with the tire heading and striation direction. In all three scenarios, the tire has the same slip angle. The striation directions, however, are different in each case, ranging from perpendicular to the tire in the no braking case, to in line with the velocity direction in the full braking case.

The ratio of the lengths of d_{actual} and $d_{freeroll}$, which are labeled in Figure 6, also define the amount of slip of the tire. As is shown in the partial braking case, the vector d_{actual} is parallel to $d_{freeroll}$ and becomes shorter in length as the angle θ decreases, which occurs as braking increases. Because d_{actual} is parallel to $d_{freeroll}$, an angle of ψ separates it from the striation direction.

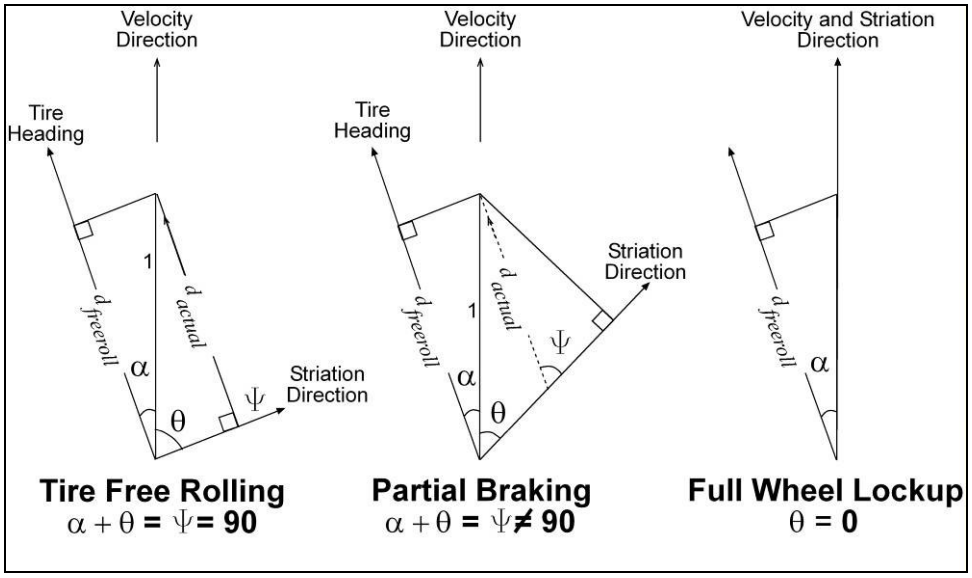

Figure 6 – Braking triangles.

Equation (21) defines the amount of slip in terms of the geometry presented in Figure 6.

$$Slip = S = 1 - \frac{d_{actual}}{d_{free\_roll}} \tag{21}$$

For the free rolling case, d_{actual} and $d_{freeroll}$ are of equal length resulting in a slip value of zero. The full lockup case, on the other hand, d_{actual} is zero resulting in a slip value of 1, or 100%. Equation (21) and Figure 6, describe mathematically the idea that striation marks are perpendicular to the tire in the absence of braking and parallel to the velocity direction in the presence of full wheel lock up. Equation (21) also offers insight into the cases where partial braking is occurring.

The triangles in the partial braking case in Figure 6 can be used to find expressions for d_{actual} and $d_{freeroll}$, as follows:

$$\sin\theta = d_{actual}\sin\psi \tag{22}$$

$$d_{actual} = \frac{\sin\theta}{\sin\psi} \tag{23}$$

$$d_{freeroll} = \cos\alpha \tag{24}$$

Equations (23) and (24) can be substituted into Equation (21), yielding Equation (25). Equation (25) can then be simplified to Equation (30), which again is equivalent to the classic equation for slip.

$$S = 1 - \frac{\sin\theta}{\sin\psi\cos\alpha} \tag{25}$$

$$S = 1 - \frac{\sin(\psi - \alpha)}{\sin\psi\cos\alpha} \tag{26}$$

$$S = 1 - \frac{\sin\psi\cos\alpha - \cos\psi\sin\alpha}{\sin\psi\cos\alpha} \tag{27}$$

$$S = \frac{\sin\alpha\cos\psi}{\sin\psi\cos\alpha} \tag{28}$$

$$S = \frac{\tan\alpha}{\tan\psi} \tag{29}$$

$$S\% = \frac{\tan\alpha}{\tan(\theta+\alpha)} \times 100 \tag{30}$$

STRIATION STUDY I: TIRE MARKS DEPOSITED FOLLOWING AN IMPACT

The simplest case examined during this research is that of a rear tire with no braking. As discussed in earlier sections, when no braking is present during a yaw, striations are deposited in a direction perpendicular to the heading of the tire. For most vehicles, which are steered by only the front tires, the heading direction of the rear tires is the same as the heading direction of the vehicle. Thus, in theory, the slip angle of a rear tire with no braking can be determined by simply aligning the tire in a direction perpendicular to a striation mark. Further, striations deposited by a rear tire can allow the reconstruction of an entire yaw sequence from a single tire mark with relative ease, so long as no braking was occurring during the yaw.

One scenario where there is often no braking, at least no braking input by the driver, is in a yaw induced by an impact. On July 23rd, 2008, the authors conducted two

Pursuit Intervention Technique tests, or PIT tests, at the Denver Police Academy. The PIT maneuver is a method used by police to end a pursuit by spinning out a suspect's vehicle. The pursuing officer positions their vehicle to one side of a suspect's vehicle such that the front quarter panel of the police vehicle aligns with the rear quarter panel of the suspect's vehicle. The officer then steers their vehicle into the rear of the suspect vehicle, causing the suspect to spin out. Figure 7 depicts images from one of the PIT tests conducted by the authors.

Figure 7 - PIT Test 1

Both vehicles used in the PIT tests were Ford Crown Victorias that had been modified by the Denver Police Department specifically for PIT training. The target vehicle in the test, the PITed vehicle, had a roll cage mounted to its interior. It also had a steel frame over its rear bumper and rear fenders to prevent damage during PIT maneuvers. Likewise, the bullet vehicle, or PITting vehicle, had a steel frame covering its front bumper and front fenders to prevent damage.

After the PIT maneuver was initiated, the driver of the PITed vehicle released his hands from the steering wheel and removed his foot from the pedals. The PITed vehicle yawed counterclockwise in the first test and clockwise in the second. After each test, the tire mark evidence and rest position of the vehicle were surveyed and photographed. Figure 8 depicts the tire marks deposited during the second test. Tape was used to identify individual striation marks which were included in the survey. The vehicle that deposited the tire marks in Figure 8 was travelling out of the page, or from the top of the photograph to the bottom.

Figure 9 depicts several positions of the PITed Crown Victoria that have been aligned to the surveyed striations in the rear left tire mark. At each position, the point on the outside edge of the rear left tire directly below the axle was aligned to the midpoint of the striation. The vehicle was then rotated in yaw until the heading of the tire was perpendicular to the striation. Figure 10 depicts the same vehicle positions and also includes the other 3 tire marks tire marks deposited by the Crown Victoria. Based on Figure 10, we can conclude that the post-impact yaw motion of a vehicle can be reconstructed using a single striated tire mark, so long as sufficient evidence is available to allow the analyst to identify which tire deposited the single tiremark. This also confirms that in the absence of braking, striations are deposited in a direction perpendicular to the tire.

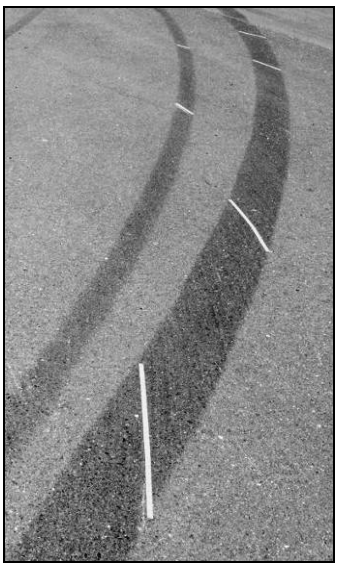

Figure 8 - Striations deposited during the PIT Test 2

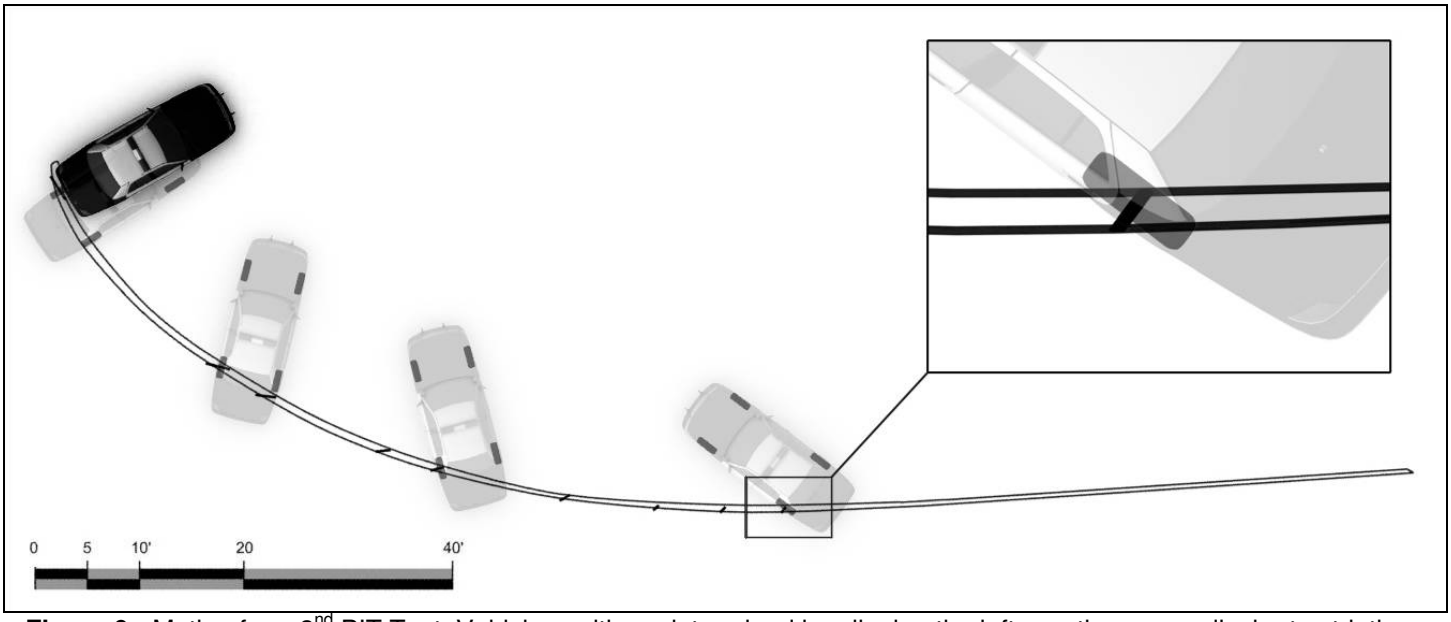

Figure 9 - Motion from 2nd PIT Test. Vehicle positions determined by aligning the left rear tire perpendicular to striations within the left rear tire mark. The remaining 3 tire marks have been hidden.

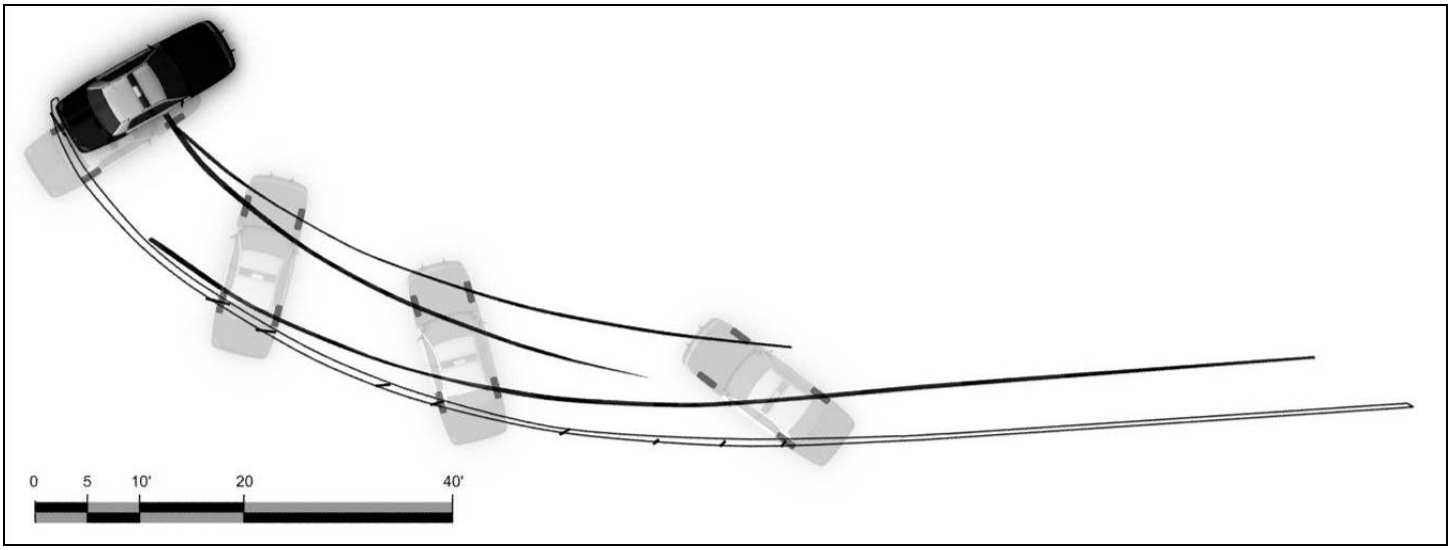

Figure 10 – Identical to Figure 9, with the exception that all the tire marks are shown.

STRIATION STUDY II: TIRE MARKS DEPOSITED FOLLOWING A LOSS-OF-CONTROL

In order to assess ability of striations to offer insight into braking and steering, the authors conducted yaw testing with a 2008 Chevrolet Malibu on August 18, 2008. The Malibu was outfitted with Hankook Winter Ipike tires, of size 225/60R16. The vehicle was also instrumented with data acquisition equipment from Racelogic. Specifically the VBOX IISX + Slip, Pitch and Roll Angle recorded the vehicle's angular and translational position and the Vehicle CAN Interface recorded wheel speeds and steering position from the Malibu's internal computer. All data was recorded at 20 Hz. Figure 11 depicts the Malibu test vehicle with the three VBOX GPS antenna attached magnetically to its roof. A professional driver was utilized for this testing.

Figure 11 – Test Chevrolet Malibu

During our testing with the Malibu, several attempts were made to induce a yaw using only steering inputs. Although tracking of the rear tires outside the front tires did occur during these attempts, yaw was insufficient to deposit striations that were distinguishable enough for this study. In order to induce yaw rotation of the magnitude needed for this study, it was necessary to apply the parking brake temporarily to initiate the yaw. After the yaw was initiated, the parking brake was released and striations were deposited using combinations of steering and braking.

The position of the vehicle at its starting and rest positions were surveyed. The tire marks and test surface were also surveyed and photographed and a test scene diagram was created. Individual striation marks were surveyed and documented photographically.

Following the test, the orientation of the front left tire associated with various steering wheel angles was surveyed across the full range of steering. During this process, the steering angles where recorded via the VBOX CAN Interface. This allowed for the authors to correlate the VBOX recorded steering data to the tire angle. The plot in Figure 12 depicts the tire angle versus the steering angle recorded by the VBOX for the front left and front right tires across the full range of steering of the Malibu. As can be seen in Figure 12, right and left tires are different, largely due to the Ackerman geometry. Figure 13 depicts three images from one of the Malibu yaw tests.

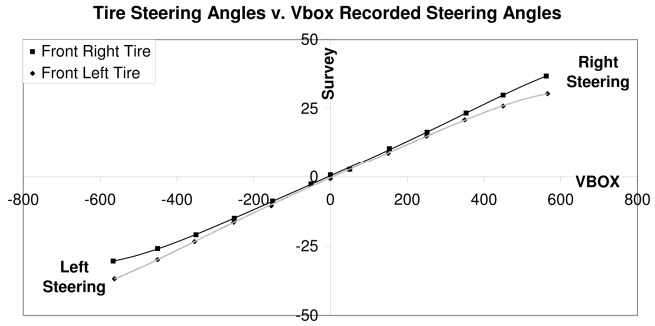

Figure 12 – VBOX recorded steering angles vs. tire angles through the full range of steering.

Figure 13 - Yaw Test 2 of Chevrolet Malibu.

As mentioned earlier, shoulder tread block sizes and spacing are variable on actual tires. The characteristics of tire marks, as one would expect, are heavily influenced by the characteristics of the tires depositing the marks. The tires used in these tests were chosen specifically for their large block shoulder tread pattern, which is similar to tires that are regularly seen on SUV's and light trucks and, which produce tire mark striations that are easier to identify. Each tire had 58 shoulder tread blocks around its circumference, which has implications in the analysis that follows. Figure 14 depicts the shoulder tread blocks as well as the shoulder wear on the front left tire as result of the testing.

The purpose of these tests was to determine the feasibility of using tire mark striations to predict braking and steering. For this vehicle, as is typically the case, only the front tires are steered. Thus, different analysis techniques can be used depending on whether a rear or front tire is of interest. In most occasions, as was the case in these tests, multiple tire marks are deposited when a vehicle yaws and the vehicle's yaw angle can be determined by alignment of the vehicle with the tire marks. Given that the yaw angle of a rear tire is the same as the yaw angle of the vehicle, the slip percentage can be easily calculated using Equation (30). This equation only requires that the slip angle of the tire and the striation angle are known. This implies that if a vehicle can be aligned with multiple tire marks, the amount of braking of a rear tire can be determined with a single striation. For front tires, both braking and steering are of interest so the spacing between the striations must be considered.

The results from analysis of the striation marks in both tests were compared to analysis of the VBOX recorded data. To achieve this comparison, it was necessary to link the VBOX data to the tire mark evidence on the roadway. This link was made possible through animation of the VBOX recorded angular and translational position of the vehicle. This data was animated over the top of the surveyed tire mark evidence which effectively linked the VBOX data and tire mark evidence in time. Once linked, VBOX data could be examined at each vehicle location of interest.

Figure 14 - Front left tire from Malibu.

TEST II

The results of the testing are more easily described beginning with the second test. In Test II, the Malibu was accelerated to a speed of approximately 48 mph. The parking brake was then applied and the driver made a steering input to the right initiating a clockwise yaw. The parking brake was then released and the driver applied the service brakes and counter-steered aggressively to the left. During the event, the vehicle yawed a total of approximately 90 degrees (see Figure 15). The driver stated that he braked significantly but that the ABS did not engage during the test. Upon inspection of the wheel speed data it was found that the ABS indeed did not engage during this test.

Seven positions along the path of the vehicle were analyzed. Six striation marks in the left rear tire mark were first examined with braking as the focus. A portion of the front left tire mark was then examined to determine steering and braking from the tire mark evidence. The positions of the Malibu analyzed are depicted in Figure 15. Position 4 is the approximate location of analysis of the front left tire. Three of the six positions of the left rear tire mark that were analyzed are indicated with tape in Figure 16. In Figure 16, the Malibu was travelling into the page.

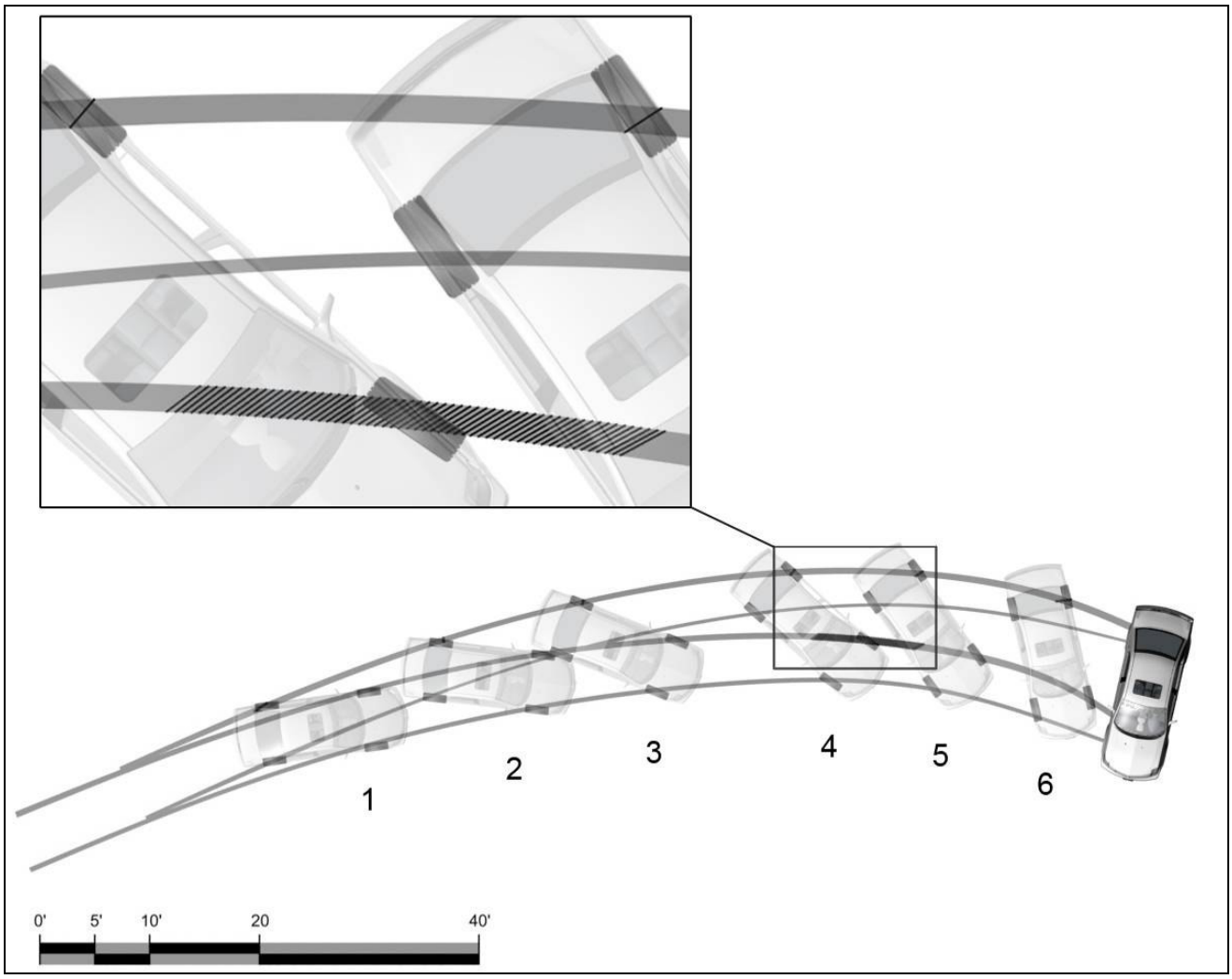

Figure 15 – Tire mark evidence, vehicle positions and rest position from Test 2.

Figure 16 - Left rear tire mark from Test 2.

Prior to performing calculations using the striation data, the VBOX collected data was analyzed for comparison purposes. To compute the slip percentage of the rear left tire using the VBOX data at each position, the slip angle, translational speed and rotational speed of the tire were required. The slip angle of the tire at each position was determined based on alignment of the vehicle on the tire marks. Since the rear tires cannot be steered, the heading direction of the rear tires are approximately the same as the heading direction of the vehicle. The slip angle of the tire, which is the angular difference between the tire's heading and tire's velocity direction, was measured. The translational speed of the rear left tire was calculated considering both the translational velocity recorded by the VBOX at the antenna location and the yaw velocity of the vehicle.

The rotational speed of the wheel output by the VBOX was given in feet per second, rather than a rotational velocity unit, due to a conversion performed by the vehicle computer, specifically, multiplication by a tire radius, r. The tires used during our testing were of slightly different radius than that used to convert the data by the vehicle computer. Therefore, the wheel speed data was scaled such that during straight line motion, when slip of the tires was zero, the translational velocity and pre-converted rotational velocity of the tire were equal. These values could then be inserted into Equation (5), shown in (5), shown in slightly different form below, to yield the VBOX slip percentage of the tire at the 6 locations.

$$S\%_{VBOX} = \frac{V_{Translational}\cos\alpha - V_{WheelSpeed}}{V_{Translational}\cos\alpha}\times 100 \quad (31)$$

The slip percentage was then calculated using the striation marks on the roadway with Equation (30), restated below, for comparison with the results from the analysis of the VBOX slip percentage.

$$S\%_{STRIATION} = \frac{\tan\alpha}{\tan(\theta+\alpha)}\times 100 \quad (32)$$

Again, α is the tire slip angle and θ is the striation angle in Equation (32). The slip angle at each position was previously calculated. The striation angle, which is the angular difference between a striation and the tire velocity direction at each respective location, was measured. The results of the slip percentage analysis at the 6 positions on the rear left tire mark in Test 2 are shown in Figure 17. The dashed line and solid line in Figure 17 connect the results from analysis of VBOX data with Equation (31) and results from the striation analysis with Equation (32), respectively.

In Test 2 the parking brake was engaged in combination with a right steering input. Once a clockwise yaw was initiated, the parking brake was released and the driver input aggressive counter-steering to the left and applied the service brakes. The sequence of the driver's braking actions is reflected in the plot of Figure 17. During the first position, the driver was in the process of releasing the parking brake, which resulted in approximately 60% slip. The next three positions have slip near 0 % and represent the time between the release of the parking brake and application of the service brakes. The slip percentage then increases to a value of over 10% by the 6th position as result of the service brake application.

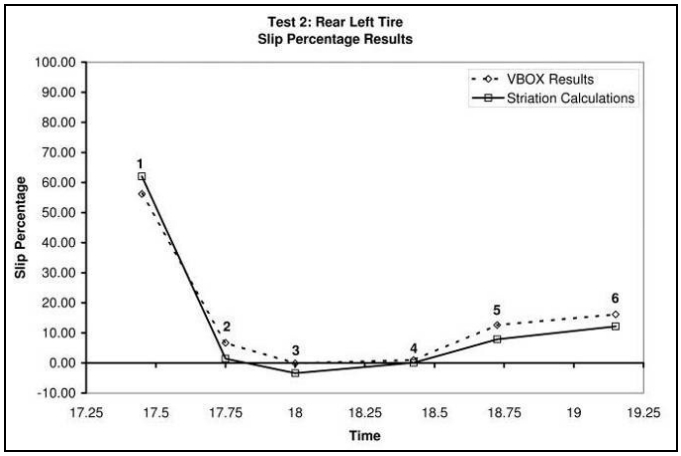

Figure 17 – Results from slip percentage analysis of the rear left tire in Test II.

The portion of the front left tire mark to be analyzed is shown in Figure 18, in which the vehicle was moving from left to right, across the page. In Figure 18, 58 striations have been identified and marked with chalk. As mentioned earlier, the tires used in this test had 58 tread blocks around their circumference. Therefore, over the course of depositing the 58 striations in Figure 18, the tire rotated one revolution. The average slip angle and average braking over the course of one tire revolution will be studied here.

Consideration of one tire revolution offered two benefits to the analysis. First, the tread blocks around the circumference are variable both in their size and in the spacing between them. To analyze the slip angle using less than 58 striations would have required knowing which individual tread blocks on the tire deposited each mark. If an entire revolution is considered however, Equation 2 can be rewritten as follows, where C_T is the circumference of the tire, and SD_{TOTAL} is the distance on the ground over which striations of number equal to the total number of tread blocks on the tire are deposited, as depicted in Figure 18. Analysis of one revolution also made the distances to be measured much larger, which reduced the sensitivity of the analysis to errors in measurements.

$$\alpha = \sin^{-1}\left(\frac{SD_{TOTAL}\sin\theta}{C_T}\right) - \theta \qquad (33)$$

Equation (33) was analyzed for the 58 striations which appear in Figure 18 using Monte Carlo Analysis. Monte Carlo analysis was used to monitor the potential measurement errors in the striation direction and spacing. The overall length of the 58 striations, SD_{total}, was varied by ±1 inch uniformly. The average striation angle, θ, between the 1st and 58th striations was used, and varied uniformly ±1 degree. The circumference of the tire, C_T, was measured at the tire shoulder. Since the steering angle of the tire is the difference between the yaw angle of the vehicle, and the slip angle of the tire, α, the yaw position of the vehicle was needed. The yaw position at the midpoint of the length SD_{TOTAL} was determined by alignment with the tire marks and varied uniformly by ±1 degree.

The steering angle was recorded by the VBOX CAN interface from the Malibu's onboard computer. The VBOX slip percentage was calculated in similar manner to that of the rear tire, with the exception that slip angle was determined using both the yaw position of the vehicle as aligned with the tire marks and the VBOX recorded steering angle.

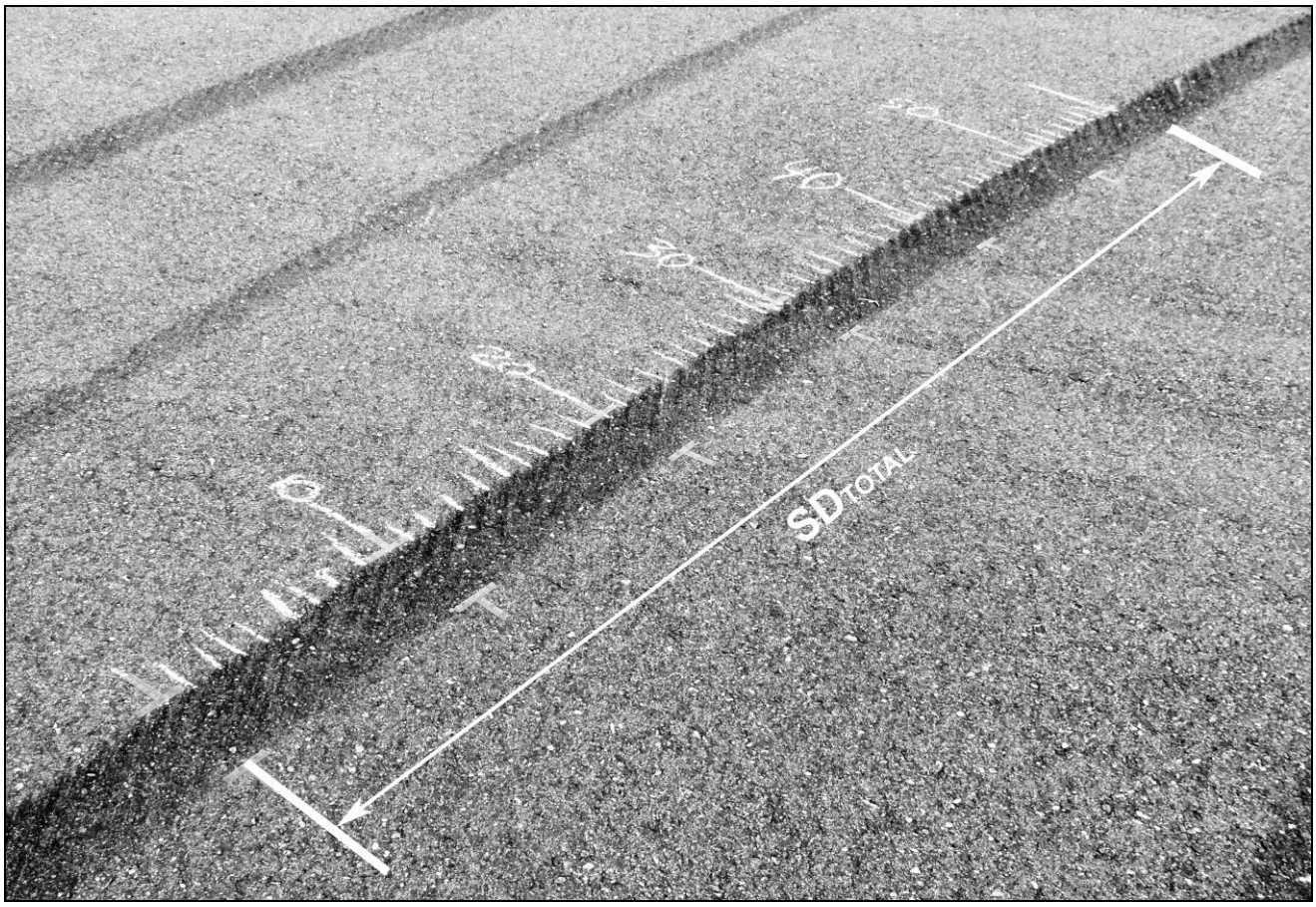

Figure 18: Front left tire mark from Test 2.

The results of the Monte Carlo analysis are displayed in the three distribution charts of Figure 19. In each plot, the actual value, as calculated with the VBOX data, is indicated with a vertical line, and numeric value. The first plot displays the range of values for the angle of the tire. The second plot displays the steering wheel angle and was calculated by multiplying the angle of the tire by the steering ratio, which is approximately 16.4 for this particular vehicle.[2] The third plot displays braking in the form of slip percentage.

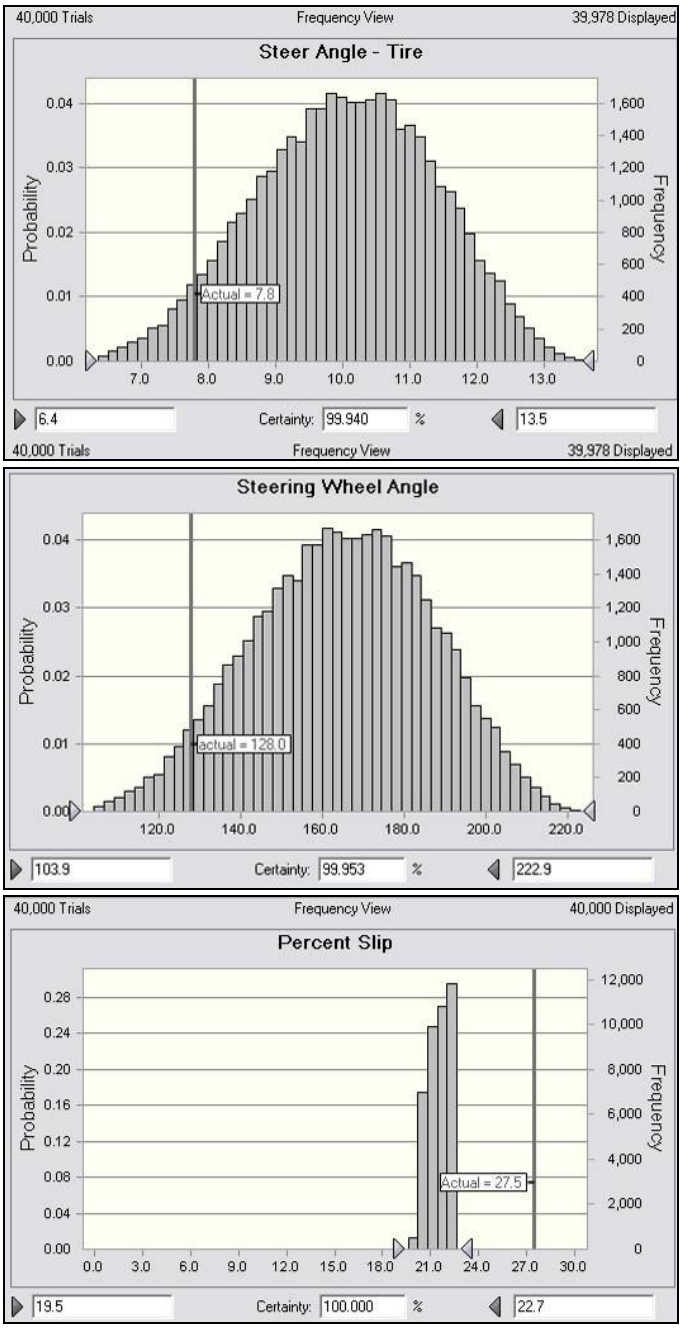

Figure 19: Results of the analysis of Test 2.

As can be seen in the first two plots, a large range of steering angles resulted from the variance of the inputs. However, all computed values indicated significant counter-steering to the left, consistent with the actions of the driver. The VBOX recorded steering angle of 7.8 degrees at the tire, or 124 degrees at the steering wheel, was encompassed in the range of values calculated from the striation marks.

The VBOX calculated slip percentage of approximately 27.5 did not fall within the range of computed values, which ranged from 19.5 to 22.7. However, the results of both the VBOX recorded and striation calculated slip percentages indicate significant braking at this analyzed position.

TEST I

In Test I, the Malibu was again accelerated to a speed of approximately 48 mph. The parking brake was applied and the driver made a steering input to the left initiating a counter-clockwise yaw. The parking brake was then released and the vehicle yawed approximately 180 degrees. Once the parking brake was released, no additional braking occurred and no attempts at counter-steering were made by the driver. The authors analyzed one section of the front right tire mark, 58 striations in length, shown in Figure 20. The vehicle was travelling into the page in Figure 20.

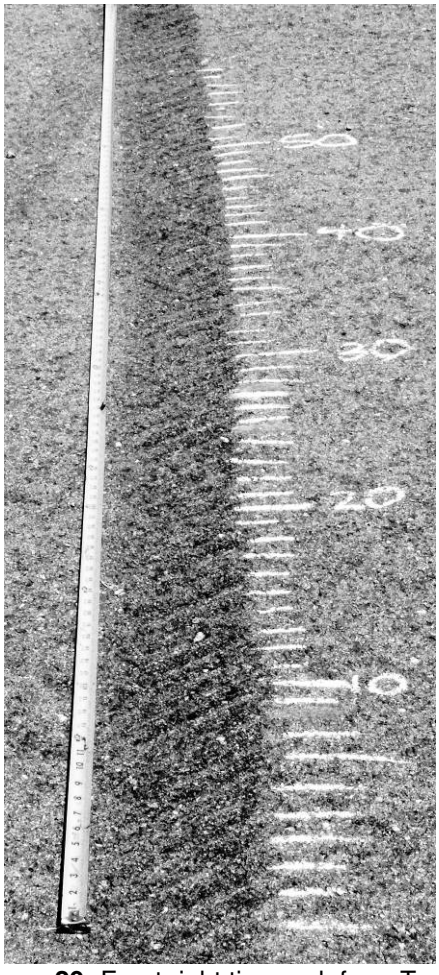

Figure 20: Front right tire mark from Test I.

[2] Manufacturer specifications.

Similar to Test II, the striations and the data recorded by the VBOX were analyzed and compared. According to the VBOX data, at the time this mark was deposited, the steer angle at the front right tire was negligible, approximately ½ degree to the left. The driver input no braking after the parking brake was released so the slip percentage throughout the yaw was zero.

The striation marks were analyzed in the same manner as Test II. All inputs were varied by the same amount. Unlike Test II, the results of the analysis of the striations in Test I were not in agreement with the analysis of the VBOX results. The striations indicated aggressive rightward steering, 40 to 240 degrees at the steering wheel when in reality the steering was negligible at this time.

The striations also indicated slip percentages between 0 and 13 percent when in reality no braking was occurring. The root cause of this disagreement was found to be the sensitivity of Equation (33) in the no braking case, when the term identified as Equation (34) approaches 1.

$$\left(\frac{SD_{TOTAL} \sin\theta}{C_T} \right) \tag{34}$$

In calculating the slip angle with Equation (33), the arcsine of the term above is evaluated. At values near 1, small changes in the term above result in large changes in the arcsine of the term. When this term equals 1, the arcsine is equal to 90 degrees. At values over 1, the arcsine results in an error. In the context of our analysis, the same range was used for the input variables in both tests, but the output ranges in Test I were much larger.

At first glance, this sensitivity in the no braking case appears to present a problem to striation analysis. However, the fact that, at least in these two cases, the model appears to return satisfactory results in the case of braking and overly sensitive results in the case of no braking can actually be of advantage. In the analysis of Test I, it was found that a value SD_{TOTAL} less than 1 inch greater than the measured value returned an error. By contrast, in the analysis of striations in Test II, the length SD_{TOTAL} could be increased by over 10 inches before errors were returned. The fact that the results in Test I resulted in errors with minor changes to SD_{TOTAL} gave good indication the tire was near zero percent slip. The sensitivity of these equations will be discussed in greater detail later.

For now, recall that in the no braking case striations are deposited perpendicular to the tire. If the proximity of the calculated slip angle to an error output was used to assume that no braking occurred at the time, the tire could simply be aligned perpendicular to the striation mark to determine the slip angle, α. The authors used this approach and aligned the tire perpendicular to the 1st and 58th striations yielding tire angles of 2.2 degrees and 0.5 degrees respectively. Again, the steering angle of the tire as recorded was 0.5 degrees. Figure 21 depicts the position of the vehicle at these two positions, as well as the rest position.

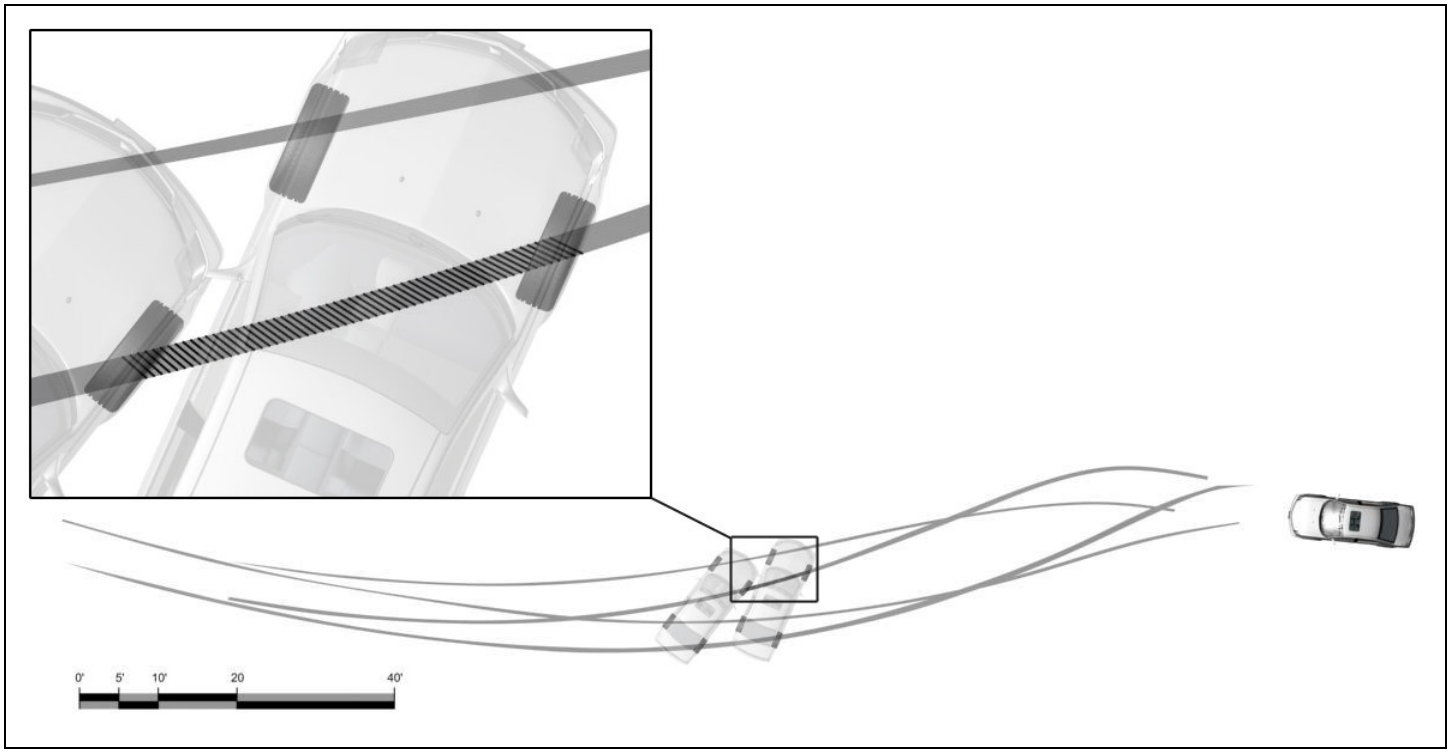

Figure 21 – Tire mark evidence, vehicle positions and rest position from Test 1.

DISCUSSION

It was found that information exists within yaw mark striations that can offer insight into the actions of the driver at the time the yaw marks were being deposited. It was also confirmed that it is possible to reconstruct post-impact yaw motion with a single striated rear tire mark. Although challenges arose from sensitivities in the measurements and in the equations, it was still possible to draw generalized conclusions from the striations, such as whether the driver was steering significantly in one direction or if the brakes were applied.

It is possible that refinements in measurement and analysis techniques could improve the results of striation analysis. In these tests, only the leading side tires deposited identifiable striations. It is often the case though, that leading and trailing side tires both deposit identifiable striated marks. If one were to analyze both the right front and the left front tire mark striations, and could reach some commonality, greater confidence in calculated steering angles could potentially be achieved. These authors will be experimenting with test conditions in the attempt to deposit distinguishable striated tire marks at all four tires.

It was found that the most significant limitation in determining steering angles was the fact that it is not the angle of the tires, but angle of steering wheel that is of interest. The steering ratio of the Malibu, or ratio between the angle of the steering wheel and angle of the tires, was approximately 16.4:1. This being the case, any errors that existed in determining the angle of the tire were multiplied by 16.4 when examining the steering wheel.

In the case of braking, it was slip percentage that was calculated in this study. In the context of accident reconstruction though, it is the rate of deceleration of the vehicle that is of primary interest. The manner in which deceleration and slip percentage are related is non-linear and is surface, tire and slip angle dependant. The authors do not intend to take up a full treatment of the topic here. For the purpose of this paper, suffice it to say that, in Test I, the test without braking, the vehicle decelerated at an average rate of approximately .46 g's. By comparison, the driver reported braking aggressively in Test II, and the vehicle decelerated at an average deceleration of .68 g's. In Test II, both the VBOX and the striations indicated that application of the brakes resulted in 10 to 20 percent slip at the rear left tire and approximately 28 percent slip at the front left tire. The fact that braking during a yaw produces different amount of slip at each tire presents another interesting topic for future work.

The results of the analysis of Test I deserve more attention. Recall that the slip angle equation, Equation (33), was extremely sensitive near the case of no braking. The authors proposed using this sensitivity to their advantage as a way to establish that no braking was was occurring at that tire. In the no braking case, the tire could simply be aligned perpendicular the striations, yielding the slip angle, and subsequently, the steering angle. The results of Test 1 revealed the sensitivity of Equation (33) in the no braking case. The sensitivity of Equation (33) is also dependant on the striation angle, θ, with larger striation angles increasing sensitivity. In comparing the results of Test I and II, the overly sensitive slip angles calculated in Test I allowed for a no braking determination to be made. Caution should be observed, however, in establishing no braking in this way. A full sensitivity study of these equations is needed before the results of these two tests can be generalized over a complete range of striation angles. This sensitivity study is currently being conducted by the authors.

The ABS did not engage in either of the tests. Since the rotational speed of the tire directly contributes to the striations that are deposited, it would be interesting to include a case where the ABS engaged in future testing. Similarly, it would be worthwhile to include vehicles equipped with ESC in a future study.

As described earlier, the equations presented in this paper assume a rigid tire. In reality, the tire does deform extensively in some high slip angle maneuvers that deposit striated tire marks. In the two tests analyzed in this study, errors due to sensitivities in the equations make it unclear how tire deformation affected the results. It is possible that modifying the model to include deformation would improve the results. It is also possible, however, that uncertainties that arise in modeling the deformation of the tire could make the model less accurate. In any case, there were some findings from this research that may be useful considerations for tire modeling theory. For one, the striations do indicate the direction of the friction force. This coupled with the ability to determine the approximate slip angle from the tire marks could be useful information for modeling tire behavior.

Consider again Figures 1 and 3, combined below in Figure 22. In the tire mark on the left, a clear distinction between light and dark striations is visible on the tire mark. The tire marks deposited in the testing performed in this study did not display a similar light/dark distinction likely due to tire and test condition differences. In tire marks that are deposited prior to actual accidents, this light/dark distinction is often present. The graphic on the right describes how one could potentially align a tire on a tire mark similar to the one on the left after determining the slip angle using the methods presented in this paper.

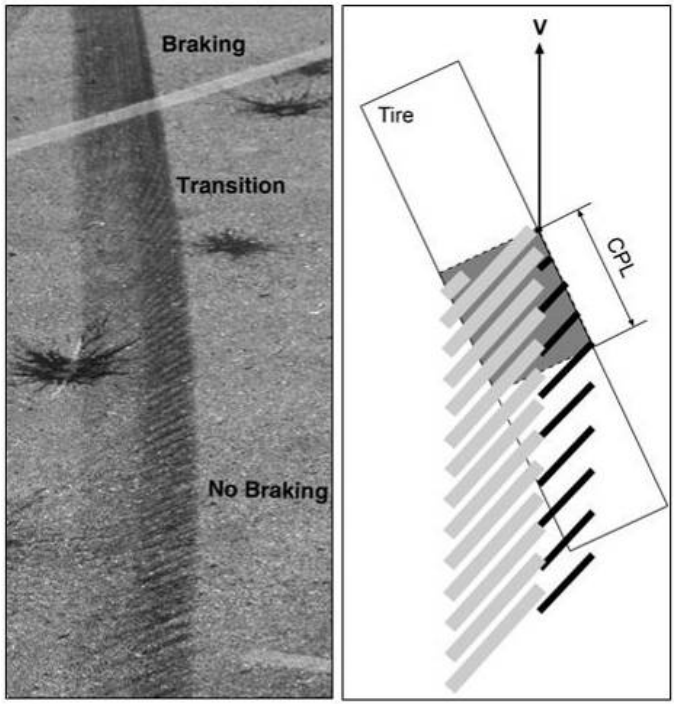

Figure 22

Alignment of a tire on a tire mark with a light/dark distinction in this way inherently reveals the actual contact patch length of the tire. The contact patch length could certainly be of use in modeling the deflection of a tire since contact patch length is directly related to deformation. Contact patch length is also directly related to tire inflation pressure. The authors are currently investigating the effect tire under inflation has on the appearance of deposited striations.

In all of the analysis presented above, it was necessary to align the vehicle over its tire marks. Due to two factors, tire deformation and steering of the front tires, alignment of the tires to the tire marks required some judgment on the part of the analyst. Tire alignment over tire marks is an area in need of more research and is another focus of ongoing work.

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REFERENCES

1. Daily, John, Shigemura, Nate, Daily, Jeremy, “Linking Road Evidence to Vehicle Performance By Using A Novel Paint Ball Marking System”, http://www.jhscientific.com/DRMS/index.html.

2. NHTSA, “An Experimental Evaluation of 26 Light Vehicles Using Test Maneuvers That May Induce On-Road, Untripped Rollover and a Discussion of NHTSA’s Refined Test Procedures: Phases 6 and 7 of NHTSA’s Light Vehicle Rollover Research Program.” October 2003

3. Gillespie, Thomas D., “Fundamentals of Vehicle Dynamics.” SAE, 1992.

4. Reveley, Mary S., Brown, Douglas R., Guenther, Dennis A., “A Comparison Study of Skid and Yawmarks.” SAE, 890635.

5. Baker, Kenneth S., “Traffic Collisions Investigation.” Northwestern University Center for Public Safety, 2001.

6. Daily, John, Shigemura, Nathan, Daily, Jeremy. “Fundementals of Traffic Crash Reconstruction.” IPTM, 2006.

7. Milliken, William F., Milliken, Douglas L. “Race Car Vehicle Dynamics.” SAE, 1995.

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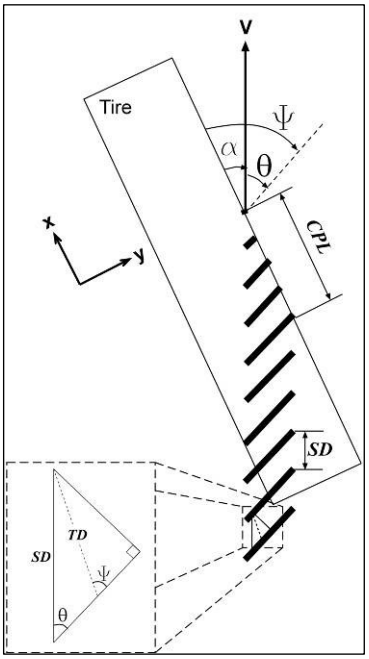
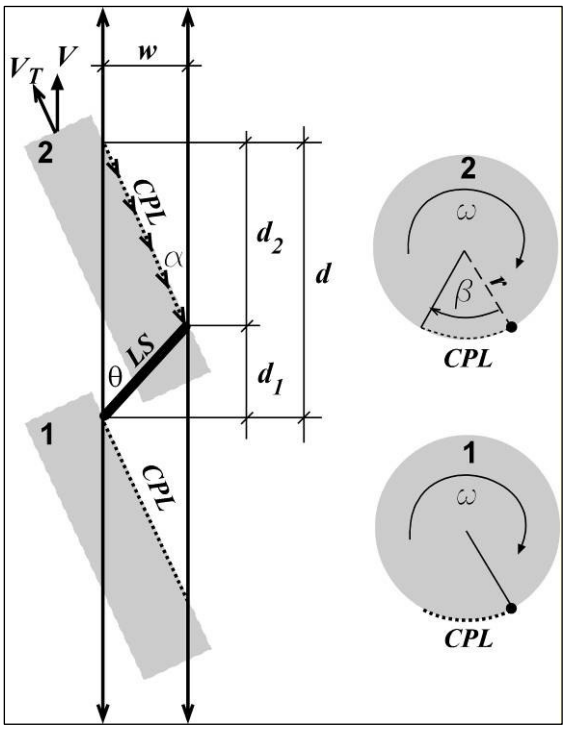
APPENDIX A: NOMENCLATURE



α	Tire slip angle
Ψ	Angle between tire heading and striation mark
θ	Angle between tire mark direction or wheel hub velocity
SD	Distance from leading edge of one striation to the leading edge of an adjacent striation, measured along tire mark direction, or wheel hub velocity direction
TD	Distance from leading edge of one striation to the leading edge of an adjacent striation, measured perpendicular to striation
V	Translational velocity of wheel hub



β	Angle rotated by tire during one point on the tire's contact with the ground
ω	Rotational velocity of tire
CPL	Contact patch length
d	Summation of d_1 and d_2
d_1	Length of striation mark measured along the tire mark direction or wheel hub velocity direction
d_2	Contact patch length measured along the tire mark direction or wheel hub velocity direction
LS	Absolute length of striation
r	Tire radius
V_T	Translational velocity of wheel hub along tire heading
W	Tire mark width

C_T	Tire Circumference
S	Braking slip
SD_{TOTAL}	Distance from leading edge of one striation to the leading edge of the x^{th} later striation, measured along tire mark direction, or wheel hub velocity direction
$S\%$	Braking slip percentage
$S\%_{STRIATION}$	Braking slip percentage calculated from striations
$S\%_{VBOX}$	Braking slip percentage calculated from VBOX recorded data
$V_{Translational}$	Translational velocity of wheel hub, calculated from VBOX recorded data
$V_{WheelSpeed}$	Converted wheel speed from VBOX, given in mph