Skid Mark Analysis: Technological Evolution And Contemporary Methodologies, A Review

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***Abstract*—Traditional measurement methods have been replaced by advanced digital documentation and analytical systems in the forensic analysis of skid marks. This thorough analysis looks at the development of techniques for analyzing skid marks, new developments in technology, and new difficulties in the reconstruction of contemporary auto accidents. The study looks at how modern data collection tools, such as photogrammetry, 3D laser scanning, and High Dynamic Range (HDR) imaging, have transformed the documentation of evidence with centimeter-level precision. A critical analysis of environmental and surface factors reveals that weather, tire-road friction coefficients, and road surface characteristics all have a significant impact on the formation and interpretation of skid marks. Traditional skid patterns have been significantly changed by the widespread use of Electronic Stability Control (ESC) and Anti-lock Braking Systems (ABS), necessitating the use of specialized analytical methods and infrared spectroscopy techniques for detection. Due to the 20% increase in tire wear that affects chemical signatures and the physical characteristics of skid marks, the rise of electric and hybrid vehicles presents special forensic challenges. The scientific rigor and dependability of forensic conclusions have been improved by sophisticated analytical techniques that include statistical uncertainty quantification, automated detection algorithms, machine learning applications, and computer-aided measurement software. Promising capabilities in pattern recognition and predictive modelling are demonstrated by the integration of artificial intelligence, specifically Support Vector Machines, decision trees, and deep learning techniques. This review shows the need for standardized protocols addressing contemporary vehicle technologies and points out significant gaps in existing approaches. The results highlight the need for a multidisciplinary strategy that combines cutting-edge computational techniques with conventional forensic knowledge in order to preserve scientific credibility in court cases.**

Keywords—Skid marks analysis, forensic investigation, accident reconstruction, ABS technology, machine learning, tire-road friction, vehicular dynamics

1. Introduction

A key component of the investigation and reconstruction of auto accidents is the forensic examination of skid marks, which offers vital information about the dynamics of the vehicle, the actions of the driver, and the conditions of the collision. In order to piece together the events leading up to an accident, forensic experts can carefully examine and interpret skid marks, which are the tire marks left on a road surface when a vehicle's tires are locked and sliding (Bullen & Ruller, 1998). Skid marks and other physical evidence are usually analyzed by trained forensic scientists, particularly in intricate crime reconstruction situations. However, skilled professionals can carry out easier sequential reconstructions (Petherick & Rowan, 2014).

The physics of tire-road interaction, which states that abrupt brake application results in wheel lockup and subsequent sliding across the pavement surface, is the foundation of forensic analysis of skid marks. The distinctive black marks seen on road surfaces are caused by a thin layer of rubber particles that are heated by friction between the tire and the road when brakes are applied abruptly (Baker, 2002). In order to derive valuable information from the properties of the skid marks themselves, this analytical procedure takes a multipronged approach, combining engineering, physics, and mathematical concepts. Important information about the vehicle's speed, braking effectiveness, and steering maneuvers prior to impact can be gleaned from the length, width, direction, and pattern of skid marks. In cases where suspects are unknown, forensic analysis aids in identifying persons of interest for further investigation, highlighting its role in both substantiating criminal charges and potentially exonerating the innocent (Wickenheiser, 2021).

Skid mark analysis in forensic investigations has long been based on conventional measurement and documentation methods. Traditional techniques use wheels, measuring tapes, or surveying equipment to measure the length of the skid mark directly. They also use standard cameras to take pictures and manually record the environmental conditions (Collins & Morris, 2007). In the past, investigators used basic equipment like chalk, measuring tapes, and simple cameras to record the patterns, widths, and directions of skid marks with roadway features. Even though these techniques were simple, they were vulnerable to environmental interference and human error, especially in places with heavy traffic or bad weather. Skid-to-Stop distances are generally calculated with the equation. $S = \sqrt{30df}$, where S ~ Speed of Vehicle in mph (miles per hour), d ~ Distance in feet, f ~ Coefficient of friction (Scallon, 2008).

Kim et al (2008) developed a new method for estimating vehicle speed from curved tire marks in traffic accident reconstruction. Through experimental testing at speeds of 60, 80, 100, and 120 km/h involving sharp turns followed by emergency braking, the researchers found that the longitudinal to lateral distance ratio of tire marks was approximately 1:0.9, with vehicles stopping at an average angle of 42° from the original direction. The friction coefficient for curved tire marks ranged from 0.43-0.48 (average 0.45), significantly lower than the 0.8 typically used for straight skid marks. The study produced a speed calculation graph as shown in Fig 1, that allows investigators to estimate initial vehicle speed using only the longitudinal and lateral components of tire mark distances.

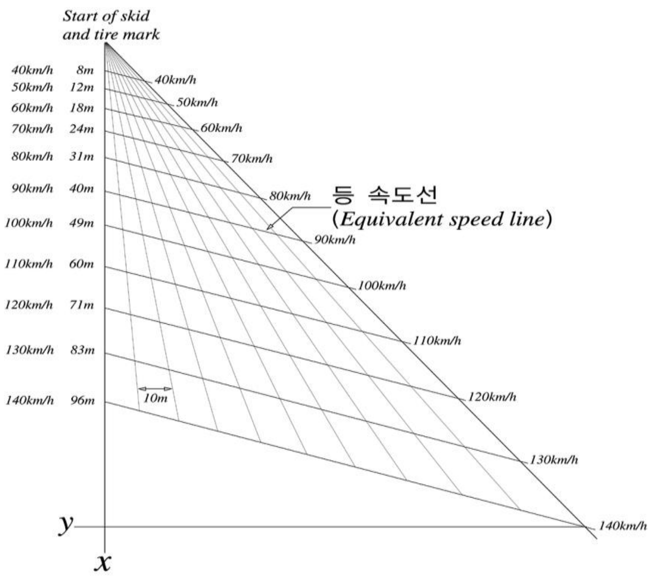

Fig 1. Speed calculation graph of skid mark and tire mark with different slopes. (Kim et al 2008)

Furthermore, the interpretation of skid marks extends beyond simple measurements, requiring a deep understanding of tire-road interactions, vehicle dynamics, and environmental factors. The length of the skid mark is influenced by numerous factors. Seven parameters were selected for this paper: car brand, displacement, weight, year of manufacture, ABS (Anti-lock Braking Systems)-equipped and non-ABS vehicles, road surfaces, and speed (Tseng & Liao 2012). Bradley et al. (2004) investigated how vehicle deceleration changed with initial speed throughout the pre-skid and skidding intervals on dry asphalt in order to more accurately assess a vehicle's speed and position at brake application. It was discovered that tire type and starting speed affected average skidding friction. It was discovered that the initial speed affected the post-brake/pre-skid speed loss, elapsed time, distance travelled, and effective friction. In comparison to traditional methods that disregard the post-brake/pre-skid interval, a method based on using skid mark length rather than skid onset to predict vehicle speed and position at brake application was demonstrated to improve estimates of initial vehicle speed by up to 10 km/h and estimates of vehicle position at brake application by up to 8m. An empirical vehicle braking test was used to evaluate Wang's (2003) distance-based matching model for classifying tire marks (skid-mark or imprint). The findings show that tire marks' heavy and light streak lengths can be used to determine the tire tread's rib and groove widths, leading to a significantly greater level of accuracy for identifying the tires in question. Geometric information on tire treads and marks can be gathered from at-scene or out-of-scene measurements in straightforward auto accidents using this method.

The force created when a tire that is unable to rotate slides across the pavement is known as skid resistance. It has been essential for improving driving safety and averting possible collisions (Ong & Fwa 2007; Pardillo & Jurado 2009). The knowledge of skid resistance offered by the pavement surface is very valuable information for road safety enhancements and analysis of skid marks. The tyre-pavement friction significantly ensures driving safety when the vehicle is on pavement. In other words, there is a strong correlation between pavement skid resistance and traffic accidents (Kuttesch 2004). According to Harish et al. (2013), a well-maintained pavement surface can offer enough friction to ensure safe driving. One direct effect of skidding is a sharp decline in the vehicle's steering and braking power, which can cause pavement damage and, in the worst situations, even fatalities. The phenomenon of hydroplaning, which occurs when a tire rolls on wet pavement at a high speed and is lifted by hydrodynamic forces, exacerbates this issue when there is water on the pavement surface. Skid resistance explains the road surface contribution to friction generation at the tire-pavement interface. Unfortunately, traffic loading and ageing continuously reduce road surface asperities, consequently diminishing skid resistance over time (Srirangam et al., 2015). Four primary categories of factors influence skid resistance: tire characteristics, vehicle operating parameters, pavement surface properties, and environmental conditions. The components within each category are detailed in Table 1, and these elements directly impact accident investigation procedures (Kumar & Gupta, 2021).

Table 1: Factors affecting available skid resistance at tire-pavement interface, Harish et al. (2013).

Surface Characteristics	Vehicle Parameters	Tire Properties	Environmental Conditions
Microtexture	Vehicle speed	Tire footprint	Temperature
Macrotexture	Slip ratio	Tread pattern	Rain intensity
Surface type	Braking action	Inflation pressure	Contamination
Aggregate properties	Tire inclination	Loading condition	–
Surface ageing	–	–	–

In a similar vein, skid mark analysis has seen a wide range of breakthroughs. These developments were based on a number of factors, such as the ABS and skid resistance under different asphalt conditions. This study focuses on reviewing all such advancements that have happened in this domain.

2. Data Collection for Skid Marks Analysis.

The evolution of data collection technologies in forensic skid mark analysis has transformed the field from traditional measurement techniques to sophisticated digital documentation systems. These advancements have significantly enhanced accuracy, reliability, and courtroom presentation capabilities while reducing analysis time and human error. Modern forensic photographers employ specialised equipment and techniques to document skid marks, tire impressions, and accident scenes with unprecedented clarity and precision (Miller & Duncan, 2019).

2.1 High Dynamic Range (HDR) Imaging

To ensure that minute tire imprint details are retained for analysis, contemporary forensic systems employ HDR techniques to record comprehensive skid mark features under various lighting circumstances (Roberts et al. 2021). When recording skid marks on various road surfaces, where contrast differences could obfuscate important evidence, this technology is especially helpful.

2.2 Spectral Photography

Previously invisible skid marks are now more visible because of advancements in alternative light photography. The range of analyzable evidence can be greatly increased by using blue light and orange filters to uncover tire markings that are not apparent in normal illumination, significantly expanding the range of analyzable evidence (Thompson & Lee, 2020).

2.3 Image Enhancement Software

Digital enhancement techniques now allow investigators to improve contrast, adjust exposure, and apply filters to reveal hidden details in skidmark patterns. Software applications can automatically detect and measure skid mark dimensions, reducing measurement errors and improving consistency across different investigators (Anderson et al. 2022)

2.4 Laser and 3D scanning

Millions of data points may be captured per second by contemporary 3D laser scanners, producing incredibly precise three-dimensional depictions of skid mark evidence and accident sites. Using systematic, scientific methods, 3D scanning technology may create lifelike 3D models of accident sites, bringing them into the courtroom. Investigators may record the exact geometry of skid marks, including their depth, width changes, and spatial linkages to other pieces of evidence, thanks to this technology. Buildings, structures, and sites are digitally documented with high-resolution photos utilising photogrammetry, which uses 3D cameras optionally coupled with LiDAR to capture 4K HDR images from a variety of locations and angles using different mounting systems. According to recent research, photogrammetry and conventional measurement methods can be used to increase the accuracy of skid mark documentation (García-Fernández et al. 2021).

Documentation protocols must account for temporal factors by establishing clear timelines between incident occurrence and evidence collection (Ahmed & Rahman, 2023). Photographic documentation should include date and time stamps, with investigators noting any visible changes in mark characteristics since the incident.

Skid mark analysis has undergone a significant transformation from subjective visual evaluation to objective, scientifically rigorous measurement procedures because of the combination of GPS coordinate systems, mobile mapping technologies, and drone-based recording. Together, these technical developments allow for quick and thorough scene documentation while preserving the integrity of the evidence and traffic flow. The accuracy of forensic studies and their presentation in court cases has been greatly improved by the capacity to create precise 3D models, create precise georeferenced datasets, and synchronise temporal documentation. The ability to record, measure, and reconstruct skid mark evidence with centimetre-level accuracy over wide geographic areas is now unheard of in modern accident investigators. The scientific underpinnings of forensic accident investigation are strengthened by this technological advancement, which signifies a paradigm change toward evidence-based reconstruction techniques.

3. Environmental and Surface Factors

Understanding the environmental and surface factors is essential for the proper interpretation of tire mark evidence and the accurate determination of pre-impact vehicle dynamics (Ahmed & Rahman, 2023).

3.1 Road Surface Characterisation Methods

Road surface characterisation has evolved from simple visual assessment to sophisticated measurement techniques that quantify surface texture and friction properties. Modern approaches evaluate pavement surface texture comprehensively on both macro- and micro-scales, with British Pendulum Number (BPN) (as shown in Table 2) commonly used as a low-speed skid resistance indicator (Miller et al., 2019). Advanced characterisation methods now incorporate texture depth measurements, surface roughness analysis, and friction coefficient testing to establish baseline surface properties.

Table 2: Relationship between BPN and skid resistance on pavements. (Yan et al., 2019)

BPN Value	Skid Resistance
27 and below	Very low
27–32	Low
32–37	Medium
37–42	Good
42+	Excellent

Recent developments in surface characterisation include the introduction of Texture Resolution Sensitivity Indices (TRSI) to evaluate variations in texture resolution that can lead to inconsistencies in texture descriptors and friction coefficient predictions for identical surfaces (Kumar et al., 2023). These indices help optimise pavement skid resistance measurement by addressing texture resolution sensitivity, ensuring more reliable forensic analysis outcomes. To measure macrotexture and microtexture properties, surface texture analysis techniques now use computerised texture analysis systems, sand patch testing, and laser profilometry (Chen et al., 2021). To evaluate skid mark evidence and determine precise friction coefficients for particular pavement-tire combinations, these measurements offer crucial baseline data.

3.2 Weather Condition Impact Assessment

Weather conditions significantly influence skid mark formation and visibility, requiring careful consideration during forensic analysis (Johnson & Mitchell, 2021). Rougher surfaces provide shorter skid marks, while wet and oily surfaces reduce friction and produce longer skid marks. Road surface contaminants, including water, oil, and mud, can significantly change the properties of friction and lengthen skid marks.

Temperature effects on pavement friction have been documented through controlled testing (Roberts et al., 2022). Research has shown that dry pavement resistance follows cubic polynomial relationships with temperature, increasing as temperatures rise due to enhanced asphalt adhesion properties. Conversely, wet pavement conditions show minimal temperature-related friction changes. Dan et al (2015) used a Pavement Friction Coefficient (PFC) tester to examine the skid resistance of asphalt pavement in various wet and low-temperature scenarios. Dry, wet, icing, snowy, and ponding pavements were evaluated in laboratory settings that replicated freezing conditions. Pavement conditions had a considerable impact on skid resistance, which showed notably steep drops on ice surfaces. Frozen surfaces showed the lowest resistance between −1.5 and −4.5 °C, increasing after that; wet pavement showed no change. Friction was further decreased by the thickness of the ice and water films. Surface friction was divided into seven safety-based levels using an empirical PFC rating methodology. Rubber block temperature also influenced results, though isolating its effects proved challenging under controlled conditions.

When vehicles lose touch with the paved surface, tire marks may be absent or drastically changed, making hydroplaning conditions very difficult for skid mark analysis. Investigators must take into consideration road debris, weather, and tire wear when analysing evidence because these factors might affect the friction coefficient and, in turn, skid mark analysis (García-Rodríguez et al., 2022).

3.3 Tire-Road Friction Coefficient Determination

Accurate determination of tire-road friction coefficients is fundamental to reliable skid mark analysis (Roberts et al., 2022). Research has shown that tire type and starting speed affect average skidding friction, and vehicle speed has a major impact on post-brake/pre-skid dynamics (Bradley et al., 2019). Numerous techniques are used in modern friction coefficient determination, including statistical analysis of historical data, portable friction measurement instruments, and controlled braking experiments.

In order to overcome the shortcomings of current systems, which are either expensive or unreliable, recent advances include affordable technologies created by forensic specialists to increase accuracy in measuring skid coefficients (Lee et al., 2020). Instead of depending just on values obtained in a lab, these devices—which are usually placed on vehicles—allow field testing under real-world accident situations. A number of variables, such as tire composition, tread design, inflation pressure, and wear characteristics, must be taken into consideration when determining the friction coefficient. Pavement characteristics include age, pollution levels, surface roughness, and material composition. Temperature, moisture content, and the presence of foreign materials are all examples of environmental factors (Chen et al., 2021).

3.4 Contamination and Degradation Analysis

Contamination of roadway surfaces significantly affects skid mark formation and interpretation. Common contaminants include motor oil, fuel spills, brake fluid, coolant, and organic debris, each producing distinct effects on tire-pavement friction (García-Rodríguez et al., 2022). Laboratory analysis of contaminated surfaces helps establish correction factors for friction coefficient calculations.

Degradation analysis looks at how road surface conditions and skid marks develop over time (Wang et al., 2021). When bituminous oils heated by friction rise to the surface of asphalt surfaces, they produce dark traces known as skid marks, which can last for months or even years. However, surface qualities are altered, and mark visibility is gradually reduced by weather exposure, traffic loading, and maintenance activities.

Surface degradation assessment includes evaluation of aggregate polishing, ravelling, rutting, and crack formation. These conditions affect local friction characteristics and must be documented for accurate analysis (Chen et al., 2021). Advanced imaging techniques now enable quantitative assessment of surface degradation patterns.

3.5 Temporal Stability

Temporal stability of skid marks refers to the degree to which the physical characteristics of skid marks remain unchanged over time after they are deposited on a road or pavement surface. The temporal stability of skid marks varies significantly based on surface type, traffic volume, and environmental exposure (Davis et al., 2020). Skid marks on asphalt can last for months or even years if conditions are favourable, while marks on concrete surfaces may persist for different durations depending on surface porosity and traffic patterns.

Factors affecting temporal stability include traffic volume and vehicle types, with heavy commercial vehicles accelerating mark degradation through mechanical wear (Wang et al., 2021). Weather patterns can rapidly alter or eliminate skid mark evidence. Modern forensic practice emphasises rapid response to preserve temporal evidence. While anti-lock braking systems reduce traditional skid marks, making analysis challenging, tire rubber abrasion still occurs, requiring investigators to adapt their documentation and analysis techniques accordingly (Bradley et al., 2019).

The integration of environmental and surface factor analysis into forensic protocols has significantly improved the reliability and accuracy of skid mark interpretation (Davis et al., 2020). These considerations ensure that forensic conclusions account for the complex interactions between vehicles, surfaces, and environmental conditions that influence skid mark evidence.

4. Anti-lock Braking System (ABS) Impact on Skid Patterns

The widespread adoption of ABS technology has revolutionised braking dynamics and consequently altered the forensic landscape of skid mark analysis. In contemporary accident scenes, traditional continuous skid marks, which are defined by continuous tire-road contact during locked-wheel braking, have become less common. Because traditional skid mark study techniques are insufficient for these intermittent braking patterns, vehicles equipped with ABS generate tire markings that are fundamentally different and call for specialist analytical methodologies (Sharma et al., 2019).

The problem of identifying tire markings associated with ABS has been tackled by a recent forensic study using creative analytical techniques. Using infrared spectroscopic analysis, Żurawski et al. (2019) showed that ABS brake traces may be detected in the mid-infrared wavelength range, giving researchers a scientific way to identify these tire imprints that were previously challenging to examine. With this innovation, forensic investigators may now differentiate between ABS-generated patterns, which usually show up as faint, sporadic markings rather than continuous dark streaks and traditional skid marks.

Beyond mark detection, ABS technology has forensic implications for speed calculating techniques. Because the anti-lock mechanism stops wheel locking and consequent tire sliding, modern cars with ABS systems leave noticeably fewer visible skid marks on the road. Alternative methods of determining vehicle speed are required due to the decrease in visible tire marks, which frequently forces investigators to rely on supplementary evidence sources, including accident dynamics modelling, electronic data, and vehicle damage patterns (NHTSA, 2007).

5. Electronic Stability Control Effects

Electronic Stability Control (ESC) systems have introduced additional complexity to vehicle dynamics during critical situations. ESC technology automatically applies brakes to individual wheels and reduces engine power when the system detects vehicle instability or loss of control, fundamentally altering the tire mark patterns produced during emergency maneuvers. These interventions create unique forensic signatures that differ significantly from traditional skid patterns. From a forensic perspective, this crash reduction translates to altered pre-impact vehicle behaviour, with ESC-equipped vehicles potentially exhibiting controlled deceleration patterns rather than traditional skidding trajectories.

According to statistical analysis by Lie et al. (2006), vehicles equipped with Vehicle Stability Control (VSC) have a roughly 35% lower casualty rate, indicating that ESC technology considerably reduces certain crash types. According to the study, ESC may prevent more collisions at higher speeds where vehicle dynamics are more significant. These figures show how crucial it is for forensic investigators to take ESC activation into account when examining accident scenes because the system's intervention may have changed the vehicle's trajectory and final resting position while also preventing the production of more severe tire marks. According to Ferguson (2007), ESC is linked to a 33% lower probability of fatal crash involvement, which includes a 20% lower risk of multiple vehicle fatal crashes.

The integration of multiple safety systems requires forensic analysts to consider complex interactions between ABS, ESC, traction control, and other electronic systems when reconstructing accident scenarios.

6. Tire Technology Evolution and Implications

The transition from conventional carbon black fillers to renewable silica reinforcement in tire manufacturing during the 1990s was primarily driven by fuel economy requirements (Bera et al., 2022). This material change has direct implications for forensic analysis, as different tire compounds produce varying skid mark signatures and wear patterns. Recent forensic research has focused on developing tire-specific identification methods. The development of tire-specific identification techniques has been the subject of recent forensic study. Because each tire is expected to produce unique skid marks based on its unique elemental makeup, forensic scientists have devised procedures to identify unique chemical signatures in tires. This development makes it possible for investigators to use chemical analysis of tire residue in skid marks to perhaps connect certain automobiles to accident scenes (Richetelli et al, 2024).

An inventive method of tire skid mark attribution is quantitative elemental analysis of tire rubber, which lends scientific legitimacy to a kind of evidence that has not been widely used in forensics in the past. Identifying how environmental elements like oil, precipitation, and road contaminants affect and alter these chemical signatures is one of the major issues, though. The incorporation of artificial intelligence in tire forensics is being demonstrated by the development of sophisticated machine learning techniques for tire tread wear identification under real-road driving situations (Zhao et al., 2023).

7. Electric and Hybrid Vehicle Considerations

The increasing number of hybrid and electric cars raises special forensic issues with regard to skid mark analysis. According to research by Emissions Analytics (2022), the aggressive torque characteristics of electric motors resulted in an approximate 20% increase in tire wear. Given that increased tire wear alters the chemical signature and physical properties of skid marks, this finding has important ramifications for forensic tire mark analysis.

The regenerative braking and instantaneous torque delivery of electric vehicles produce unique tire-road interaction patterns. Skid mark formation during emergency braking events is influenced by the increased vehicle mass brought on by battery systems as well as distinct weight distribution characteristics. Furthermore, since cars can slow down considerably without using traditional brakes, regenerative braking systems might make traditional skid marks less noticeable (Green Car Congress, 2022).

8. Analytical Method Developments

Computational developments and the incorporation of complex algorithms have greatly accelerated the development of analytical techniques in skid mark analysis. With the help of these advancements, forensic accident reconstruction has moved from largely manual, measurement-based procedures to extensive digital analysis systems that offer improved statistical rigor, accuracy, and reproducibility.

8.1 Computer-Aided Measurement Software

The integration of computer-aided measurement software has revolutionized the precision and efficiency of skid mark analysis in forensic investigations. Modern software platforms enable investigators to conduct detailed measurements from digital photographs and 3D models, eliminating many sources of human error inherent in traditional manual measurement techniques (Roadway Dynamics Inc., 2024). Advanced 3D laser scanning systems can create detailed models of accident scenes, including precise locations of skid marks, debris, and vehicle damage, demonstrating the comprehensive nature of contemporary measurement capabilities.

Computer-aided design (CAD) tools have become particularly valuable in forensic reconstruction applications. Roadway Dynamics Inc. (2024) notes that the latest advancements in computer-aided design render forensic scientists far more helpful to attorneys, with far less effort, than ever before. These tools enable the creation of detailed three-dimensional models that can be manipulated and analyzed to extract precise measurements of skid mark length, width, and trajectory angles. The visual nature of CAD models provides significant advantages in legal proceedings, as the organisation emphasises that "a computer-aided design (CAD) model is worth a thousand pictures."

Specialised forensic mapping software has emerged as a critical component in accident reconstruction workflows. These platforms integrate measurement tools with database management systems, allowing investigators to maintain comprehensive records of measurements while performing statistical analysis and generating standardised reports. The software enables real-time calculation of vehicle speeds, stopping distances, and impact angles based on measured skid mark parameters.

8.2 Automated Skid Mark Detection Algorithms

The development of automated detection algorithms represents a significant advancement in reducing the subjective nature of skid mark identification and measurement. Contemporary research addresses the problem of vehicle speed prediction from tire yaw marks, recognizing that evidence from accident scenes is often the main information source for preparing accident reports (Chen & Fang, 2007). Automated systems address the challenge of consistent identification across different lighting conditions, surface materials, and environmental factors.

Line-based segmentation systems have been developed to automatically identify and delineate skid marks in digital images. Chen and Fang (2007) demonstrated that analysis of tire yaw marks when vehicle speed is too great to maintain the proposed trajectory provides critical evidence for speed determination. These algorithms utilize image processing techniques to distinguish tire marks from other road surface features, improving the consistency and objectivity of evidence identification.

Machine learning approaches have shown particular promise in automated skid mark detection. Vinhal et al. (2023) explored the transformative role of machine learning algorithms, including deep learning and natural language processing (NLP), in digital forensics, with key applications including cybercrime investigation, fraud detection, malware analysis, and encrypted data recovery. The adaptation of these technologies to physical evidence analysis demonstrates the expanding role of artificial intelligence in forensic science.

Contemporary automated detection systems incorporate multiple image processing techniques, including edge detection, pattern recognition, and texture analysis. These systems can process large volumes of scene photographs rapidly, identifying potential skid marks and flagging them for expert review. The algorithms are designed to minimize false positives while maintaining high sensitivity for relevant evidence.

8.3 Statistical Analysis and Uncertainty Quantification

The incorporation of rigorous statistical analysis and uncertainty quantification has become essential for maintaining the scientific credibility of skid mark analysis. Modern forensic practice recognizes that all measurements contain inherent uncertainty, and proper quantification of this uncertainty is crucial for reliable conclusions. Bayan et al. (2014) focused on the uncertainty of simulation results in accident reconstruction, noting that since the Monte Carlo Method (MCM) requires a large number of simulations, sophisticated computational approaches are necessary for comprehensive uncertainty analysis.

Response Surface Methodology combined with Monte Carlo methods has emerged as a powerful approach for uncertainty quantification in accident reconstruction. Bayan et al. (2014) demonstrated that the evaluation of simulation uncertainty in accident reconstruction via combining Response Surface Methodology and Monte Carlo Method provides a framework for understanding the propagation of measurement uncertainties through complex analytical models.

Statistical validation of measurement techniques has become increasingly important as forensic evidence faces greater scrutiny in legal proceedings. Zhang et al. (2022) emphasized that "quantifying uncertainty associated with our models is the only way we can express how much we know about any phenomenon." Incomplete consideration of model uncertainties can lead to overconfident conclusions and potentially incorrect forensic interpretations.

Modern statistical approaches incorporate confidence intervals, sensitivity analysis, and error propagation calculations to provide comprehensive uncertainty assessments. These methods enable investigators to present results with appropriate confidence levels and to identify the measurement parameters that contribute most significantly to overall uncertainty.

8.3 Machine Learning Applications

Machine learning applications in skid mark analysis have expanded rapidly, offering new capabilities for pattern recognition, classification, and predictive modeling. Brito et al. (2023) evaluated the ability of state-of-the-art machine learning models, namely SVM (support vector machines), DT (decision tree) and MLR (multiple linear regression), to predict pavement skid resistance. These applications demonstrate the potential for automated analysis of complex tire-road interaction phenomena.

SVMs have shown particular effectiveness in skid mark classification tasks, enabling automated distinction between different types of tire marks and surface conditions. Decision tree algorithms provide interpretable models for relating skid mark characteristics to vehicle and environmental parameters. Multiple linear regression techniques offer robust approaches for speed estimation and trajectory analysis (Brito et al., 2023).

Deep learning approaches are increasingly being applied to image-based skid mark analysis. Sharma and Kumar (2025) noted that in the dynamic landscape of digital forensics, the integration of Artificial Intelligence (AI) and Machine Learning (ML) stands as a transformative technology. Convolutional neural networks can be trained to recognize skid mark patterns across diverse environmental conditions and surface types, potentially improving the consistency of expert analysis.

Machine learning models also enable the development of predictive capabilities for skid mark formation under different conditions. These models can incorporate vehicle characteristics, tire properties, road surface conditions, and environmental factors to predict expected skid mark patterns, providing valuable comparison standards for forensic analysis.

8.4 Database Comparison and Pattern Recognition Systems

The development of comprehensive databases and pattern recognition systems has enhanced the comparative analysis capabilities available to forensic investigators. These systems enable the comparison of skid mark characteristics across large datasets, facilitating the identification of similar cases and the validation of analytical approaches.

Pattern recognition algorithms can identify subtle similarities and differences in skid mark morphology that might not be apparent to human analysts. These systems incorporate statistical pattern matching techniques to compare new evidence against historical databases, providing quantitative similarity measures and potential case precedents.

Database systems also support the standardisation of measurement protocols and analytical procedures. By maintaining comprehensive records of measurement techniques, environmental conditions, and analytical results, these systems enable the continuous improvement of forensic methods and the identification of best practices.

Contemporary database systems incorporate machine learning algorithms to continuously improve pattern recognition capabilities. As new cases are analyzed and added to the database, the system's ability to identify relevant patterns and provide accurate comparisons is enhanced through automated learning processes.

The integration of multiple data sources, including vehicle specifications, tire characteristics, road surface properties, and environmental conditions, enables comprehensive pattern analysis that considers the complex interactions affecting skid mark formation. This holistic approach provides more reliable comparative analysis and supports more robust forensic conclusions.

9. Conclusion

The forensic analysis of skid marks has evolved from a predominantly manual, measurement-based discipline to a sophisticated, technology-driven scientific field that incorporates advanced digital documentation, computational analysis, and artificial intelligence applications. This comprehensive review demonstrates that modern skid mark analysis requires integration of multiple technological approaches to address the complexities introduced by contemporary vehicle safety systems and emerging automotive technologies.

The ability to document evidence has been drastically altered by the technological revolution in data collection. With the use of photogrammetry, 3D laser scanning, and high dynamic range imaging, investigators can now gather skid mark evidence with previously unheard-of accuracy and produce extensive digital records that can be thoroughly examined and presented in court. Analysis of surface and environmental factors has become essential to accurate skid mark interpretation. The development of standardized surface characterization techniques, such as Texture Resolution Sensitivity Indices and British Pendulum Number evaluations, offers crucial baseline information for precise friction coefficient calculation. The intricate relationships between vehicles, surfaces, and environmental factors that affect the formation of skid marks are taken into account in forensic conclusions through the use of contamination analysis and weather condition impact assessments.

The extensive use of electronic stability control and anti-lock braking systems has required significant adjustments to analytical methodologies. The scientific rigor of skid mark analysis has been greatly improved by sophisticated analytical techniques that include computer-aided measurement software, automated detection algorithms, and machine learning applications. Artificial intelligence integration shows great promise for enhancing pattern recognition skills and lessening the subjective nature of expert analysis, especially when it comes to Support Vector Machines, decision trees, and deep learning techniques. The Response Surface Methodology and Monte Carlo techniques for statistical uncertainty quantification offer crucial frameworks for comprehending measurement uncertainties and displaying results with the right degree of confidence.

However, significant challenges remain in the field. The integration of multiple safety systems requires forensic analysts to consider complex interactions between ABS, ESC, traction control, and other electronic systems when reconstructing accident scenarios. The need for standardized protocols addressing modern vehicle technologies is evident, as is the requirement for comprehensive training programs to ensure investigators can effectively utilize advanced analytical tools.

Future research should focus on creating standardized methods for analyzing skid marks from vehicles equipped with state-of-the-art safety features, creating large databases of tire-specific chemical signatures, and creating machine learning algorithms that can manage complex multi-variable interactions that result in skid marks. Combining conventional skid mark analysis with Internet of Things (IoT) technologies and vehicle telematics data presents opportunities for enhanced accident reconstruction capabilities. The conversion of skid mark analysis from subjective visual evaluation to objective, scientifically rigorous measurement procedures represents a paradigm shift toward evidence-based reconstruction techniques. Skid mark analysis will continue to offer vital insights into vehicle dynamics, driver behavior, and collision circumstances in an increasingly complex automotive landscape, thanks to this evolution, which also reinforces the scientific foundations of forensic accident investigation.

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Author contributions,

Akhith N. (AN) conducted the comprehensive literature review, performed the analysis, and prepared the manuscript. V. R. conceptualized and envisioned the study, provided critical guidance throughout the review process, and contributed to the refinement of the manuscript. Both authors reviewed and approved the final version of the manuscript for submission.ˇ

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List of Abbreviations

1. **3D – Three Dimensional**
2. **ABS – Anti-lock Braking Systems**
3. **BPN – British Pendulum Number**
4. **CAD – Computer-aided Design**
5. **ESC – Electronic Stability Control**
6. **GPS – Global Positioning System**
7. **HDR – High Dynamic Range**
8. **km/h – Kilometre per hour**
9. **LiDAR – Light Detection and Ranging**
10. **mph – Miles per hour**
11. **PFC – Pavement Friction Coefficient**
12. **SVM – Support Vector Machines**
13. **TRSI – Texture Resolution Sensitivity Indices**
14. **VSC – Vehicle Stability Control**