Vehicle collision simulation based on non-classic tire traces

M Śledziński\textsuperscript{1} and A Lewandowski\textsuperscript{2}

\textsuperscript{1}Poznań University of Technology, Piotrowo 3, 61-138 Poznań, Poland
\textsuperscript{2}Institute of Forensic Research in Cracow, Westerplatte 9, 31-033 Kraków, Poland

E-mail: michal.sledzinski@put.poznan.pl

\textbf{Abstract.} In traffic conditions, vehicle collisions often result in tire traces on the road, vehicles and humans. Tire traces on the road can have diverse characteristics. A non-classic form of such traces is the subject of the present analysis. The selected non-typical trace form is characterized by a segmental course with diverse geometric features. The goal of this work is a full analysis of the trace generation mechanism using modern simulation tools. In the paper, the influence of selected vehicle parameters and road surface characteristics on the trace form have been analyzed. Research results indicate the usefulness of PC-Crash software for analyzing road accidents, also in regards to non-typical tire traces.

1. Introduction

As a result of vehicle collision, damage and displacement occurs, causing, among others, the formation of tire traces on the road. The vehicle collision mechanism is varied, resulting in a variety of tire trace types. The resulting tire traces can form a straight line or a more complex shape. Typical tire traces formed on the road surface after collision are, for example: tire prints, brake marks, traces of friction or yaw marks [1]. Figure 1 demonstrates an example of classic tire trace types. As a result of the frictional forces acting at the point of contact between the tire and the road, particles of tire material are left on the road surface. This process depends on the temperature at the point of contact and the structure of the road surface. The geometry of the tire trace on the road surface can be described with parameters such as: direction of tire trace application, tire trace curvature radius, tire trace grain. Analyzing the above mentioned geometric characteristics of the tire trace provides a number of useful information from the standpoint of reconstructing of the vehicle accident. Such data include: type of crash and forces occurred, post-collision displacement of vehicles, changes in velocity and place of collision. The examination of macroscopic characteristics in form of striae in the tire trace allow to determine the change in vehicle acceleration characteristics during unstable movement [2–4]. The characteristics of the vehicle tire traces when decelerating allow to calculate the delay in the braking process on different surface types [5]. The characteristics of acceleration marks of vehicles equipped with snow chains may be the basis for determining the traction characteristics in winter conditions [6].

2. Tire trace characteristics

Right characterization of the tire traces located on the road surface should include photographic documentation together with detailed measurements of tire trace geometry at the location of the traffic accident [7]. This facilitates further processing of such data with employment of advanced methods of analysis, e.g. photogrammetry [8]. Selected examples of classical vehicle tire traces on the road surface are shown in figure 1.
Figure 1. Classic vehicle tire traces: a – straight; b – curved.

The straight line tire trace (figure 1a) constitutes a typical traces left by blocked vehicle tires, which is left when the braking moment is the same on both sides of the vehicle. The tire trace shape varies with changing coefficient of tire adhesion to the road surface, e.g. when driving over wet, icy or contaminated area of the road [6]. Different factors cause curved tire traces to be left on the road surface. Such factors can include, among others: maneuvers attempted by the driver, local changes in road surface condition or failure to adapt the driving speed to the situation and road conditions. Figure 1b presents a classic curved tire trace. The presented skid mark was formed by sudden change of driving direction without engaging the brakes. Figure 2 presents the macroscopic imaging of skid marks in form of characteristic, striae the characteristics thereof including trace width and inclination of the line between the tangent and the trace striae allow to determine the variance in accelerations of the vehicle in its curvilinear motion [4].

Figure 2. Macroscopic imaging of vehicle yaw traces.

Tire traces with complex structure [9], referred to in this work as “non-classical” are different from straight-line tire traces as shown in figures 1 and 2.

3. Analyzing the tire trace geometrical characteristics identified during a traffic accident

The subject of the analysis is the tire trace formed during an actual traffic accident involving a collision between a school bus and a truck [10]. The tire trace represents the motion of the rear left wheel of the bus after the collision as shown in figures 3 and 4.

The methodology of accident analysis involved: measuring the geometric characteristics of the tire trace, the data from the bus tachograph unit, geometric data and vehicle weight information as well as carrying out simulations. Figure 4 demonstrates a photogrametric transformation which allows to analyze the geometrical properties of the tire trace [11]. The tire trace indicated above consists of a curved line resulting from the wheel yaw [4] and a straight-line section caused by wheel rolling until the vehicle stopped. The graphic methods were used to determine: the length of the initial section of the
tire trace (1.2 m) and the average angle of the trace in relation to the driving direction of the bus prior to the collision (54°) the length of the straight line section (0.7 m), its angle of inclination (27°). The simulation analysis of convergence of the simulated and actual tire trace allows to determine the parameters of motion of vehicles at the moment of impact, e.g. the sought parameters of motion of the truck involved in the collision [12].

Figure 3. Bus wheel tire trace. Figure 4. Photogrammetric transformation of the bus wheel tire trace.

4. Simulation testing of the influence of collision parameters on tire trace geometry
Factors affecting the tire trace include: type and quality of the tire and road surface, mass and moment of inertia of both vehicles as well as the pre-collision movement parameters of the vehicles [9]. For the purpose of analyzing individual factors affecting the tire trace, an advanced simulation software PC-Crash [13, 14] was employed. The basis for comparative analysis was assumed to be the simulation of an actual collision of a bus and a truck. A number of vehicle motion parameters in the actual traffic incident were determined, including: vehicle speed (measured by a tachograph), angular positioning of the vehicles in the moment of collision determined by tire traces prior to the accident, collision eccentricity, vehicle weight and tire adhesion coefficients. A number of simulations were made for the provided data listed, which aimed to determine the unknown speed of the other vehicle. The criterion for ending the simulation test was an acceptable degree of conformity of the actual and simulated tire trace line. The graphical representation of the performed testing results is shown in figure 5.

Figure 5. Simulation of traffic collision using actual parameters for the vehicles and road surface – the baseline arrangement for analyses; the examined tire trace and vehicle is marked in red on the illustration.
The compatibility of the simulated tire trace shape and actual tire trace indicate that the proposed simulation method is usable for simulating traffic accidents with complex tire trace shapes. This method allows analyzing the influence of various physical factors related to the vehicles, together with the road surface affecting the geometrical characteristics of non-classical tire traces.

5. Analysis of the influence of selected parameters on the geometrical properties of the tire trace

5.1. Vehicle center of mass position
In a bus, passenger distribution affects the center of mass of the vehicle. Figure 6 provides simulation results for the altered center of mass position.

![Figure 6](image)

**Figure 6.** Simulated collision for altered center of mass position.

Figure 6 demonstrates that an alteration in the center of mass position caused a significant change in the tire trace geometry of the left rear wheel of the bus. The curve of the resulting tire trace is characterized by two points of inflexion as a result of the altered characteristics of forces and moments generated by the collision.

5.2. Total vehicle weight
In the actual accident, the passenger load of the bus was not full. In order to analyze the effect of increased weight, a simulation was carried out with figure 7 demonstrating its results.

![Figure 7](image)

**Figure 7.** Simulated collision with increased weight of the bus.
It was determined that the observed tire trace geometry in this case was characterized by an altered angular position of the first section and shortening of the second section of the tire trace.

5.3. Coefficient of tire adhesion to road surface
The condition of the road surface together with the atmospheric conditions have a significant influence on tire adhesion to road surface, which affects the motion after the collision. The actual traffic accident occurred under conditions typical for winter time. Vehicle collision took place on a snow-covered road. Such conditions are characterized by low value of tire adhesion coefficient. In order to analyze the tire trace geometry under altered conditions, a simulation was performed for an increased value of the tire adhesion coefficient. Figure 8 demonstrates the result of the simulation in graphic form.

![Figure 8. Simulated collision at surface conditions with increased tire adhesion coefficient value.](image)

The observed variation in the geometry of resulting tire trace mostly entails shortening its sections and a slight reduction of angles of inclination of these sections in the driving direction of the bus before the incident.

6. Analysis of transverse forces acting on the left rear wheel of the bus
The paper examines the graph lines of forces acting on the left rear wheel of the bus. The tire trace geometry results from these forces acting on the wheel and road surface arrangement. The characteristics of these forces during the post-impact motion of the vehicle in the baseline arrangements in the transverse direction is provided in the figure 9.

The variance of force values observed on the graph for and transverse forces (figure 9) results from the change in wheel load, caused by the collision of vehicles.

Figures 10 – 12 demonstrate the characteristics of transverse forces acting on the wheel of the bus for altered parameters, e.g. the weight of the vehicle, weight distribution as well as wheel adhesion coefficient.

Analyzing the graph lines for the transverse forces, an initial increase with a various degree of intensity is observed, which in connection with the change in vertical load of the wheel resulted in a transverse displacement represented by the curvilinear section of the tire trace. Moreover, one can observe the stepwise decrease in the transverse force in each case under analysis. The cause of this phenomenon is the ceasing of the transverse displacement of the wheel and initiating the rolling motion of the wheel which corresponds to the straight line section of the tire trace. A noticeable correlation was observed between the geometric characteristics of the tire trace and the characteristics of transverse forces.
7. Conclusion
The article describes the methodology for solving problems related to reconstruction of road accidents employing simulations together with the sophisticated PC-Crash software. The possibility to utilize the geometric characteristics of vehicle tire traces with complex structure was demonstrated for the purpose of determining the parameters of movement in the moment of impact, which would prove much more difficult if only classical methods were to be employed together with a much lower accuracy. Moreover, the PC-Crash software enables to carry out the examination study of the influence of various vehicle parameters such as: own weight, load and its distribution, as well as the influence of the surface characteristics on the course of the post-collision movement. The performed study demonstrates that the PC-Crash software is fully suitable for carrying out advanced analyses of non-classical tire traces identified on the road surface. This knowledge may be helpful in reconstructing and analyzing similar traffic accidents.

8. References
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