

SURROGATE SAFETY ANALYSIS-LEVERAGING ADVANCED TECHNOLOGIES FOR SAFER ROADS

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Abstract

This article presents a thorough review of traffic safety research, concentrating on surrogate safety assessment methods. It explores how advanced technologies can innovate approaches to enhance road safety. Surrogate safety assessment utilizes near misses, traffic conflicts, and other precursors to predict potential hazards proactively. Incorporating state-of-the-art technologies like connected vehicles, advanced sensors, and simulators, this study aims to establish a robust framework for surrogate safety analysis. It includes a comparative analysis of various surrogate safety indicators to assess their effectiveness in predicting and preventing traffic incidents, with a focus on vulnerable road users. By integrating machine learning and deep learning techniques, this research enhances the predictive capabilities of surrogate safety models, facilitating proactive safety interventions. The findings contribute to ongoing discussions on transportation safety, offering insights into the evolving field of surrogate safety analysis. They aim to guide policymakers, urban planners, and transportation professionals in implementing evidence-based strategies to mitigate safety risks and improve overall road safety.

Keywords: Proactive approach, Safety indicators, Surrogate safety measure, Traffic conflict technique

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Introduction

Road safety is crucial for safeguarding lives and promoting sustainable development worldwide. Effective measures ensure safer journeys, reducing the significant toll of accidents and fatalities on communities and economies alike. In 2021, there were approximately 1.19 million global road traffic deaths, a 5% decrease from 2010. India experienced 461,312 road accidents in 2022, resulting in 168,491 fatalities and 443,366 injuries, marking an 11.9% increase in accidents and a 9.4% rise in fatalities compared to the previous year (MoRTH, 2022). Traditional crash-based assessments analyze past accidents to evaluate road safety but have limitations. They rely on historical data, leading to reactive measures, and often face issues with data accuracy and completeness. Low-frequency crash sites and near-miss incidents are often overlooked, limiting a comprehensive safety evaluation (Singh *et al.*, 2024b). Surrogate safety analysis, characterized by indirect measures such as near misses and traffic conflicts, stands out as a promising approach to proactively assess and enhance road safety (Islam *et al.*, 2023). This research delves into the application of surrogate safety analysis, specifically focusing on how advanced technologies can be leveraged to usher in a new era of safer roads. However, shifts the paradigm by utilizing proactive indicators that precede actual safety incidents. By tapping into advanced technologies such as connected vehicles, sophisticated sensor systems, and machine learning (ML) algorithms, this study aims to augment the precision and effectiveness of surrogate safety measures (Astarita *et al.*, 2020).

Extensive research has been conducted on safety analysis using surrogate safety measures (Singh *et al.*, 2023a; 2023b; 2024c). Previous reviews have typically focused on specific themes within safety analysis, such as micro-simulation and traditional conflict analysis. While many of these reviews have included safety analysis for vulnerable road users, there is a notable gap in comprehensive reviews that encompass multiple themes. Existing studies often lack an integrated analysis that includes connected vehicle technology, traffic management systems, Advanced Driver Assistance Systems, ML for predictive analytics, augmented reality for navigation, smart infrastructure, emergency vehicle warning systems, naturalistic driving studies, and driving simulators all within a single review. The current study aims to address this research gap by providing a broad and integrated review of these diverse themes in safety analysis. By doing so, it offers a more

comprehensive understanding of the various technologies and methodologies that can be employed to enhance road safety. This holistic approach not only highlights the individual contributions of each theme but also explores their synergies and potential for improving overall traffic safety management. Integrating advanced technologies has revolutionized the road safety landscape, offering innovative solutions to mitigate risks and enhance overall safety. Here, we discuss some key advanced technologies that play a pivotal role in making roads safer.

Connected Vehicle Technology

Connected vehicle technology revolutionizes transportation by enabling seamless communication between vehicles and infrastructure. This breakthrough facilitates a dynamic exchange of real-time information, including updates on traffic conditions, potential hazards, and other pertinent data (Arvin *et al.*, 2020). The merits of this technology are numerous, as it significantly enhances situational awareness for drivers, aids in cooperative collision avoidance, and empowers adaptive traffic management systems. However, its effectiveness relies heavily on widespread adoption, and data security and privacy concerns persist. Striking a balance between the undeniable advantages and addressing these apprehensions is crucial for successfully integrating and optimizing connected vehicle technology in our evolving transportation landscape (Yang *et al.*, 2017).

Advanced Driver Assistance Systems (ADAS)

Autonomous vehicles, also known as self-driving cars, utilize advanced technologies, including sensors, cameras, and artificial intelligence, to navigate and operate without human intervention. These vehicles can perceive their surroundings, make decisions, and execute driving tasks autonomously (Cavadas *et al.*, 2020). Autonomous vehicles have the potential to significantly reduce traffic accidents caused by human error, as they eliminate factors like distraction and fatigue. They can enhance overall road safety, optimize traffic flow, and increase mobility for individuals with limited driving abilities (Liu *et al.*, 2021). Additionally, autonomous vehicles could lead to more efficient fuel consumption and reduced congestion. Challenges in achieving full autonomy under all driving conditions persist, particularly in complex urban environments and adverse weather conditions (Thej *et al.*, 2017). Ethical considerations, regulatory

hurdles, and uncertainties related to liability and insurance also pose significant challenges. Additionally, the public may need time to trust and adapt to this transformative technology. As with any technological advancement, there are concerns about cybersecurity and potential vulnerabilities to hacking.

Traffic Management Systems

Traffic Management Systems leverage sophisticated technologies by integrating data from sensors, cameras, and connected vehicles to optimize traffic flow and alleviate congestion intelligently (Chen *et al.*, 2022). These systems analyze real-time information to adjust dynamically, such as optimizing traffic signal timings and suggesting alternate routes. The merits of these systems are evident in their ability to significantly enhance overall traffic efficiency, minimize delays, and improve emergency response capabilities by facilitating faster and smoother passage for emergency vehicles (Islam *et al.*, 2023). However, the implementation of such advanced systems requires substantial initial infrastructure investments. Moreover, concerns about potential vulnerabilities, including the risk of system failures or cyber-attacks, underscore the need for robust cybersecurity measures to ensure the reliability and security of these integral components of modern urban transportation.

Machine Learning for Predictive Analytics

ML for Predictive Analytics is a cutting-edge approach that harnesses the power of artificial intelligence to analyze traffic data and identify patterns, enabling the prediction of future events or trends (Jones *et al.*, 2022). By analyzing large datasets, ML algorithms identify patterns and correlations that are not easily discernible through traditional methods. For example, studies have shown that road features like curvature, slope, and surface type significantly influence accident rates (Ahmed *et al.*, 2023; Singh *et al.* 2024a). Traffic conditions, including vehicle density and flow, also play a crucial role in predicting accident likelihood (Parvez *et al.* 2024; Singh *et al.* 2024a). Environmental factors like weather conditions can further impact road safety, with adverse weather being a notable contributor to accidents (Delen *et al.* 2006). Additionally, ML models can assess driver behavior, such as speed, fatigue, and distraction, which are critical in understanding and predicting accidents (Ghandour *et al.*, 2021; Singh *et al.* 2024d). By integrating these factors, ML provides a comprehensive and nuanced analysis of road safety, enabling more effective prevention strategies.

Smart Infrastructure

Smart infrastructure represents a transformative leap in urban planning by incorporating sensors and communication technologies into traditional infrastructure, such as roads and transportation networks, to gather and process real-time data (Zheng *et al.*, 2022). This integration enables cities to monitor and manage various aspects of their infrastructure more efficiently. The merits of smart infrastructure are evident in its capacity to enhance traffic management through the continuous collection of data on traffic patterns, road conditions, and congestion. Additionally, the wealth of real-time information gathered by smart infrastructure serves as valuable input for predictive analysis, helping city planners anticipate future needs and optimize resource allocation (Mattas *et al.*, 2020). However, the implementation of smart infrastructure necessitates significant initial investment in technology and deployment, which can pose financial challenges for some municipalities. Furthermore, ongoing maintenance is crucial to ensure the continued reliability and functionality of the integrated systems, presenting an additional consideration for cities seeking to maximize the benefits of this innovative approach to urban development.

Augmented Reality for Navigation

Augmented Reality (AR) for navigation represents a groundbreaking advancement in driving technology by overlaying digital information onto the driver's surroundings, offering enriched navigation and safety details in real time (Yanni *et al.*, 2021). This innovative system enhances driver awareness by directly projecting route guidance, traffic updates, and relevant points of interest onto the windshield or a heads-up display. The merits of AR for navigation are conspicuous in its ability to provide crucial information without diverting the driver's attention from the road, contributing to increased safety and reduced distraction (Bernal *et al.*, 2023). However, the widespread adoption of AR navigation systems faces challenges due to the associated costs of implementation and the need for compatible infrastructure. Additionally, there is a concern about potential information overload, as presenting too much data simultaneously may overwhelm drivers. Striking a balance between maximizing the benefits and addressing these challenges will be essential for the successful integration and broader acceptance of AR navigation in the automotive landscape.

Emergency Vehicle Warning Systems

Emergency Vehicle Warning Systems represent

a critical innovation in road safety, utilizing vehicle-to-vehicle communication to promptly notify drivers of approaching emergency vehicles. These systems leverage advanced technologies to transmit signals from emergency vehicles to nearby cars, triggering immediate alerts that help drivers make informed decisions (Lee and Joerger, 2018).

The merits of Emergency Vehicle Warning Systems are evident in their potential to significantly enhance response times for emergency vehicles, ensuring swift and unimpeded passage through traffic. This improvement not only aids emergency responders in reaching their destinations more efficiently but also contributes to overall road safety by reducing the risk of collisions and facilitating smoother traffic flow. However, the effectiveness of these systems relies on widespread adoption, as the benefits are most pronounced when a majority of vehicles on the road are equipped with this technology. Additionally, concerns about false alerts, where drivers may receive notifications unnecessarily, underscore the need for precise and reliable communication protocols to maximize the efficiency and trustworthiness of these critical safety systems. Advanced technologies are transforming the paradigm of road safety, offering a multifaceted approach to accident prevention and traffic management. While these technologies present significant advantages, addressing challenges such as standardization, privacy concerns, and infrastructure investment is crucial for their widespread and effective implementation. These technologies' ongoing development and integration promise to create safer and more efficient roadways for all users.

This research aims to establish a comprehensive framework for surrogate safety analysis, examining its applications across diverse traffic scenarios. Through a comparative evaluation of surrogate safety indicators, we seek to identify key proxies that offer reliable insights into potential safety

hazards. Additionally, this study explores the integration of ML methodologies to enhance the predictive capabilities of surrogate safety models, enabling timely and targeted interventions. Understanding and harnessing the potential of surrogate safety analysis becomes imperative as we navigate the intricate landscape of transportation safety. The insights derived from this research have the potential to inform evidence-based strategies, guiding policymakers, urban planners, and transportation professionals in their pursuit of safer roads for all road users.

Methodology

This systematic literature review aims to comprehensively analyze research articles related to surrogate safety measures from 2014 to 2023 (Singh *et al.*, 2023a). The review employed a rigorous inclusion and exclusion process, utilizing the Scopus Database and SCI Database. A total of 6,620 initial search results were identified using the search term 'surrogate AND safety'. The subsequent steps involved a series of filtering criteria to refine the dataset.

The review excluded 4,422 articles by limiting the publication years to '2013 to 2023'. Additionally, 4,200 articles were excluded due to their classification as conference papers, review papers, or articles not falling within the scope of original research. A further exclusion of 4,099 articles was implemented based on the criterion of English language, ensuring a focus on relevant literature for a more nuanced analysis. Moreover, 2,001 articles were excluded based on their accessibility, with preference given to Open Access and Green Open Access publications.

Following these exclusion criteria, the review proceeded with a detailed examination of the remaining 178 articles, emphasizing the importance of abstract reading to ensure alignment with the

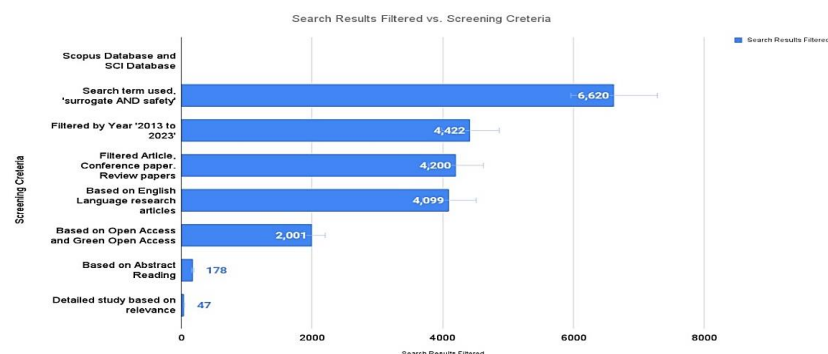


Figure 1. Systematic Literature review adopted for this research

research focus. Subsequently, 47 articles were selected for a more in-depth analysis based on their relevance to the objectives of the study. Screening process is shown in Figure 1.

The selected studies cover a wide range of topics related to surrogate safety measures, providing insights into the advancements, challenges, and future directions in this critical domain. The review's findings contribute to the existing body of knowledge on surrogate safety, offering valuable information for researchers, practitioners, and policymakers involved in enhancing safety measures across various domains.



Figure 2. Countries leading the research on surrogate safety analysis

Quantitative Analysis

Surrogate safety analysis has gained widespread traction globally, reflecting its pivotal role in bolstering road safety efforts as shown above Figure 2. This approach is prominently utilized across diverse regions, indicating its effectiveness as a safety assessment tool on a global scale. Specifically, the United States emerges as the frontrunner, representing 19% of the total research output. Following closely behind are China, making up 13% of the contributions, and the Netherlands with 9%. Similarly, Australia each contributes 9% to the overall research pool. Collectively, these nations showcase a significant portion of the global research endeavor. Notably, the remaining countries collectively contribute 49%, indicating a diverse spread of research activities across the globe. This widespread adoption emphasizes the global recognition of Surrogate safety analysis as a valuable tool for evaluating and improving road safety, reflecting its adaptability to diverse traffic scenarios and infrastructure contexts.

The use of surrogate safety analysis has spurred a diverse range of research documents across various formats, showcasing the tool's versatility and widespread applicability. Articles lead the pack with 79.1 %, reflecting extensive in-depth studies and empirical analyses. Research articles, totalling 34 documents, are pivotal in advancing surrogate safety analysis by offering

in-depth evaluation and analysis. With 20.9%, 9 documents, conference papers, book chapters, showcasing its real-world implementation and impact as shown in Figure 3. This diverse array of document types highlights the multidimensional role of surrogate safety analysis in advancing research and discourse related to surrogate safety analysis, with each format contributing uniquely to the tool's evolving narrative in the academic and professional realms.

Thematic Analysis

Perkins and Harris, while working as engineers at General Motors in 1967, developed the Traffic Conflict Technique (TCT) as a means to identify safety hazards related to vehicle construction. Their pioneering research led to a significant revelation - they found a strong correlation between conflict patterns on the road and the types of accidents that occurred. Surprisingly, they concluded that the prevalence of conflicts among road users could serve as a better predictor of risk than simply looking at accident rates alone. To define conflicts in a traffic context, Hydén (1987) proposed a straightforward yet insightful perspective: conflicts are situations in which two or more road users would collide if none of them took evasive actions. This definition hinges on the concept of Time to Collision (TTC), where the values of TTC and vehicle speeds are used to gauge the severity of these conflicts.

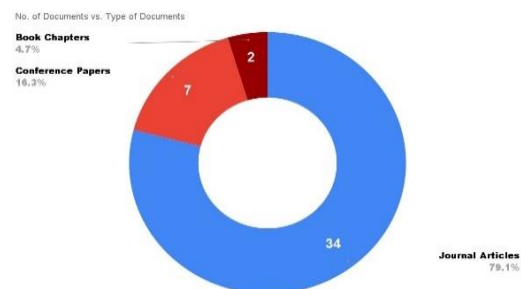


Figure 3. Types of research documents being published

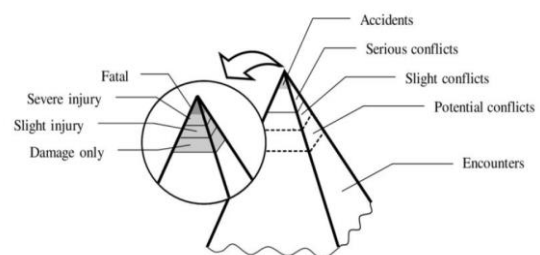


Figure 4. Hydén Safety Pyramid (Hydén, 1987)

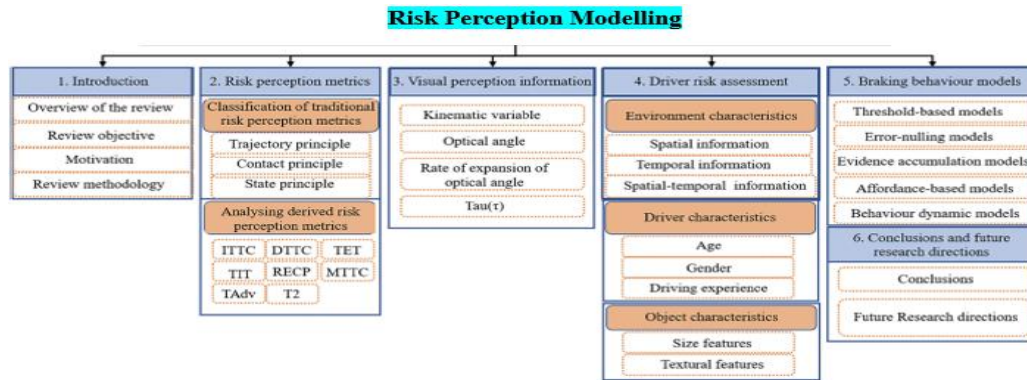


Figure 5. Risk perception modelling

Hydén's groundbreaking work further visualized the relationship between the severity and frequency of elementary traffic events through the use of a safety pyramid, as depicted in Figure 4. Within this framework, conflicts are positioned as events that occur more frequently than actual crashes, underscoring their importance in assessing road safety. Notably, conflicts and crashes share a common trait - they both imply a proximity to a collision, making conflicts valuable indicators of potential safety risks.

Building upon this foundation, Amundsen and Hydén (1977) provided a succinct definition of traffic conflicts as observable situations wherein two or more road users approach each other in both time and space to such an extent that the risk of collision exists if their movements remain unchanged. These conflicts, often likened to near-crashes, offer a unique advantage in safety assessment. They precisely capture the spatial and temporal proximity aspects of risky interactions on the road, offering a more detailed and immediate view of potential hazards compared to traditional accident data. In the realm of proximal safety indicators, researchers have proposed several metrics to evaluate traffic facility safety using conflicts as a basis. These metrics encompass a range of factors, including TTC, Deceleration Rate (DR), Post-Encroachment Time (PET), Maximum Speed (Max S), Delta Speed (Delta V), Proportion of Stopping Distance (PSD), among others.

Each of these indicators provides a nuanced perspective on road safety, offering valuable insights into the complex dynamics of traffic conflicts and their implications for overall road safety. The TCT development of pioneering research and refined over the years, has thus become an indispensable tool for understanding and improving road safety by focusing on conflicts, the precursors to potential collisions.

Surrogate safety analysis involves the use of various tools and techniques to assess and enhance safety measures.

The provided Figure 5 outlines the sections of a literature review on the visual risk perception in human drivers' braking behavior, beginning with an introduction that sets the stage for the study. It progresses to detail traditional and derived risk perception metrics, delves into the nuances of visual perception information, and assesses driver risk based on environmental, personal, and object characteristics. The review then examines various braking behavior models before culminating in conclusions and recommendations for future research. This structure ensures a thorough analysis of the factors influencing drivers' risk assessment and braking responses.

Challenges in Implementing Surrogate Measures

In response to challenges related to crash databases, alternative methods for assessing road safety have been developed (Mahmud *et al.*, 2017). These methods focus on analyzing roadway and environmental features rather than relying solely on crash data (Soames Job *et al.*, 2012). Two major categories of these methods are Road Safety Audit or Inspection (RSA/RSI) and the Safe System Approach. However, both of these methods have subjective elements and face methodological and practical challenges. RSA/RSI requires specialized expertise and can be challenging to implement in developing countries due to a lack of qualified professionals and institutional structures for accreditation (Mahmud *et al.*, 2016). It primarily focuses on engineering features and may overlook factors like vehicle condition. On the other hand, the Safe System Approach allows for a subjective evaluation of various initiatives but is not immune to challenges, particularly in developing nations.

Its efficacy and limitations are still being studied. Given these challenges, alternative techniques that utilize non-crash data, such as speed variations, unpredictable driving behavior, traffic violations, and traffic conflicts, have been proposed (Kumar *et al.*, 2014). Among these, TCTs have emerged as a proactive option for identifying road safety issues (Singh and Das, 2023). Numerous research studies have explored various measures to assess traffic conflicts in different road scenarios, providing an alternative to relying solely on historical crash data. This section examines the origins of surrogate safety measures and the challenges associated with implementing traffic conflict techniques.

Surrogate Safety Measures Classification

Temporal Proximity Measures: These measures, including TTC and PET, assess how closely vehicles approach each other in time (Arun *et al.*, 2021). **Spatial Proximity Measures:** Metrics such as PSD and Distance to Intersection (DTI) analyze the spatial proximity of vehicles, offering a comprehensive view of conflicts (Noble *et al.*, 2016; Mahmud *et al.*, 2017). **Kinematic Measures:** These involve parameters like acceleration and deceleration, with a focus on heavy braking as an indicator of conflicts (Lee and Joerger, 2018; Songchitruksa and Zha, 2014). **Mix of Measures:** Some methods combine multiple conflict indicators, such as aggregated cross-tendency measures, which blend TTC, reaction time, and deceleration rate (Guo *et al.*, 2010; Wang and Stamatiadis, 2013). **Combination of Measures:** Researchers have used various combinations of conflict measures to capture diverse safety aspects during traffic interactions (Saunier *et al.*, 2011; Zheng and Sayed, 2019). These classifications help in comprehensive conflict analysis (Arun *et al.*, 2021).

Traffic Conflict Technique

TCT, widely used by safety professionals since 1997, is instrumental in assessing conflict severity and crash prevention measures (Parker and Zegeer, 1989). The Federal Highway Administration (FHWA) published guidelines for data collection and analysis using TCTs, assisting engineers and observers in evaluating operational and safety issues at intersections (Parker and Zegeer, 1989). TCTs identify conflicts when one user puts another at risk of collision, and the second user takes evasive action to avoid it. These techniques have specific stages for measuring conflict boundaries, helping in the identification of safety issues and crash data analysis (Parker and Zegeer, 1989). There are six main traffic conflicts, including those in the same direction, left-hand side, cross traffic, red in a right

turn, pedestrians, and the secondary (Parker and Zegeer, 1989). Each type of conflict represents different hazardous situations at intersections, as observed through manual traffic surveys conducted by trained observers over several hours to days (Parker and Zegeer, 1989).

Modelling traffic conflict frequency and severity

Traffic conflict analysis involves Modelling conflict frequency and severity, considering various factors like traffic conditions, road attributes, driver behavior, and the environment. One common approach is the use of generalized linear regression models, including Poisson, negative binomial, and Poisson-lognormal models, to handle non-negative and discrete conflict data. These models can also incorporate random effects to address temporal correlations and unobserved heterogeneity. Additionally, alternative methods like hidden Markov models, Bayesian networks, and deep learning (DL) models offer ways to predict conflicts and assess their severity. These diverse Modelling techniques contribute to a comprehensive understanding of traffic conflict dynamics and safety implications (Zheng *et al.*, 2021).

Naturalistic Driving Study

The application of Naturalistic Driving Study (NDS) data in safety analysis has become increasingly significant, particularly in the context of predicting and preventing safety-critical events (SCEs). NDS data provide a wealth of information on real-world driving behavior, including crucial kinematic parameters such as longitudinal acceleration, lateral acceleration, jerk, yaw rate, and swerve. These parameters serve as valuable indicators for assessing dangerous driving behavior and identifying potential SCEs. Researchers have leveraged ML techniques, including XGBoost and deep learning artificial neural networks (DLANN), to analyze NDS data and predict near crashes with high accuracy. Additionally, the integration of kinematic triggers and thresholds for different road geometries have been explored to enhance the applicability of NDS data in diverse driving scenarios. Overall, NDS data, coupled with advanced analytical approaches, offer a promising avenue for improving safety analysis by proactively identifying and mitigating road safety risks.

Video-Based Surrogates

Video-Based Surrogates offer a valuable tool for transportation professionals, relying on detailed video footage to provide nuanced insights into traffic movements and potential safety issues. The merits of this approach lie in its ability to

Table 1. various tools and techniques used for surrogate safety analysis at different traffic facilities

Tool/Technique	Merits	Demerits	Data Used	Results	References
Video-Based Surrogates	- Detailed analysis of traffic movements	- Limited field of view	- Video Footage	- Identification of near misses	Navarro <i>et al.</i> (2022)
Connected Vehicle Data	- Real-time insights into traffic patterns	- Relies on widespread vehicle connectivity	- Data from connected vehicles	- Early detection of safety issues	Khanal and Edelman (2023)
Microsimulation Models	- Individual vehicle movement simulation	- Resource-intensive	- Traffic flow data, vehicle characteristics	- Predictive analysis of safety events	Jehad <i>et al.</i> (2018)
Driving Simulators	- Controlled virtual environment	- Lack of real-world complexity	- Driver behavior data, simulator outputs	- Understanding driver reactions	Ka <i>et al.</i> (2020); Almallah <i>et al.</i> (2024)
Field Operational Tests	- Real-world data collection	- Limited control over variables	- Instrumented vehicles, naturalistic data	- In-depth insights into natural driving behavior	Barnard and Koskinen (2023)
Data Mining Techniques	- Identification of patterns in large datasets	- Dependence on data quality and availability	- Large-scale transportation data	- Correlation analysis for safety predictions	Jiang <i>et al.</i> (2021); Mirbod and Dehghani (2023)
ML & DL Algorithms	- Predictive Modelling based on historical data	- Overfitting, interpretability challenges	- Historical crash data, traffic variables	- Improved accuracy in predicting safety outcomes	Badarinath <i>et al.</i> (2021)
Empirical Bayes Methods	- Statistical estimation of crash risk	- Sensitivity to small sample sizes	- Crash data, roadway characteristics	- Estimation of crash risk on specific roadways	Katicha and Flintsch (2023)
Eye-Tracking Studies	- Understanding driver's attention	- Limited external validity	- Eye movement data, driving scenarios	- Insights into visual behavior and distractions	Vetturi <i>et al.</i> (2020)
Cognitive Task Analysis	- Examination of cognitive processes in tasks	- Subject to participant bias	- Task-specific data, participant feedback	- Identification of cognitive challenges	Bhattacharya <i>et al.</i> (2023); Khan <i>et al.</i> (2014)
Hazard Rating Systems	- Systematic assessment of roadway elements	- Subjectivity in hazard ratings	- Road infrastructure data, safety audits	- Identification of high-risk road elements	Eriebe <i>et al.</i> (2024)
Geographic Information Systems (GIS)	- Spatial analysis and mapping	- Limited to available spatial data	- GIS data, spatial features	- Identification of spatial patterns and clusters	Navarro <i>et al.</i> (2022)
Conflict Technique	- Quantitative measure of potential collisions	- Sensitivity to measurement errors	- Vehicle trajectories, speed data	- Assessment of collision risk	Mattas <i>et al.</i> (2020)

capture rich, visual data that enables a more comprehensive understanding of traffic dynamics (Kronprasert *et al.*, 2021). Video-based surrogates aid in analyzing near misses and critical events for road safety but are hindered by limited camera views, potentially missing crucial incidents. Nevertheless, they provide valuable data for improving traffic safety strategies. Table 1 presents an analysis of different tools and techniques utilized in surrogate safety analysis. It outlines their advantages, drawbacks, the type of data employed, and the resulting insights, highlighting their role in enhancing transportation safety.

Connected Vehicle Data

Connected Vehicle Data emerges as a powerful tool in modern transportation systems, leveraging real-time insights to provide a dynamic perspective on traffic patterns and enabling the early detection of safety issues. The merits of this approach are evident in its ability to offer timely and relevant information, facilitating proactive responses to potential hazards (Arvin *et al.*, 2020). By relying on data generated from connected

vehicles, transportation authorities can comprehensively understand road conditions and identify safety concerns in real-time. However, the effectiveness of Connected Vehicle Data is contingent on widespread vehicle connectivity, which may pose challenges in certain regions or contexts where such technology adoption is limited. Despite this dependency, the early detection and real-time analysis of safety concerns through connected vehicle data remain crucial in enhancing overall traffic management and ensuring the safety of road users.

Micro-simulation Models

Microsimulation Models stand as valuable tools in transportation planning, offering a detailed understanding of traffic dynamics by simulating the movements of individual vehicles. The merits of these models lie in their ability to capture intricate details of traffic behavior, allowing planners to gain insights into the nuances of road systems (Hasanpour and Persaud, 2022). By utilizing traffic flow data and vehicle characteristics, microsimulation models enable predictive analysis

of safety events in simulated environments, aiding in assessing potential risks and developing targeted mitigation strategies. However, the resource-intensive nature of microsimulation models can limit scalability, making them less practical for large-scale applications. Additionally, the accuracy of model predictions hinges on the quality of input parameters, emphasizing the importance of obtaining precise and reliable data to ensure the fidelity of simulation results. Despite these challenges, microsimulation models play a crucial role in advancing transportation planning and safety analysis by offering a granular perspective on traffic behavior and its implications.

Driving Simulators

Driving simulators serve as invaluable tools in studying driver behavior by providing controlled virtual environments for the examination of specific scenarios. The merits of these simulators lie in their ability to recreate diverse driving conditions, allowing researchers and practitioners to gain insights into how drivers respond to various situations (Alrassy *et al.*, 2023). Researchers can better understand the intricacies of human behavior behind the wheel by utilising driver behaviour data and analysing simulator outputs. However, a notable demerit of driving simulators is the potential lack of real-world complexity, which may affect the generalizability of findings to actual driving situations. While simulators offer controlled environments for studying specific aspects of driver behavior, the challenge remains in ensuring that the insights gained can be applied to the unpredictability and complexity of real-world driving conditions. Despite this limitation, driving simulators continue to be valuable tools for research, training, and the exploration of driver reactions in controlled settings.

Field Operational Tests

Field Operational Tests (FOTs) are valuable endeavors in transportation research as they involve the real-world deployment of instrumented vehicles to collect naturalistic driving data. The merits of FOTs are evident in their ability to provide authentic insights into driver behavior and interactions within genuine traffic environments (Barnard and Koskinen, 2023). By observing and analyzing data from instrumented vehicles operating in real-world conditions, researchers gain in-depth knowledge about various aspects of driving behavior, vehicle performance, and interactions with the surrounding environment. However, a notable demerit of FOTs lies in the limited control over variables, as the dynamic nature of on-road scenarios may introduce

confounding factors that could affect the accuracy and generalizability of the findings. Despite this challenge, the richness of real-world data collected through Field Operational Tests remains invaluable in advancing our understanding of how drivers behave in their natural driving environment, contributing to the development of safer and more efficient transportation systems.

Data Mining Techniques

Data Mining Techniques play a pivotal role in the analysis of large-scale transportation data by facilitating the identification of patterns and correlations. The merits of these techniques lie in their ability to extract valuable insights from vast datasets, allowing for correlation analysis that can reveal hidden relationships among various variables (Mirbod and Dehghani, 2023). In the context of transportation, data mining techniques enable the identification of patterns related to traffic flow, driver behavior, and safety outcomes. However, a notable demerit is the reliance on the quality and availability of data, as the robustness of findings is contingent upon the accuracy and completeness of the input information. Ensuring data quality and addressing potential biases are essential for producing reliable results. Overall, data mining techniques enhance safety predictions and inform evidence-based decision-making in transportation systems by uncovering meaningful patterns within complex datasets.

Machine Learning Algorithms

ML Algorithms stand out as powerful tools in transportation safety analysis, leveraging predictive Modelling based on historical data to enhance accuracy in safety predictions. The merits of these algorithms lie in their capacity to uncover complex patterns and relationships within large datasets, enabling more precise forecasting of safety outcomes on the road (Badarinath *et al.*, 2021). By utilizing historical crash data and relevant traffic variables, ML algorithms can identify factors contributing to accidents and assess their impact. However, a notable demerit is the challenge in interpretability, as the intricate nature of some algorithms may make it difficult to understand the underlying decision-making processes. Additionally, the risk of overfitting, where models become too tailored to historical data and struggle to generalize to new scenarios requires careful consideration. Despite these challenges, ML algorithms play a crucial role in advancing safety predictions in transportation by providing a data-driven approach that can uncover insights for effective preventive measures and policy planning.

Empirical Bayes Methods

Empirical Bayes Methods represent a statistical approach to estimating crash risk by leveraging observed and expected frequencies. The merits of these methods lie in their ability to provide a robust estimation of crash risk on specific roadways (Ali *et al.*, 2023). This provides a nuanced assessment of roadway risks by comparing actual crash rates with expected rates from larger datasets or reference groups. However, a notable demerit is the sensitivity of these methods to small sample sizes, as limited data can impact the reliability of risk estimates. Ensuring an adequate dataset for analysis is essential to mitigate this challenge. Overall, Empirical Bayes contribute valuable insights into assessing crash risk on specific roadways, aiding in targeted interventions and improvements to enhance overall transportation safety.

Eye-Tracking Studies

Eye-tracking studies serve as a valuable methodology in understanding driver attention by analyzing eye movements in various driving scenarios. The merits of these studies are evident in their ability to provide direct insights into where and how drivers allocate their visual attention. By tracking eye movements, researchers can better understand visual behavior, identifying patterns related to hazard perception, distraction, and information processing (Tolvanen *et al.*, 2022). However, a notable demerit of eye-tracking studies is the potential limitation in external validity, as the controlled and artificial conditions of a laboratory setting may not fully replicate the complexities of real-world driving. The impact of these artificial conditions on participant behavior and the generalizability of findings to everyday driving scenarios must be considered. Despite this limitation, eye-tracking studies contribute significantly to our understanding of driver behavior and offer valuable information for designing interventions to minimise distractions and improve overall road safety.

Cognitive Task Analysis

Cognitive Task Analysis plays a crucial role in exploring the cognitive processes involved in driving tasks. The approach lies in its ability to delve into the mental operations that individuals undergo while performing specific driving-related activities. By examining task-specific data and collecting participant feedback, researchers can identify and understand the cognitive challenges inherent in driving (Khan *et al.*, 2014). However, a notable demerit is its susceptibility to participant bias, as self-reported data may not always align with

actual cognitive processes. Additionally, the findings may not fully capture the complexities of real-world driving scenarios, as the controlled environment of a study may differ from the dynamic and unpredictable nature of on-road experiences. Moreover, cognitive task analysis remains a valuable tool in uncovering cognitive aspects of driving behavior, contributing insights that can inform training programs, safety interventions, and the design of user-friendly automotive technologies. The discussion highlights the variety of tools and techniques in surrogate safety analysis, chosen based on analysis goals, resources, and safety concerns. Using various methods together gives a thorough understanding for making safe transportation decisions based on evidence.

Overall Findings and Future Avenue for Research

In recent road safety research, SSMs have gained prominence as effective tools for assessing road safety without solely relying on historical crash records. Smartphone-based SSMs have become popular due to technological advancements, offering cost-effective data collection compared to instrumented vehicles. These SSMs often focus on harsh driving behavior events like harsh braking and acceleration, which have been found to correlate positively with various road crash counts and risks. This relationship suggests that these harsh events could serve as proactive variables in statistical models without needing historical crash data. Traffic conflict indicators, primarily collected through video analysis, have also been used to investigate the relationship with historical crash counts or predict road crash occurrences. Generalized Linear Models (GLMs) and their modifications are the dominant statistical tools in such studies, with some utilizing specialized approaches to account for unobserved heterogeneity and spatial dependence. Notably, ML techniques are less frequently employed. Additionally, a significant finding of this research is that the time periods for collecting SSMs are often much shorter than those for historical crash data, shedding light on this temporal aspect in road safety analysis.

The future research directions emerging from the reviewed studies on SSMs for historical crash record investigations encompass several critical areas. Firstly, there is a pressing need to delve deeper into the assessment of injury severity in road crashes. Most studies have primarily concentrated on aggregating all injury road crashes without distinguishing between different severity levels. To enrich road safety analyses, future research should

thoroughly explore the relationship between SSMs and crash severity, specifically focusing on serious or fatal incidents, which have a significant societal impact.

Furthermore, a substantial portion of existing research has considered road crashes involving all types of road users collectively. However, specific categories of road users, particularly vulnerable road users (VRUs) such as pedestrians, cyclists, and the growing population of e-scooter users, require more dedicated attention. These VRUs are particularly susceptible to injuries in vehicular collisions due to their limited external protection. Research should therefore delve into how various SSMs can be effectively harnessed to enhance the safety of these road users, especially with the emergence of new micromobility transport modes.

While the majority of reviewed studies have focused on microscopic analyses of road segments and intersections, a promising avenue for future research lies in adopting a macroscopic perspective. Expanding the scope of analysis to regional areas, such as cities, metropolitan areas, or local administrative units, presents an opportunity to incorporate a broader array of factors. This includes demographic, socioeconomic, and traffic exposure variables, which can significantly enrich the understanding of road safety dynamics at a higher level. However, researchers must grapple with the challenge of capturing unobserved heterogeneity as the size of the analyzed region increases.

Moreover, the application of ML and DL techniques in road safety analysis represents a burgeoning field. These approaches have shown remarkable predictive capabilities and have begun challenging the traditional dominance of Statistical Modelling. Yet, their adoption in studies exploiting SSMs for historical crash record investigations has been limited. To address this, future research should consider integrating ML and DL methods, utilizing model-agnostic tools for accurate result interpretation. This hybrid Modelling approach could lead to methodological advancements in traffic conflict-based crash estimation models.

Lastly, the constant evolution of technology offers abundant opportunities for enhancing road safety analysis. Smartphones, capable of collecting extensive driving data in real road conditions, have become a valuable resource. Additionally, the rollout of fifth-generation networks (5G) presents a transformative potential in creating a more connected traffic environment. Leveraging 5G technology for Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Everything (V2X) communication can significantly

contribute to real-time data collection and the extraction of diverse SSMs for integration into traditional road safety analysis. These technological advancements open new horizons for improving road safety through innovative solutions and comprehensive data integration. As we move forward, the insights derived from this study can guide policymakers and practitioners in developing targeted interventions tailored to specific road safety challenges. The discussion also prompts further exploration into refining surrogate safety models, expanding the scope of applicable technologies, and considering integrating surrogate measures into broader traffic management and urban planning strategies. Overall, the synergy between advanced technologies and surrogate safety analysis opens avenues for a proactive and adaptive approach to road safety, with implications for reducing the frequency and severity of traffic incidents.

Conclusions

This research has significantly advanced our understanding of surrogate safety analysis and its application in the realm of road safety, particularly in harnessing advanced technologies for safer roads. The study has yielded several key conclusions that underscore the importance of adopting a proactive and data-driven approach to enhance traffic safety. Firstly, the efficacy of surrogate safety indicators has been highlighted, with the research emphasizing their varying reliability across different traffic scenarios. This underscores the need to carefully select indicators based on specific contexts, acknowledging their potential to predict safety incidents effectively. Secondly, the integration of advanced technologies, such as connected vehicles, sensor systems, and ML algorithms, has proven instrumental in refining and expanding the applicability of surrogate safety measures. Real-time data and predictive Modelling have provided a more nuanced understanding of traffic dynamics, enabling targeted interventions to improve road safety. Furthermore, the research places a particular focus on vulnerable road users, demonstrating the specific effectiveness of surrogate safety measures in addressing their safety concerns. This recognition emphasizes the importance of understanding and mitigating risks for pedestrians, cyclists, and motorcyclists as essential components of a comprehensive road safety strategy. Moreover, the study sheds light on the implications of proactive safety planning facilitated by ML and predictive Modelling. The ability to anticipate and prevent potential

safety incidents contributes to evidence-based strategies that enhance overall road safety. The research encompasses a comprehensive review of the use of SSMs in road safety studies, with a specific emphasis on their correlation with historical road crash records. Traditionally, road crash data has served as the primary indicator for assessing road safety, necessitating extended periods to gather reliable samples. In contrast, SSMs, designed to offer sustainable metrics, have emerged as an alternative or complementary approach. The review delves into various types of SSMs, their data collection methods, Modelling approaches, and the temporal dimension of data collection. Importantly, it highlights the growing significance of smartphones as tools for collecting SSMs under real road conditions. One notable finding from the review is the significant difference in data collection periods between road crash data and SSMs when utilizing smartphones and connected vehicles. On average, road crash data periods are 50 times longer than SSM collection periods, underscoring the potential for SSMs to provide more up-to-date insights into road safety. The review also underscores methodological considerations in statistical Modelling, emphasizing the importance of addressing spatial autocorrelation and unobserved heterogeneity when analyzing crash data. Future research directions should focus on examining how SSMs correlate with road crashes across different injury severities and types of road users. Leveraging advancements in technology, such as LiDAR for improved data collection, and employing interpretable DL algorithms offer promising avenues for exploring these relationships. Additionally, applying extreme value theory and Copula theory for detailed analysis in heterogeneous traffic conditions can enhance our understanding further. These insights contribute to evidence-based approaches to transportation safety, guiding stakeholders in developing proactive strategies to mitigate risks and improve overall road user safety.

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Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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