

Tire Mark Analysis of a Modern Passenger Vehicle with Respect to Tire Variation, Tire Pressure and Chassis Control Systems

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ABSTRACT

Tire mark analysis is an important factor in accident reconstruction. A precise determination of pre- and post-crash speeds as well as longitudinal and lateral accelerations from tire marks contributes significantly to a reliable accident reconstruction.

Continuous advancements in tire and vehicle technology – in particular with respect to modern control systems such as anti-lock braking systems (ABS) – raises the question what role tire marks play in accident reconstruction today. Moreover, this accompanies the question to what extent potential interventions by vehicle control systems such as the electronic stability program (ESP®) resp. the electronic stability control (ESC) can be identified in a tire mark. The widespread use of these systems today makes them increasingly important in accident reconstruction.

In response to these questions, as well as how different tire pressures (very low, normal, very high tire pressure) and tire types (summer, winter, run-flat tires) affect tire marks, a modern passenger car was equipped with extensive measuring technology to collect vehicle driving dynamic data. Longitudinally and laterally dynamic driving maneuvers, as well as combinations of both, were carried out systematically on a test track under nearly constant conditions.

ESC control system interventions were strategically triggered for tire mark analysis during highly dynamic evasive maneuvers.

All driving maneuvers were recorded using onboard instrumentation. The tire mark tracks produced were measured and documented photographically.

Based on the correlation of the tire marks to the objective measuring data, important insights were gained concerning circumstances under which tire marks can result from passenger cars, both in laterally and longitudinally dynamic accident scenarios, as well as under the influence of chassis control systems.

INTRODUCTION

According to DANNER/HALM [1], tire marks on paved road surfaces (asphalt, concrete, etc.) are caused by friction marks. DANNER/HALM [1] define the term “friction marks” as all mechanical removal or any chemical alterations that can be traced back to a relative, sliding motion. Hence, longitudinal and lateral slip take on a central role when friction marks are produced. According to DANNER/HALM [1], other factors influencing tire mark properties are suspected, such as tire design and construction, tire pressure and the road surface.

It is suspected that there is a direct correlation between the intensity of a tire mark track made on paved road surfaces and the percentage of bitumen content [1] in the road surface. Other sources such as DIEKEL [2] or police accident reports also suggest that the bitumen content in an asphalt road surface is the primary reason for a dark, substantial tire mark. In contrast, concrete

road surfaces are characterized by a less intense tire mark.

The existing trade literature has only briefly addressed the conditions and boundaries necessary to create tire marks. DANNER/HALM [1] claim a longitudinal slip of 8% - 10% at the wheel while driving straight, or a 5° to 10° side-slip angle at the wheel while cornering as a prerequisite for producing a tire mark. The longitudinal slip s and the side slip angle α at the wheel are defined by (see Figure 1):

$$s = \frac{v_F - v_w}{v_F} * 100\% \quad \text{with} \quad v_w = r * \omega \quad (\text{eq. 1})$$

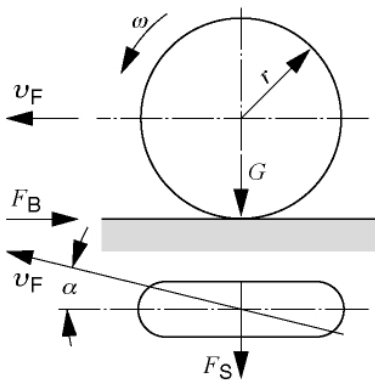


Figure 1: Wheel while braking and cornering, α tire slip angle, v_F vehicle speed, r tire radius, ω angular velocity, F_B braking force, F_s lateral force, G force due to weight [11]

Experts in accident reconstruction state that the visibility threshold for braking tire marks on asphalt is a minimum deceleration of approx. -6 m/s². However, DIEKEL [2] maintains that when cornering, tire marks only occur in the range of maximum lateral acceleration.

Obtaining as precise as possible deceleration values in longitudinal and lateral directions, while a visible tire mark is being produced, is considered a reliable basis to calculate pre-accident vehicle speed. REVELEY et al. [3], among others, have examined the main qualifying factor that has been established for reverse calculation methods. According to BRACH [4], reverse calculation becomes particularly difficult if the vehicle was also braked while cornering, or if the vehicle became unstable, which DICKERSON et al. [5] confirms. CLIFF et al. [6] states that there is no significant impairment to this process of reverse calculating if only light braking (up to 0.3g) occurs during cornering. However, it is primarily the assumed coefficient of friction in the lateral direction that is consistently considered crucial to accurately reverse calculate and reconstruct the accident sequence.

In addition to visibility thresholds, the maximum achievable deceleration values for braking, cornering

and braked cornering are considered primary factors for reconstructing accidents.

The introduction of modern control systems such as the anti-lock braking system (ABS) and the electronic stability program (ESP®) raises the question to what extent such systems affect tire mark creation.

Figure 2 shows the ABS braking mark tracks of one of the first systems from the early 80s. The ABS braking marks were less intense than locked-wheel braking marks in years prior to anti-lock braking intervention, and were clearly broken up into segments. These intermittent braking marks were referred to as “control patches,” which are due to the increase and decrease of a braking wheel’s slip during ABS control interventions.

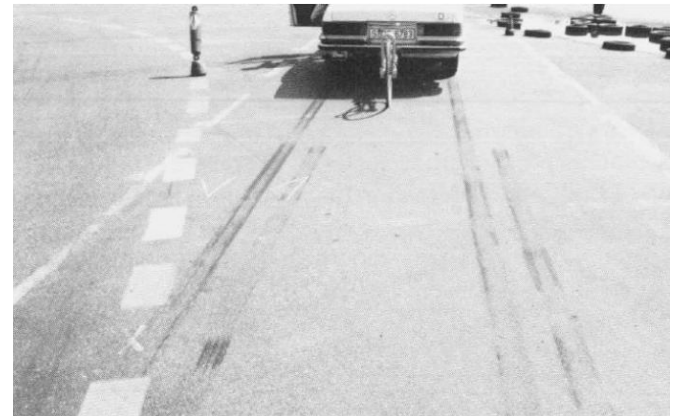


Figure 2: ABS-induced braking mark tracks from one of the first vehicles equipped with ABS, according to BURKHART [7]

In 1989, GRANDEL [8] examined the differences between ABS braking marks in comparison with those created using braking with wheel lock, and found that intensity of ABS-induced braking marks were considerably lighter, and in approx. 20% of cases, were no longer discernible. In 1990, ENGELS [9] assumed that ABS braking marks were a suitable factor in accident reconstruction, but he also stated that in three-fourths of all cases, these types of tire marks were either not discernible, or, not discernible enough to be evaluated. ENGELS [9] anticipated that in the future, braking marks would become even less visible due to either improvements/minimization in the control cycles in modern anti-lock braking systems. An assumption found in current literature [2] also claims that an ABS-induced braking mark consists mainly of “control patches,” and does not possess the properties of a solid, continuous tire mark.

Information and assumptions regarding tire mark properties that passenger vehicles produce serve as an important basis for reconstructing accidents, but some of these assumptions are now more than 20 years old. Since then, tires, suspension, the brake system, and in particular, modern driving dynamics control systems such as the anti-lock braking system (ABS) and the

electronic stability control (ESC) have undergone constant advancement.

A test concept was developed in order to analyze the tire mark characteristics produced by a contemporary passenger vehicle equipped with modern tire generations and chassis control systems. Extensive driving tests were performed, and the resulting tire marks were analyzed with the use of precise measuring technology.

METHODOLOGY

Tire marks on asphalt road surfaces can be produced in longitudinal driving maneuvers (straight line braking), and in lateral dynamic driving maneuvers (stable and unstable cornering) (see Table 1). Combinations based on these two main maneuvers are also possible.

Table 1: Tire mark classification and evaluation

Tire Mark Classification and Evaluation	
Longitudinal Vehicle Dynamics	Lateral Vehicle Dynamics
Braking marks (straight line braking)	Yaw marks (stable cornering)
	Skidding marks (unstable cornering)
→ Evaluation of tire mark by intensity and characteristics	

Accordingly, the test concept to analyze tire marks included straight line braking maneuvers and stationary cornering at varying levels in longitudinal and lateral acceleration. Furthermore, a dynamic evasive maneuver was performed to produce “spin-out” skidding marks and to evaluate the influence of the chassis control system. The produced tire marks were analyzed for tire mark intensity (i.e. visibility) and characteristics.

Table 2: Test matrix: Scheme of variation for evaluating tire marks

maneuver	tire variations (dimension 225/45 R17, 91Y/H)						acceleration		chassis control	
	brand	type (speed index)	tire pressure [bar]				longitudinal/lateral		ABS/ESC	
			2.3 (standard)	3.3	1.3	0	maximum	gradation	On	Off
braking marks	Continental Sport Contact 3	summer (Y)	x	x	x	-	x	x	x	-
	Pirelli Sottozero W210	winter (H)	x	x	x	-	x	x	x	-
	Goodyear Excellence ROF	run-flat (Y)	x	-	-	x	x	-	x	-
yaw marks	Continental Sport Contact 3	summer (Y)	x	x	x	-	x	x	x	-
	Pirelli Sottozero W210	winter (H)	x	x	x	-	x	x	x	-
	Goodyear Excellence ROF	run-flat (Y)	x	-	-	x	x	x	x	-
skidding marks (unstable)	Continental Sport Contact 3	summer (Y)	x	-	-	-	(x) unstable	(-)	x	x
	Pirelli Sottozero W210	winter (H)	x	-	-	-	(x) unstable	(-)	x	x
	Goodyear Excellence ROF	run-flat (Y)	x	-	-	-	(x) unstable	(-)	-	-

Tire design, construction and tire pressure are fundamental parameters influencing tire mark properties. For this reason, three tire variants were selected with the tire dimension 225/45 R 17, which is in widespread use on modern, mid-class passenger vehicles (see Figure 3 and appendix A1. for static tire contact area with standard tire pressure):

- Summer tire (Conti Sport Contact 3)
- Winter tire (Pirelli Sottozero W210)
- Run-flat tire (Goodyear Excellence ROF, summer)

It was suspected that a run-flat tire would produce altered tire marks due to the reinforced tire shoulders.



Figure 3: The tire variants used (dimension 225/45 R17)

In order to analyze the influence of the tire pressure on tire mark characteristics the standard 2.3 bar (33 psi) tire pressure for the test vehicle was varied by +/- 1 bar (15 psi). These deviations are barely noticeable by looking at the tire, and therefore mimic everyday situations in which vehicles are not properly maintained. At reduced tire pressure, BAKER [10], among others, describes an altered tire mark characteristic in the tire shoulder areas, which become stressed from assuming a greater portion of the load. In addition, driving tests were executed on depressurized run-flat tires in order to evaluate tire mark properties as well. Table 2 shows the complete test matrix.

The test vehicle was a modern Mercedes-Benz CLK500, MY 2005 passenger vehicle (data see appendix A2.) equipped with modern chassis control systems (ABS¹, ASR², BAS³ and ESC). It was outfitted with extensive measuring technology to accurately record the various driving conditions (Figure 5). In addition to an inertial measuring platform (iMAR iDIS-FMS-1) to capture the precise vehicle motion (installed in the area of the passenger seat, close to the center of gravity), an optical Correvit-sensor was used to accurately and independently record vehicle ground speed.

In addition, various measured data was recorded from the vehicle's internal communication network (CAN⁴ bus), e.g. the wheel rotational speeds, which were used as the basis for calculating longitudinal slip at the wheels (see appendix A3. for recorded channels). The longitudinal slip at the wheels was calculated using eq. 1.

The tire slip angles were estimated based on simplified bicycle-model assumptions, which were applied to static steering ratio and precisely measured factors for the steering wheel angle, vehicle speed, yaw rate and side-slip angle of the vehicle. The bicycle model represents a reasonable approximation for tire slip angle.

Tire slip angles are calculated using the following equations and Figure 4:

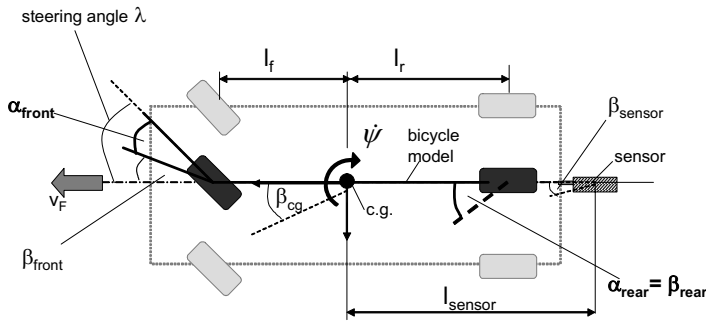


Figure 4: Bicycle model for calculation of tire slip angles

The side slip angle at center of gravity β_{cg} is calculated using the precisely measured side slip angle β_{sensor} and yaw-rate $\dot{\psi}$ by

$$\beta_{cg} = \arctan \frac{v_{y,cg}}{v_F} = \arctan \left(\tan \beta_{sensor} - \frac{l_{sensor}}{v_F} \dot{\psi} \right) \quad (\text{eq. 2})$$

The tire slip angle α_{rear} at the rear axle is estimated to be consistent with the vehicle's side slip angle at the rear axle β_{rear} :

$$\alpha_{rear} = \beta_{rear} = \arctan \left(\tan \beta_{cg} + \frac{l_r}{v_F} \dot{\psi} \right) \quad (\text{eq. 3})$$

The tire slip angle α_{front} at the front axle can be estimated with the bicycle model to

$$\alpha_{front} = \lambda - \beta_{front} = \frac{\lambda_s}{i_G} - \arctan \left(\tan \beta_{cg} - \frac{l_f}{v_F} \dot{\psi} \right) \quad (\text{eq. 4})$$

with

λ	steering angle at front axle
λ_s	steering wheel angle
i_G	static steering ratio
v_F	vehicle speed

All data were collected with a sampling rate of 200 Hz.

One important basic principle of this research was to link precise measured data with the tire marks that were produced, as well as the photographic documentation.



Figure 5: Test vehicle (Mercedes-Benz CLK) with measuring equipment

A light barrier was installed at the front of the vehicle and a corresponding reflector was affixed to the test track (Figure 5) so that the measured data could be precisely assigned to the proper tire mark. The reflector also served as a point of reference for measuring the tire marks and for the photographic documentation. Starting with this point of reference (the reflector), pylons were set up every 10 meters. After each driving test, the road surface was photographed at these distance intervals using a high-resolution, digital SLR camera. Pylons were positioned on the outside of each tire mark track. Figure 6 shows a typical measuring setup.

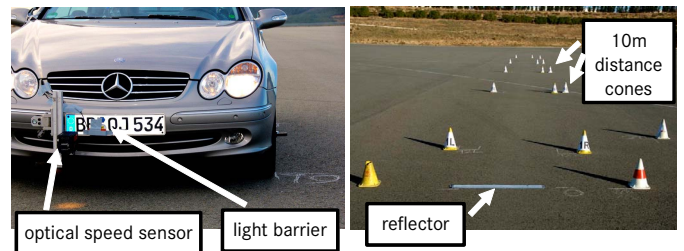


Figure 6: Measuring technology and measuring setup for documenting tire marks.

¹ ABS - anti-lock braking system

² ASR - anti-slip regulation

³ BAS - brake-assist system

⁴ CAN - controller area network