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Impact of Rutting on Traffic Safety: A Synthesis of Research Findings

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Abstract: Quantifying the impact of rutting on traffic safety contributes to the development of objective models for evaluating pavement performance. However, the existing literature shows significant discrepancies in the impact of rutting on traffic safety. To this end, this study analyzed about 40 studies to comprehensively understand the impact of rutting on traffic safety in field observations and simulation studies. This study analyzed the influence of ten factors that may impact the relationship between rutting and traffic safety, such as weather, speed, and road type. It also established rutting limits and developed machine learning-based prediction models for accident rates caused by rutting under varying conditions. These findings reveal distinct trends, with simulation studies generally suggesting a higher impact of rutting on safety compared to field observations. This discrepancy is attributed to the limitations of simulation models in capturing human factors, such as drivers' ability to anticipate and adjust their behavior to mitigate risks. These results provide valuable insights for highway agencies and policymakers to develop more accurate rut limits and maintenance guidelines. These results also underscore the importance of considering rutting in the development of autonomous vehicles to ensure effective handling of rutting under varying conditions. This study highlights the need for more comprehensive field studies using larger datasets that account for various environmental and traffic factors. Additionally, integrating real-world driver behavior into simulation models could improve their accuracy.

Keywords: rut; rut depth; pavement; safety; accident; pavement condition; pavement performance; prediction models

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1. Introduction

In recent years, advancements in sensing technologies, computing capabilities, and processing algorithms have significantly enhanced the automatic and accurate assessment of pavement condition distresses [1–3]. However, the quantification of pavement distresses often lacks utility for decision-makers at the network level on their own [4]. Therefore, pavement condition indices have been developed to translate measured distresses into meaningful evaluations, facilitating comparisons between the condition of pavement sections and guiding maintenance prioritization. Nevertheless, the development of these indices is often undermined by subjectivity and bias, as the relative importance of different distress types is subjectively evaluated [4]. Alternatively, there is a growing trend towards objective quantification methods of the pavement condition impact [5–7]. The impact of pavement distresses, such as roughness, rutting, pumping, and potholes, is multifaceted, encompassing safety, economic, social, and environmental dimensions. In particular, the impact of ruts on traffic safety has been a focus of multiple studies in the past few decades [8–11].

Researchers have identified multiple traffic safety risks associated with the presence of ruts on road pavements. The accumulation of water in ruts reduces the skid resistance and increases the risk of hydroplaning [10]. Loss of control when a vehicle is steered out of a rut constitutes another safety concern [10]. Attempting to avoid the rut can also lead to loss of control [12]. Moreover, during rainy seasons, the spray from other vehicles may reduce visibility for pedestrians and vehicles, causing distractions [12]. However, ruts may also contribute to speed reduction on roads, potentially reducing the occurrence of crashes when they are visible [10,13]. Nevertheless, this may not hold true during night-time driving or when ruts are obscured by water ponds or on curved roads [10]. Subsequently, multiple studies have reported a prominent impact of rutting on the accident risk [14,15]. On the contrary, other studies concluded that the accident risk is generally independent of rutting in road pavements [8–11,16]. Therefore, quantifying the impact of rutting on traffic safety under varying conditions remains a challenging task.

The impact of rutting on traffic safety has been a subject of debate for many years, stemming from three main complexities. Firstly, drivers have the ability to adapt to changes in pavement conditions by adjusting their speed and exercising caution, which can influence the perceived impact of rutting. Secondly, various factors, such as the dryness or wetness of the pavement surface, driving speed, traffic volume, clarity of the rutting, and types of vehicles, interact with rutting to affect traffic safety differently. Thirdly, the scarcity of adequate open-access databases limits researchers' ability to conduct comprehensive analyses of rutting's impact on traffic safety. The lack of consensus on the effect of rutting on traffic safety may hinder the adoption of safety as a quantitative and objective method for pavement performance assessment. Therefore, it is important to identify the sources of these discrepancies to strive for a more comprehensive understanding of rutting's effects on traffic safety.

This study aims to analyze the available literature to comprehensively understand the impact of rutting on traffic safety under various conditions. Relevant literature was retrieved from the Scopus and Google Scholar databases, encompassing journal articles, conference papers, and technical reports. Simulation and field observation studies were critically examined to identify discrepancies in the reported impact of rutting under different conditions. The findings of previous studies were synthesized to propose rut depth limits. Data extracted from eleven field observation studies were further utilized to develop machine learning (ML)-based prediction models for quantifying accident rates associated with rutting under diverse conditions. Additionally, this study explored the limitations of prior research and identified future directions.

Ultimately, this study contributes to the body of knowledge by providing a comprehensive review of the relationship between rutting and safety under varying conditions. Additionally, it introduces ML-based prediction models. These findings offer valuable insights for highway agencies and policymakers to establish more effective rut management strategies. Furthermore, this study advances the pursuit of a more objective and data-driven evaluation of pavement performance.

2. Research Methodology

The methodology employed in this study is outlined in Figure 1. This study unfolded in three consequent stages. Initially, the first stage involved retrieving literature studies analyzing the relationship between rutting and traffic safety. Subsequently, the second stage focused on analyzing the gathered literature to investigate the influence of various factors on the significance of rutting's impact on traffic safety. Lastly, the third stage involved constructing a dataset from the previous literature and leveraging it to develop prediction models for accident rates, considering rut depth under varying conditions.

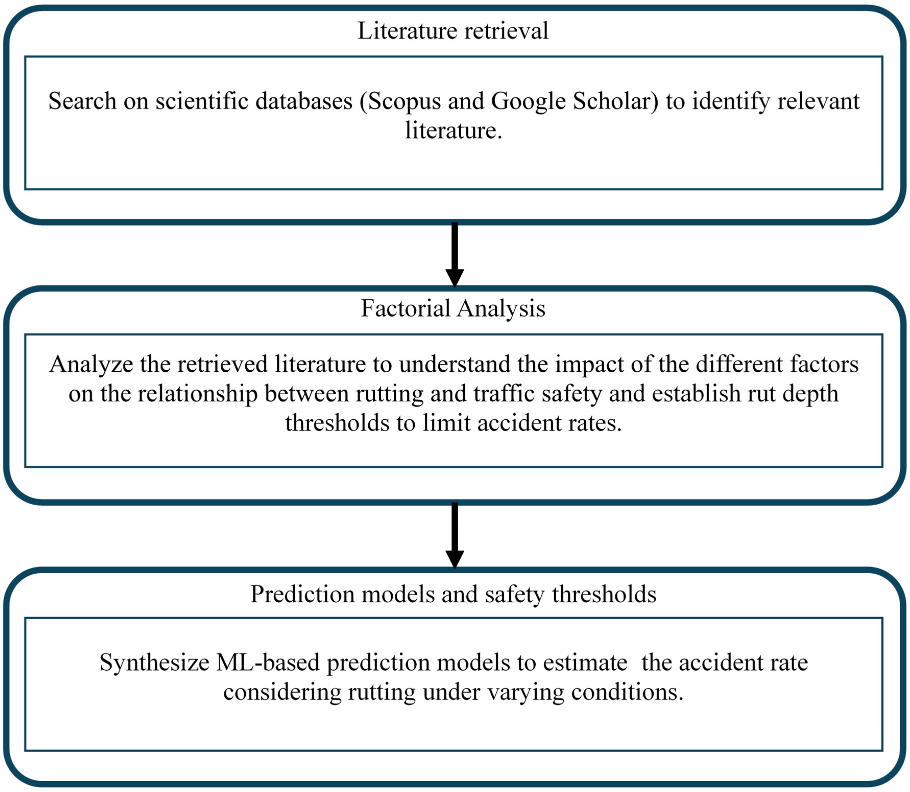


Figure 1. Research methodology.

2.1. Data Retrieval

The current study involves conducting a systematic review of existing literature on the relationship between traffic safety and rutting. Figure 2 provides an overview of the data-retrieval process, which includes identification, eligibility assessment, screening, and snowballing to identify relevant studies. Initially, a search was performed using the Scopus database, which is widely regarded as the largest and most comprehensive literature database [17]. The search query was designed to include a combination of three categories of keywords, as presented in Figure 2. The first category focused on rutting distress, with terms such as 'rutted', 'rut depth', 'rutting', 'transverse profile', and 'transverse unevenness.' The second category included keywords related to roads, such as 'roads' and 'pavement.' The third category contained safety-related keywords, including 'road safety', 'crash', 'accident', 'injury', 'stability', and 'hydroplaning.' The search was limited to article titles, abstracts, and keywords. The search resulted in 305 research items, as shown in Figure 2.

The next step involved refining the results by limiting eligibility to studies within the subject areas of Engineering, Computer Science, Social Science, and Multidisciplinary fields. This eligibility criteria reduced the number of articles to 275, as shown in Figure 2. The screening process aimed to select articles directly relevant to the study area, resulting in the retrieval of only 19 articles, as illustrated in Figure 2. Finally, forward and backward snowballing techniques were applied to identify any potentially overlooked studies using the Scopus and Google Scholar databases. As a result, 38 studies were identified for further analysis, as shown in Figure 2. The retrieved literature includes journal papers, conference papers, and technical reports from various highway agencies in countries such as Sweden, Finland, and the USA.

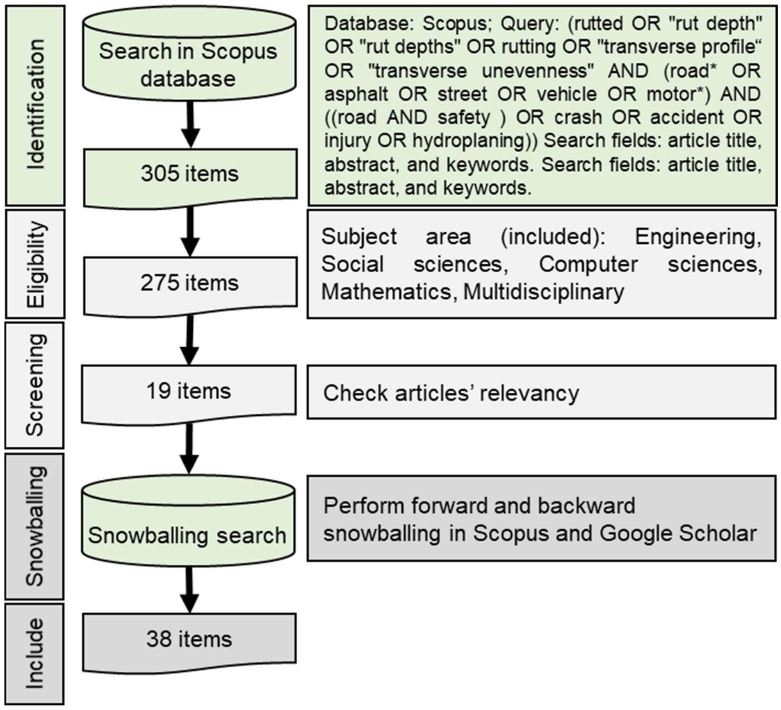


Figure 2. Literature-retrieval methodology.

2.2. Examination of Factors Influencing Rutting's Impact on Traffic Safety

The second stage of this study involved analyzing the retrieved literature to understand the influence of various factors on the impact of rutting on traffic safety. The studies were scanned to identify the studied factors. Ten factors were identified to have a potential impact on the reported significance of rutting on traffic safety. The potential factors include study type, weather conditions, lighting conditions, road geometry, driving path, vehicle type, traffic volume, and study location. Also, rut depth limits were established considering varying conditions. These limits were identified through a critical analysis of the available literature.

2.3. ML-Based Prediction Models

The estimation of the accident rate represents a regression problem. Due to the existence of multiple dependent variables, previous studies utilized regression models such as negative binomial regression [9,18–20], zero-inflated Poisson regression [20], maximum likelihood estimation of a Poisson regression [15], logistic regressions [21], seemingly unrelated regression equations [22], and random-parameters negative binomial regression [23]. However, the advances in ML algorithms open new horizons that can improve the prediction of the accident rate. Therefore, this study employed multiple ML algorithms to develop prediction models using the extracted dataset.

Subsequently, the third stage involved developing prediction models for traffic accident rates based on rut depth values under varying conditions. Figure 3 illustrates the different phases in the process of developing ML models and evaluating the criticality of various features used as inputs for prediction. The first phase involved building the database by reviewing and selecting relevant literature, followed by the extraction of data points. Necessary pre-processing was performed, such as selecting a uniform unit for accident rate; in this case, the number of crashes per 100 million vehicle kilometers a year (100 MVkm) was adopted. Ultimately, a dataset representing the relationship between rutting and accident rates was constructed by extracting data points from a subset of studies.

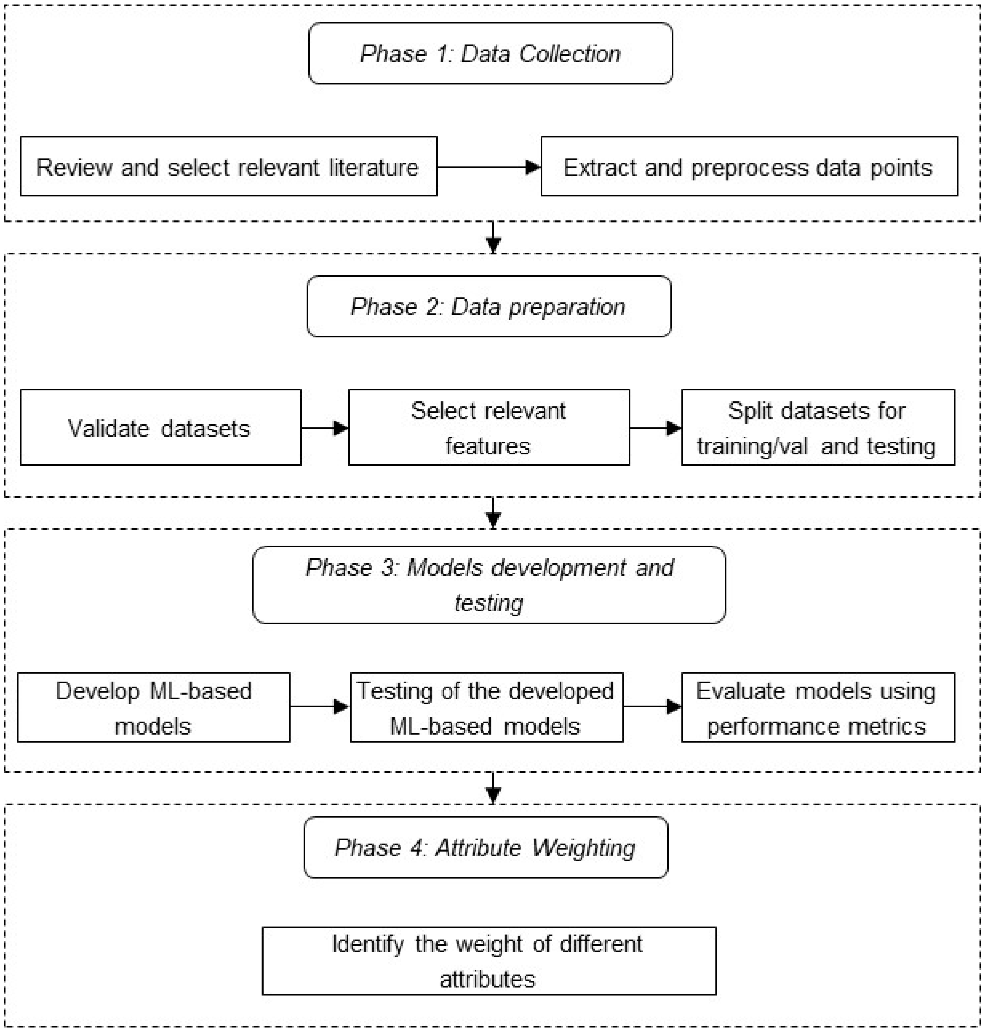


Figure 3. Workflow for the development of ML-based models.

As presented in Figure 3, the second phase focused on preparing the data for the development of the ML models. Initially, the dataset was validated, and the relevant features were selected. Next, the dataset was divided into 90% for training and validation and 10% for testing. K-fold cross-validation was employed to validate the models and minimize the risk of overfitting. The remaining 10% was used for testing. The next phase involved the development and evaluation of the ML models. The developed models included decision trees (DT), random forests (RF), artificial neural networks (ANN), and support vector machines (SVM). Model performance was assessed using root mean square error and absolute root mean square error. Finally, the weights of different attributes were evaluated. The development of the models was carried out using the student version of Altair AI Studio software 2024.0.0 (formerly RapidMiner Studio) [24].

3. Results and Discussion

3.1. Description of the Retrieved Articles

A total of 38 articles were retrieved, consisting of five reports, 24 journal papers, and nine conference proceedings. These articles were published between 1990 and 2024. The reviewed studies employed multiple simulation- and field observation-based approaches. Additionally, a variety of rutting and safety measures were utilized, differing distinctly between simulation and field observation studies.

3.1.1. Investigation Approaches

Two main approaches were utilized in the reviewed studies to investigate the relationship between rutting and traffic safety: simulation and field observation approaches. The simulation methods employed included mathematical models [25,26], finite element models [27,28], and vehicle dynamics models [29,30]. Field observation studies typically employed regression models such as negative binomial regression [9,18–20], zero-inflated Poisson regression [20], maximum likelihood estimation of a Poisson regression [15], logistic regressions [21], seemingly unrelated regression equations [22], and random-parameters negative binomial regression [23]. However, the use of machine learning algorithms was lacking across the reviewed studies. The field observation studies were conducted in eight countries: Germany, Sweden, Norway, Australia, New Zealand, the USA, Japan, and China.

Field observation studies vary in their approach to analyzing rutting, either in isolation or as part of a broader investigation. Some studies [8,9,11,19] have focused exclusively on the relationship between accident rates and rut depth or considered only a limited range of contributing factors. This approach introduces methodological limitations that can challenge the validity of the findings, particularly when working with small datasets. Overlooking the influence of other variables while lacking the ability to ensure their uniformity or negligible impact weakens confidence in the derived conclusions. Conversely, a few studies [20,22] have adopted a more comprehensive approach, examining the impact of rutting alongside other relevant factors such as traffic characteristics, environmental conditions, and additional pavement attributes, including road geometry and skid resistance.

3.1.2. Rutting Measurements

While various measures are available for characterizing rutting in pavement, rut depth emerges as the most commonly used measure in safety analysis contexts. Researchers overwhelmingly rely on rut depth assessment for evaluating pavement rutting [2]. The wire and straight edge models are frequently employed for rut depth calculation, often measuring rut depth for both the left and right wheel paths. However, the reliability of rut measurements may be compromised in some studies, as they calculate the average rutting in both wheel paths instead of the maximum depth. This approach may underestimate the true severity of rutting, as hydroplaning incidents can pose safety risks even when occurring in only one wheel path [31]. Other measures utilized for rutting assessment include side slope [29], rut width [32], and width–height ratio of the rut [33]. In addition to rut depth, simulation studies often utilize a variety of indices to characterize the rutting of road pavements, such as rut length and rut width-to-height ratio.

3.1.3. Traffic Safety Measures

There were two distinctive types of measures for safety risks used in studies adopting field observation and simulation data. Field observation-based studies often utilize statistics describing the frequency of accidents, fatalities, and injuries. Crash rate, measured as the number of crashes per MVkm, is widely employed by researchers. The crash rate can be calculated using Equation (1) [34]. Some studies calculate crash rates by distinguishing between different types of accidents, such as single-car accidents and multiple-car accidents. Others differentiate accidents based on their involvement in fatalities and injuries.

$$AR = \frac{number\ of\ accidents \times 10^6}{AADT \times 365 \times T \times L} \tag{1}$$

where AR is the accident rate; AADT is the annual average daily traffic; L is the length of the investigated section in km; T is the length of the investigated time period in years; and 365 represents the number of days in a year.

In contrast, simulation-based studies evaluate the impact of pavement rutting on driving safety by measuring the vehicles' responses instead of the direct measurement of accident rates. As presented in Table 1, these studies utilized a variety of measures to assess vehicle stability and steering control, particularly focusing on the potential for vehicle rollover and sideslip. Chen et al. [29] and Tian et al. [33] studied the risk of vehicle rollover and sideslip. In addition, Chen et al. [30] and Zheng et al. [32] utilized vehicle steering stability to explain driving safety. Chu et al. [27] utilized the hydroplaning potential due to the sideslip on the existence of water in ruts to evaluate driving safety. Differently, Jia et al. [35], Zhang et al. [36], and Zheng et al. [32] utilized vehicle performance, namely, lateral acceleration, roll angle, yaw angle, and lateral offset, to indicate driving quality.

Table 1. Impact of rutting on traffic safety based on simulation studies.

Study	Rut Index	Safety Index
Chen et al. [29]	Rut depth, side slope	Vehicle rollover (based on LTR) and Vehicle sideslip (based SI)
Zheng et al. [32]	Rut depth, rutting average width, side angle of rut	Vehicle Steering stability based on maximum slide angle and RA
Tian et al. [33]	Width–height ratio of rut	Sideslip stability based on LA and slip angle and rollover stability based on LTR and RA
Chen et al. [30]	Rut depth	Rotation degree of the steering wheel
Aleksandrov and Semenova [26]	Rut depth	Coefficient of adhesion of the tire to the surface
Vansauskas and Bogdevičius [25]	Rut depth	Custom vehicle-stability criterion
Chu et al. [27]	Rut depth	Hydroplaning speed of pavement
Jia et al. [35]	Rut depth, width–height ratio	Lateral acceleration, roll angle, YA, lateral offset
Fwa et al. [37]	Rut depth	Braking distance
Guo et al. [38]	Rut depth	LO, LA
Aleksandrov et al. [39]	Rut depth	Angles of departure and dynamic load of the wheel when the vehicle leaves or enters the rut
Yan et al. [28]	Rut depth	Risk of lateral slip
Zhang et al. [36]	Rut width, rut length, rut depth	LO, LA

RA: roll angle; LA: lateral acceleration; YA: yaw angle; LO: lateral offset; LTR: load transfer ratio; SI: sideslip index.

3.2. Literature Analysis

3.2.1. Impact of Various Factors on Rutting and Traffic Safety Interactions

The perceived significance of rutting on traffic safety may vary due to a variety of factors. Table 2 summarizes the impact of ten factors on the criticality of rutting on traffic safety, including data type, weather conditions, lighting conditions, driving speed, driving trajectories, and road geometry. The results showed that the mode of investigation in terms of the use of simulation and field observation data was the most impactful factor on the perceived criticality of rutting. Simulation-based studies were found to be more likely to suggest a significant impact of rutting on traffic safety.

Several other factors were found to exacerbate the perceived impact of rutting on traffic safety. Rainy weather, resulting in wet pavement and water pooling, generally increases the impact of rutting by reducing skid resistance and heightening the potential for hydroplaning [27]. Additionally, rainy conditions can reduce the visibility of ruts [12]. Path changes while driving can increase the difficulty of steering control, leading to higher accident risks [10]. Curved roads increase the significance of rutting as they become less identifiable and more dangerous, especially in the presence of water [14]. Higher speeds exacerbate the impact of rutting on traffic safety [35,37]. Rutting is more hazardous at nighttime due to lower visibility and reduced ability to identify and adjust driving behaviors accordingly [31]. Light vehicles are more prone to rutting, and vehicles with wheel widths larger than the rut width are more likely to be impacted [40]. Moreover, the study location can significantly impact the findings, making it challenging to generalize results from one specific country to others. However, the impact of annual average daily traffic (AADT) is complex and cannot be understood without considering speed.

Table 2. Influence of various factors on the impact of rutting on safety.

Factor	Attributes	Notes
Study Type	Field observation, simulation	Simulation studies show a more significant impact of rutting on traffic safety.
Weather Conditions	Dry weather, rainy weather (wet surface)	Wet pavement reduces skid resistance and increases hydroplaning. Also, rainy weather hinders rut visibility.
Driving Path	Same path, path-changing	Path changes make steering control harder, increasing accident risks.
Road Geometry	Straight, curved	Curved roads amplify rut dangers, especially on wet pavement.
Speed	Low to high speeds	Higher speeds increase the impact of rutting on traffic safety.
AADT	Low to high AADT	AADT effects are complex and depend on speed.
Lighting Conditions	Daytime, night-time	Night-time reduces rut visibility, increasing risks.
Vehicle Type	Light to heavy vehicles	Light vehicles and those with wheel widths larger than the rut are more affected.
Road Type	Urban, rural, highway	Rutting is more critical on highways.
Study Location	Country of study (field observation)	Trends vary by country, making generalization challenging.

AADT: Annual average daily traffic.

Study Type

Two types of data were utilized to study the impact of rutting on traffic safety, namely, field observation and simulation. Field observation data are used to empirically study the relationship between mainly rut depth and accident ratio. However, simulation-based studies examine the relationship between the simulated rut and parameters describing the susceptibility of traffic accidents, such as rollover angle. Figure 4 summarizes the impact of rutting on traffic safety. As shown in Figure 4, the slight majority of the reviewed case studies (21) utilized field observation data. Also, simulation studies clearly indicated a critical impact of rutting on traffic safety, whereas field observation-data-based studies have reported diverse conclusions.

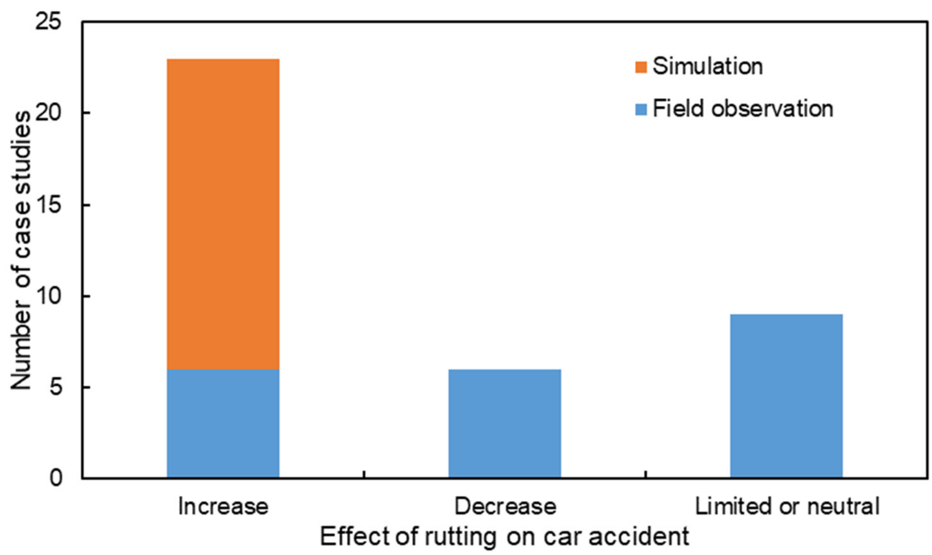


Figure 4. Influence of study type on the perceived impact of rutting on accident risk.

The discrepancy in the results between the field observation and simulation studies can be largely related to the drivers' responses when driving on rutted roads in field observation studies. Drivers were reported to reduce their speed and increase their vigilance when driving on rutted roads, which can mitigate the risk of traffic accidents. This explanation is also supported by the increased risk of rutting during night-time driving, where drivers may not be able to recognize the existence of a rut [10].

Field Observation Studies

As shown in Figure 4, the analysis reveals significant disagreement regarding the effect of rutting on the accident rate. Only six studies reported a significant impact of rutting on reducing traffic safety [11,14,15,22,41,42]. However, the majority of studies showed no or minimal impact, or even a reduction in accident rate, due to increased rutting [8–10,18,20,21,43]. Some of these studies reported a meaningful relationship between rutting and accident rates under special circumstances such as rainy weather and night-time [19,31]. Thus, field observation-based studies are particularly useful to understand the impact of various factors in real-world streets.

Multiple studies concluded no statistically significant relationship between rutting and accident rate. Ihs et al. [13] and Cairney and Bennett [44] concluded that no statistically significant relationship existed between rut depth and crash rate. Cairney and Bennett [43] reported a fluctuating effect of rut depth on the accident rate. Alhasan et al. [18] did not find a clear trend between rut depth and accident frequency. Ihs et al. [45] found no significant effect of rutting on traffic safety when dealing with data without distinguishing between dry and wet pavement. Chan et al. [9] found no significant relationship between rut depth and accident rate, possibly due to the low rut depth values (average 1.2 mm and max 7.6 mm) in their data. Chan et al. [31] did not find a statistically significant relationship except for data models at night and during rainy weather.

Multiple studies have reported a positive impact of rutting on traffic safety. Cenek et al. [10] found that the crash rate was reduced from 20 to about 11 crashes per 100 MVkm when the rut depth increased from 0 to 20 mm. Lehtonen et al. [46] found an increase in accident risk with rut depths of 6–10 mm but a decrease when depths reached 10–16 mm, possibly due to drivers reducing speed and increasing awareness.

Some studies reported a negative impact of rutting on traffic safety. Data presented by Lin et al. [47] showed a clear effect of rut depth on crash rate. Christensen and Ragnøy [21] noted an increase in accident risk by about 25% when the rut depth increased from about 3 mm to about 25 mm. Othman et al. [41] found that roads with rut depth exceeding 15 mm had an accident rate increase from about 32 to about 57 accidents per 100 MVkm. Anastasopoulos and Mannering [23] reported a statistical relationship between rut depth and accident rate for rut depth classes of 0–3 mm, 3–5 mm, and greater than 5 mm. However, these rut depth values are small and typically considered acceptable by highway agencies. Baskara et al. [8] found that most accidents occurred on roads with lower rut depths. However, the significance of this conclusion is diminished by the fact that most roads exhibited low rut depths.

Simulation Studies

As shown in Figure 4, there is a consensus among the simulation-based research on the impact of rutting on traffic safety [25–30,32,33,35–39,48–51]. Notably, simulation-based studies utilized the flexibility of simulation models to investigate the impact of different factors on the effect of rutting, including environmental conditions, pavement surface conditions, driving speed, and driving paths.

Several studies have focused on the impact of rutting on steering stability, which directly affects drivers' steering control. Chen et al. [30] found that rutting causes vertical displacement of the vehicle, leading to a loss of steering control. This effect is more pronounced in vehicles without steering assist systems. Zheng et al. [32] examined the influence of rutting side angle and average width on steering control. They found that while rutting width does not significantly affect steering stability, rutting depth and side angle have substantial impacts on the steering control system. Tian et al. [33] concluded that while the load transfer ratio (LTR) does not affect safety, the roll angle fluctuates beyond safety limits when crossing ruts. Jia et al. [35] stated that rutting depth impacts the roll angle but has a minimal effect on lateral acceleration on dry pavement. They emphasized the need for greater attention to wet pavement conditions, where rutting has a significantly higher impact on safety.

Weather Conditions

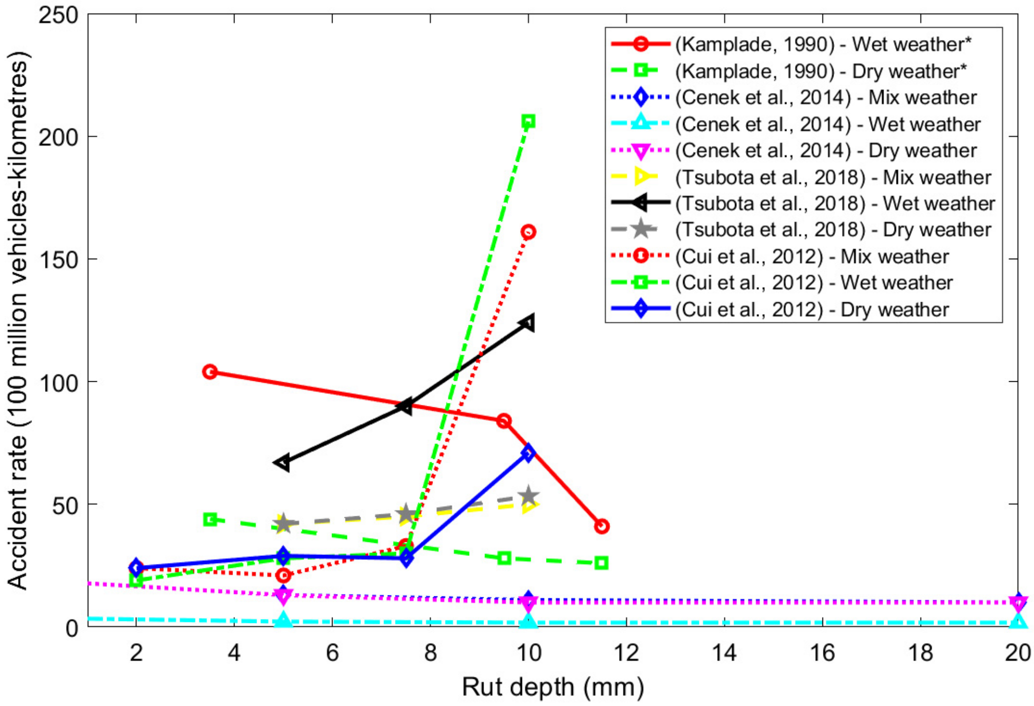
Table 3 summarizes the impact of weather conditions on the relationship between rutting and accident rates across multiple studies. In dry conditions, ruts form depressions that serve as wheel paths, posing hazards when drivers attempt to steer out of them, especially if the rut depth is significant. However, additional risks arise when the pavement is wet due to reduced friction and potential water accumulation in ruts, increasing the risk of hydroplaning. Hydroplaning occurs when a layer of water causes the vehicle's tires to lose contact with the road surface, creating a separation due to fluid pressure under the tires [10]. Generally, weather conditions, particularly wet conditions, significantly exacerbate the negative impact of rutting on traffic safety. Field observations and simulation studies both underscore the heightened risks associated with wet ruts, highlighting the need for stricter rutting limits in areas with higher precipitation.

Table 3. Impact of rutting on traffic safety under the effect of different weather conditions.

Citation	Study Type	Findings Summary
Tsubota et al. [15]	Field observation	Crash rates increase significantly with RD in rainy weather.
Cenek et al. [10]	Field observation	Crash rates decrease as RD increases, especially in dry conditions.
Cui et al. [14]	Field observation	RD larger than 7.5 mm is more critical on wet pavement.
Chan et al. [31]	Field observation	RD is more critical in rainy weather and night-time conditions.
Kamplade [52]	Field observation	- Crash rates are higher under wet conditions. - Under wet conditions, higher RD might reduce the accident risk due to driver behavior changes.
Aleksandrov and Semenova [26]	Simulation	Increased water depth reduces tire–pavement adhesion, affecting safety.
Tian et al. [33]	Simulation	Pavement wetness increases sideslip risk and impacts LA.
Jia et al. [35]	Simulation	Under wet conditions, RD has a very significant effect on the safety and stability of vehicles due to increased LA, RA, and LO, even with minor rut defects.
Zhang et al. [36]	Simulation	- Under wet conditions, the imbalance of the left rut and right rut can reduce vehicle stability. - Rutting has a significant impact on the lateral and control stability of a vehicle.
Chen et al. [29]	Simulation	Ponded ruts increase the risk of rollover and sideslip.
Yan et al. [28]	Simulation	Water depth imbalance between right and left ruts increases sideslip risk; stability decreases at speeds > 120 km/h; speed should be reduced to 80 km/h.
Chu et al. [27]	Simulation	Increased RD (0–15 mm) decreases hydroplaning speed (90–80 km/h) as surface water flow depths increase (0 mm to 10 mm).
Guo et al. [38]	Simulation	Water depth has minimal impact below 60 km/h but reduces stability above 80 km/h.
Vansauskas and Bogdevičius [25]	Simulation	Rutting has a limited impact on dry/wet pavement but reduces stability on snowy or icy surfaces.

RD: rut depth; RA: roll angle; LA: lateral acceleration; LO: lateral offset.

As presented in Table 3, multiple field observation studies emphasize a more pronounced impact of rutting in wet conditions compared to dry conditions. Chu et al. [27] explained that the reduction in hydroplaning speed due to rutting would reduce vehicle stability. Chan et al. [31] argued that drivers' awareness of pavement with ruts is lower in bad weather conditions. Data describing the relationship between rutting and accident rates under different weather conditions were obtained from multiple studies [10,14,15,52] to create Figure 5. In the original studies, the data were provided either as numerical values [52] or in graphical form [10,14,15]. Graphical data were extracted using the online tool WebPlotDigitizer [53]. Notably, the data from Kamplade [52] account for accidents involving injuries or serious damage and for pavements with a µSRM80 (skid resistance measured at a speed of 80 km/h) locked wheel value ≥ 5. Figure 5 plots the relationship between the rut depth and accident rate for multiple weather conditions, as presented in multiple studies. As presented in Figure 5, Cui et al. [14] concluded that ruts deeper than 7.5 mm are more critical on wet pavement. Tsubota et al. [15] reported a similar trend. Differently, Cenek et al. [10] found no significant difference in the analysis of wet and dry data. However, the accident rate in their study is significantly low, putting doubts on the generalization of the results. Kamplade [52] suggests that higher rut depth on wet and dry pavement would reduce crash rates, as drivers tend to slow down their vehicles while driving. However, the reported results clearly show a higher accident rate in wet weather compared to dry weather.



* Limited to accidents involving injuries or serious damage on pavement with skid resistance (µSRM80) ≥ 5.

Figure 5. Influence of weather conditions on the impact of rutting on accident risk in field observation studies [10,14,15,52].

Multiple studies compared the impact of rutting on dry and wet pavement using simulation by adjusting the coefficient of friction. For example, Tian et al. [33] set the friction coefficient at 0.8 to simulate dry pavement conditions. In contrast, friction coefficients ranging from 0.6 to 0.4 were employed to simulate pavement under light and heavy rain conditions. As presented in Tables 1 and 3, most simulation-based studies concluded that pavement ruts in wet conditions reduce vehicle stability, mainly due to friction loss, adversely affecting driving safety. Wet pavement ruts were found to exacerbate the risks of rollover, sideslip, and hydroplaning.

Zhang et al. [36] suggested that an imbalance of the left and right ruts could affect the lateral stability and control stability of vehicles on wet pavement. Aleksandrov and Semenova [26] and Chen et al. [29] investigated the impact of rutting on safety with only a water-filled rut model, where both studies found that rutting negatively affects driving safety in wet conditions. Yan [28] indicated that wet pavement with ruts increases the risk of vehicle rollover and sideslip. In addition, Chu et al. [27] concluded that an increase in rut depth would lead to deeper water depth, thus significantly reducing the hydroplaning speed. Tian et al. [33] found that wet ruts have greater effects on the lateral stability of the vehicle compared to driving on dry ruts. Similarly, Zhang et al. [36] and Jia et al. [35] reported a lower lateral stability loss when driving on wet ruts compared to dry ruts. However, Vansauskas et al. [25] concluded that vehicle stability under wet and dry conditions does not significantly contribute to road safety. Instead, they found that rutting affects safety primarily on snowy and icy roads.

Moreover, some studies investigated how vehicles responded to rutting with different water depths in the pavement. Chu et al. [27] concluded that an increase in rut depth would decrease hydroplaning speed with different surface water flow depths. Guo et al. [38] established that lateral stability decreases with the increase in water depth accumulated in ruts, as lateral acceleration decreases down to 0.4, which exceeds safety thresholds. However, Chu et al. [27] concluded that an increase in rut depth would always allow vehicles to slip no matter the water amount ponded in ruts. Yan et al. [28] and Zhang et al. [36] further investigated the effects of water depth on the different rut depths on the left and right sides. Zhang et al. [36] found that the imbalance of left and right ruts and water depth would negatively affect lateral stabilities. Yan et al. [28] explained that an imbalance of ponded ruts would increase the magnitude of tire vertical displacement up to 20 mm. Thus, there will be more risk of vehicle sideslip.

However, several studies have reported a limited impact of rut depth under both wet and dry conditions. Ihs et al. [45] reported a limited effect of rut depth on the crash risk in wet and dry conditions. The crash rate was found to increase by less than 5% when the RD increased from 0 to about 20 mm. However, a slight reduction in the accident rate was reported on the further increase in the rut depth. Vansauskas and Bogdevičius [25] stated that both dry and wet pavement have minimal impact on driving safety.

Driving Trajectory (Path Changing and Straight Line)

The impact of driving trajectory was explored in a limited number of studies. Some field observation studies hinted at the increased risk of rutting when drivers try to exit or enter the rut grooves. For instance, Cenek et al. [10] reported an accident caused by control loss while exiting a rut on pavements. Although seemingly intuitive, there is insufficient analysis to conclusively determine the significance of the driving path's influence on the impact of rutting on traffic safety, primarily due to the lack of detailed data in accident databases. However, multiple simulation studies have considered the impact of rutting on driving stability when changing the path compared to driving on the same path [29,51]. Rutting was found to be more dangerous when intersecting ruts compared to driving along the ruts [29,51]. Therefore, prioritizing the management of rutting on multi-lane roads where lane changes are anticipated is essential.

Road Type

The type of road is expected to influence the impact of rutting due to variations in AADT and speeds. However, there is a lack of comprehensive evidence on how different road types affect the relationship between rutting and traffic safety. Existing studies comparing various road types generally report minimal or even positive impacts of rutting on traffic safety. Cairney and Bennett [43] observed differences in the impact of rutting on traffic safety between urban and rural roads. In urban roads, accident rates decreased significantly at rut depths greater than 10 mm, in contrast to fluctuations observed on rural roads. Tehrani et al. [20] reported a statistically insignificant impact of average rut depth on traffic safety across three highway classes. The same study found that maximum rut depth was statistically insignificant for two highway classes and marginally significant for the other. The averaging of rut depth over large segments is thought to minimize the statistical significance between rut depth and accident rate.

Speed

Although rutting is expected to impose a higher accident risk on higher-speed roads, the limited field observation studies do not provide sufficient evidence to support this notion. Table 4 summarizes the results reported by Ihs et al. [13] on the impact of rutting at different speeds and AADT across different Nordic countries. In the data analyzed for Sweden, Finland, and Norway, rutting was reported to have a minimal or positive impact on traffic safety. However, the results vary across different AADT and speed classes and are inconsistent with those of adjacent classes, making the findings difficult to interpret and less useful for establishing maintenance guidelines.

Table 4. Impact of driving speed on rutting to safety [13].

Country	Speed (km/h)	Findings Summary
Sweden	0–50	No significant impact
	50–100	Decreased accident rates (up to 50%) when RD increased from 0–5 to 21 mm.
	110–120 (AADT < 10,000)	Increase in crash rate for RD of 17–21 compared to other RD values.
Finland	0–80	Decreased accident rates (up to 50%) when RD increased from 0–5 to 17 mm.
	80–100	No significant impact
	100–120	Increase in crash rate for RD of 17–21 compared to other RD values.
Norway	0–90 (AADT $\leq$ 5000 and AADT $\geq$ 10,000)	No significant impact
	0–90 (5000 $\leq$ AADT $\leq$ 10,000)	Decreased accident rates (up to 50%) when RD increased from 0–5 up to 17 mm. No significant impact is observed above 17 mm.

RD: Rut depth; AADT: Annual average daily traffic.

In contrast, simulation studies clearly show a critical impact of speed on the risk imposed by rutting [26–28,30,33,35,37–39,51]. Furthermore, multiple studies have emphasized the importance of limiting the speed on roads with higher rut depths, particularly in rainy weather [35,37].

Traffic Volume

The available literature on the impact of traffic volume on the influence of rut depth on accident rates is limited and contradictory, making the task of understanding and explaining its impact challenging. Generally, Ihs et al. [13] indicated a higher risk of accidents because of rutting AADT higher than 8000. Figure 6 illustrates the relationship between rut depth and accident rates at different AADT levels based on models developed by Chan et al. [19] for night-time and rainy weather conditions. As presented in Figure 6, accident rates increase with higher AADT for the night-time model, while they decrease for the rain model, given the same rut depth values. Additionally, in the night-time model, the impact of rut depth on accident rates is exacerbated as AADT increases, indicated by the steeper slope of the linear fit. Conversely, in the rain model, increased AADT mitigates the impact of rut depth on accident rates.

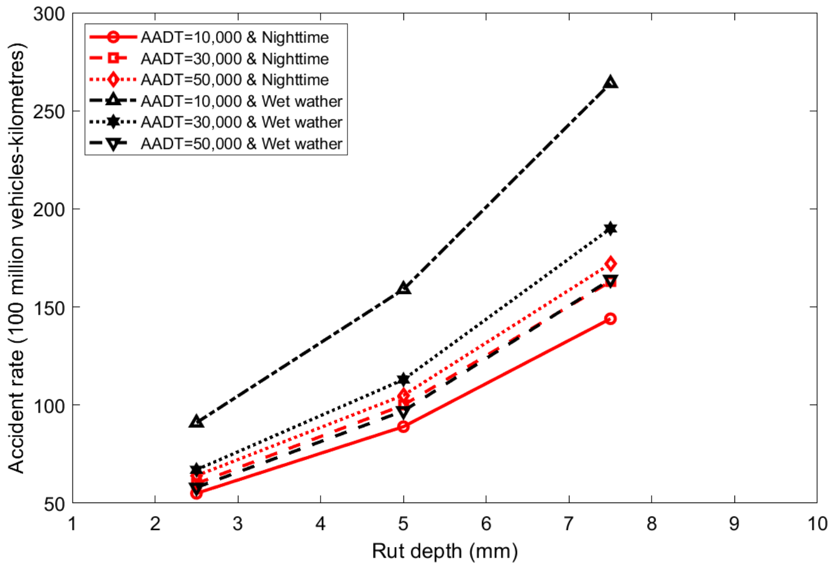


Figure 6. Influence of traffic volume on the impact of rutting on accident risk [19].

Road Geometry

Essentially, road geometry influences traffic safety. As illustrated by Othman et al. [41], roads with curved geometry are associated with a higher accident risk compared to straight roads. Multiple field observation and simulation studies have investigated the impact of road geometry on the criticality of rutting on traffic safety by comparing straight roads and curved roads [10,14,29,33,51]. Figure 7 illustrates the relationship between rutting and accident rates considering different road geometries, as reported by Cenek et al. [10] and Cui and Wang [14]. Cenek et al. [10] reported no critical impact of rut depth on accident rate for all roads and curved road models. Differently, Cui and Wang [14] showed a significant impact of rutting, with a higher accident risk on curved roads when the rut depth exceeds 7.6 mm.

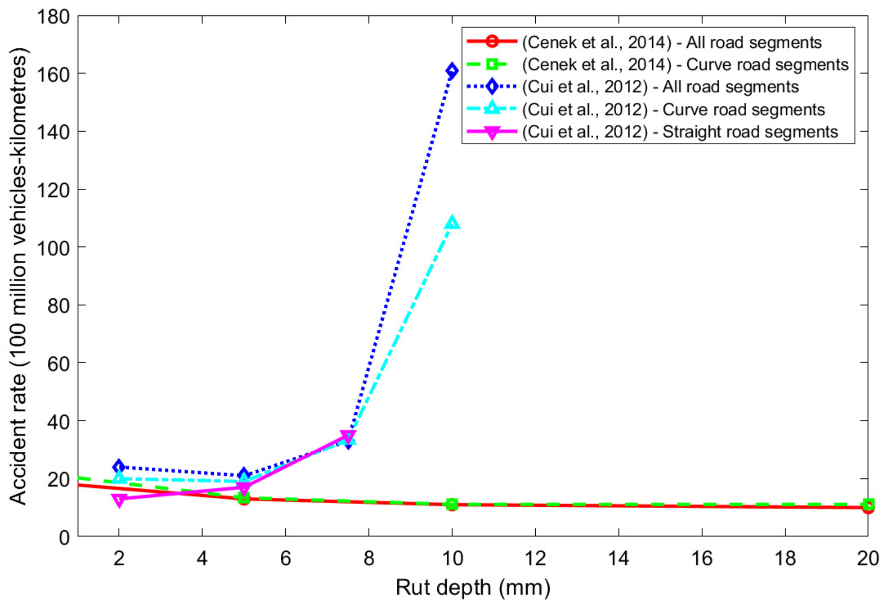


Figure 7. Influence of road geometry on the impact of rutting on accident risk in field observation studies [10,14].

Multiple studies have utilized simulation to investigate the impact of road geometry on the severity of rutting on traffic safety, comparing straight and curved roads [29,33,51].

Chen et al. [30] demonstrated that rutting exerts a more pronounced effect on curved roads compared to straight ones due to decreased vehicle stability when drivers attempt to change trajectory or speed. Under wet conditions, D'amico et al. [51] concluded that higher rut width and depth consistently pose skid-related safety concerns on curved roads.

Lighting Conditions

The visibility of rutting is crucial for timely detection and appropriate response by drivers. As lighting conditions are particularly relevant to driver responsiveness, investigations were limited to field observation data. Notably, Chan et al. [31] reported no significant effect of rut depth on accident rates during daytime hours. However, the impact of rut depth at night was found to be significant, particularly in wet and dark conditions. Conversely, Cenek et al. [10] found only a marginal reduction in crash rates due to increased rutting during night-time compared to all data. Thus, further research is needed to confirm the impact of rutting on traffic safety at night-time.

Vehicle Type

In general, smaller vehicles are more sensitive to road surface discontinuities such as ruts [10]. Two-wheel vehicles like motorcycles are more prone to rut-related traffic risk. This was explained due to the difficulty in exiting the rutted track [10]. Wambold [40] indicated that a rut can be particularly problematic for trucks with wheels wider than the rut width. However, there is a lack of statistical analysis of field observation data to support these explanations.

Study Location

Figure 8 presents the results obtained from eleven field observation studies on the relationship between rutting and accident rates according to the location of the study. As shown in Figure 8, there are distinct trends in different parts of the world. For example, studies conducted in the USA, as illustrated in Figure 8a, and in China and Japan, as shown in Figure 8c, indicate that rutting has a significant impact on accident rates. In contrast, rutting appears to have a minimal or even positive impact on traffic safety in New Zealand and Australia, as shown in Figure 8d. These differences may have arisen from the specifics of the studies, such as the scope of the data, parameters considered, and modeling techniques. However, considering the accident rates in different countries, it is compelling to relate these differences to the countries' differences.

Generally, the accident rate varies significantly across countries. For example, researchers often highlight the inverse relationship between the income level of a country and its fatality and injury rates. Statistics frequently show that low- and middle-income countries have higher accident and fatality rates compared to high-income countries [54]. Although comparing accident rates across different countries may involve certain limitations, significant discrepancies in accident rates seem to exist even among high-income countries and regions, as demonstrated in Figure 9. For example, the accident rate in the USA is about two to fifteen times higher than that in New Zealand and Sweden, respectively. Therefore, it is expected that the location of the study will influence the relationship between rutting and traffic safety.

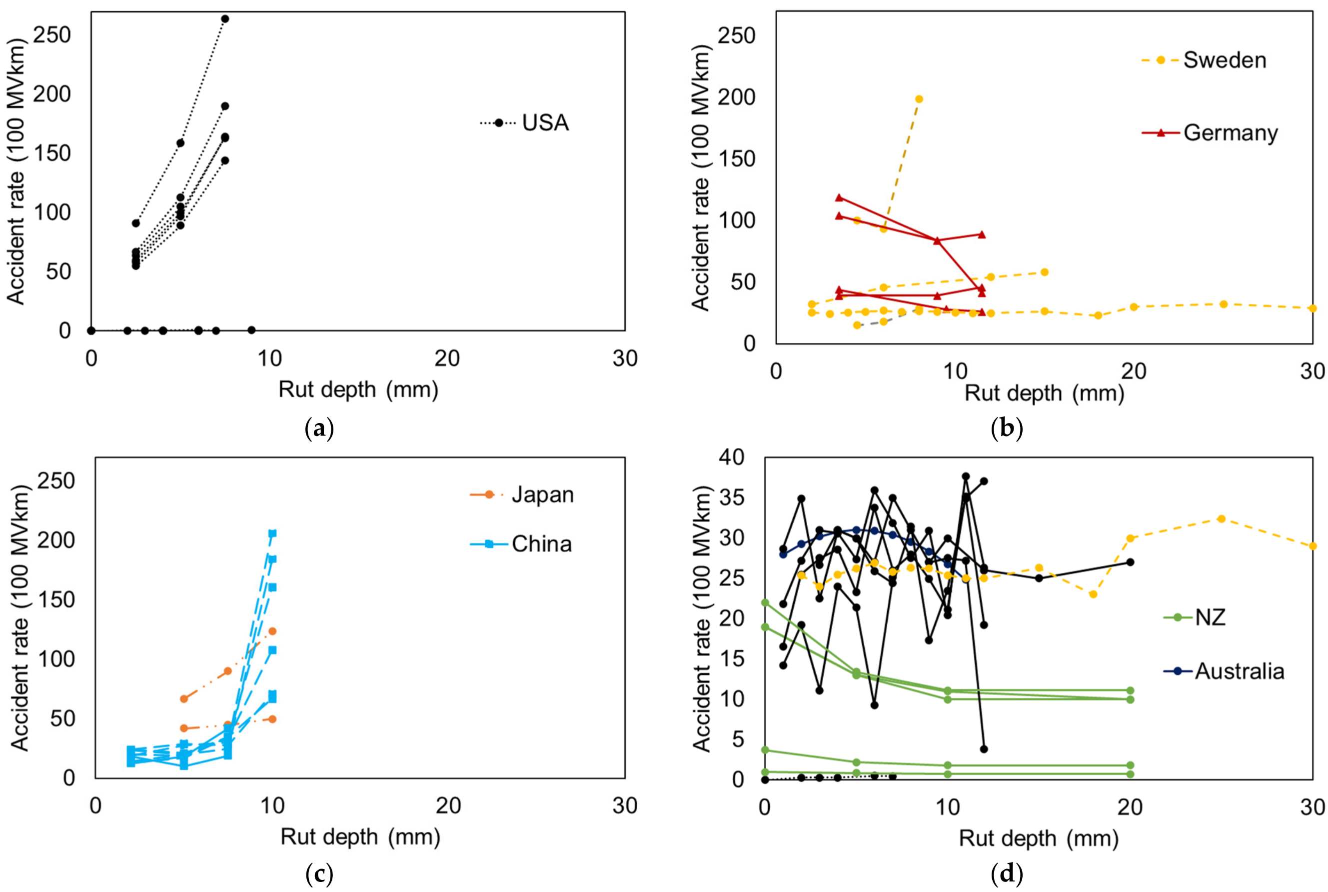


Figure 8. Visual representation of reported accident rates associated with rut depth from studies conducted in (**a**) North America, (**b**) Europe, (**c**) Asia, and (**d**) Australia.

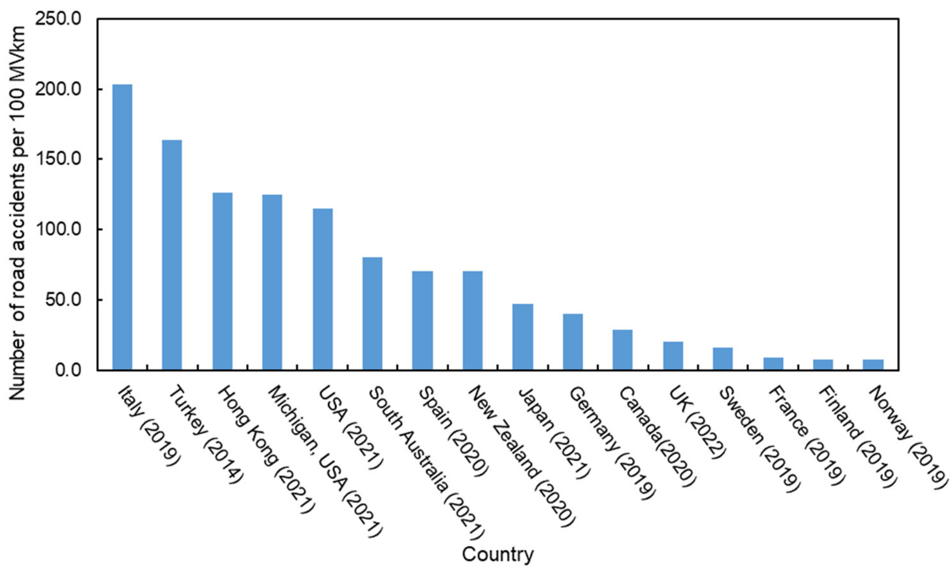


Figure 9. Road accident rate per 100 MVkm in multiple countries [55].

3.2.2. Rut Depth Limits

Table 5 presents the rut severity classification adopted by multiple highway agencies, as reported by Fwa et al. [37] and Baskara et al. [8]. Generally, ruts with depths lower than 10–13 mm are considered low severity, while ruts with depths higher than 19–25 mm are classified as high severity. However, these limits do not account for the impact of the rutting based on other interrelated factors such as weather conditions and speed. As shown in the aforementioned discussion, rutting is more dangerous when the pavement is wet, the road is curved, the driving is at low illumination, and the driving trajectory is across the rut groove. Simulation studies have also clearly shown that rutting poses more risk when driving at higher speeds. Therefore, it is crucial to establish rut depth limits considering these various conditions.

Table 5. Rut severity classification by highway agencies based on rut depth [8,37].

Highway Agency	Low (mm)	Medium (mm)	High (mm)
Pavement Condition Index	6.3–12.7	12.7–25.4	>25.4
Pavement surface evaluation and rating manual, asphalt roads	0–12.7	12.7–25.4	>25.4
Washington State Department of Transportation	6.3–12.7	12.7–19.1	>19.1
Ohio Department of Transportation	3.2–9.5	9.5–19.1	>19.1
Massachusetts Highway Department	6.3–9.5	12.7–38.1	>38.1
Ministry of Transportation and Infrastructure, British Columbia	3–10	10–20	>20
Malaysia	0–10 *	5–20	>20

* Combine good and fair condition.

Table 6 presents the rut limits suggested or induced by multiple studies. Start et al. [42] suggested limiting the rut depth to about 7.6 mm, although highway agencies often consider the upper bound of the low rut severity to be higher than this value. Mamlouk et al.'s [11] results suggested a limit that largely corresponds to the upper limit of low-severity ruts used by multiple highway agencies, as presented in Table 5. Fwa et al. [37] recommended different rut limits for various driving speeds on wet pavement. For high-speed roads (>90 km/h), the rut depth should be kept below 5 mm during the rainy season. However, for urban roads where the speed is less than 70 km/h, the rut depth can be tolerated up to 25 mm. For dry pavement, they suggested limiting the rut depth to 20 mm for roads with a speed limit of 100 km/h. Fwa et al. [48] extended the analysis by considering skid number (SN) in their simulations, recommending a rut depth limit of 6 mm for roads with an SN of 30 at 60 km/h under wet conditions. For roads with an SN of 25 at the same speed, they suggested a higher limit of 25 mm, reflecting the combined influence of surface friction and rut depth on safety. These studies collectively highlight the need for context-specific rut depth limits, accounting for factors such as speed, road conditions, and environmental conditions to ensure optimal safety.

Table 6. Rut limits suggested by various field observation and simulation studies.

Reference	Study Type	Special Factors	Speed (km/h)	Critical RD
Start et al. [42]	Field observation	Wetness	-	7.6 mm
Mamlouk et al. [11]	Field observation	-	-	8.9–10.1 mm
Fwa et al. [37] *	Simulation	Wetness (hydroplaning)	90	5
			87	10
			83	15
			75	20
			70	25
Chen et al. [30]	Simulation	-	120	6 mm
Yan et al. [28]	Simulation	Water-filled rut, rut length = 220	100	7 mm
Chu et al. [27]	Simulation	Water-filled rut (hydroplaning)	80	13 mm *
Jia et al. [35]	Simulation	Dry	100	20 mm
	Simulation	Water-filled rut	120	10 mm
Fwa et al. [48]	Simulation	Wet weather, SN = 30	60	6
	Simulation	Wet weather, SN = 25	60	25

* Total water depth; RD: rut depth; SN: Skid number.

3.3. Prediction Model

Data points representing the relationship between rut depth and accident rate were extracted from field observation studies. A total of 167 data points were extracted from eleven studies, as presented in Table 7. For each data point, information was searched based on ten prediction features and a prediction label. The prediction features constitute rut depth value in addition to ten previously identified factors. The constructed dataset was validated to check the completeness of the data and the usability of the different attributes. Consequently, the study type was excluded since all considered studies were of the field observation type. Driving trajectory, lighting conditions, speed, and vehicle type were also excluded due to limited data availability. The prediction label was set as the accident rate per 100 MVkm. This dataset was utilized to develop ML-based prediction models that explain the relationship between rut depth and accident rates.

Table 7. Sources and number of data points collected for this study.

Study	Number of Data Points
Mamlouk et al. [11]	8
Tsubota et al. [15]	9
Kamplade [52]	6
Chan et al. [19]	18
Cenek et al. [10]	20
Cairney and Bennett [43]	36
Cairney and Bennett [56]	11
Othman et al. [41]	4
Cui et al. [14]	33
Ihs et al. [13]	6
Ihs et al. [45]	16
Total	167

The frequency distribution of the prediction inputs and outputs is presented in Figure 10. As shown in Figure 10, the data exhibit substantial diversity in rut depth values (0–30 mm) and accident rate values (0–250 accidents per 100 MVkm), as illustrated in Figure 10a and b, respectively. Additionally, the dataset includes information from seven countries, as depicted in Figure 10c. The data also encompass various road types, traffic volumes, and weather conditions, as presented in Figure 10d, e, and f, respectively. The considerable diversity within the dataset supports the development of more comprehensive models.

However, it is important to note that the data are imbalanced for both the inputs and outputs. For instance, only a limited number of data points correspond to road sections with rut depths exceeding 12 mm, as shown in Figure 10a. Similarly, the majority of data points pertain to accident rates below 50 accidents per 100 MVkm, as indicated in Figure 10b. This limited availability of data for severe rut depths and the imbalance in accident rates may affect the reliability of the developed models. Data imbalance is a well-documented challenge in developing machine learning models for crash-related predictions [57]. Moreover, most of the data points represent highway roads, as shown in Figure 10d. A significant portion of the data corresponds to undefined traffic volumes and weather conditions, which are labeled as “mixed”, as presented in Figure 10e and f, respectively. These limitations in the dataset must be addressed in future research to develop more reliable models.

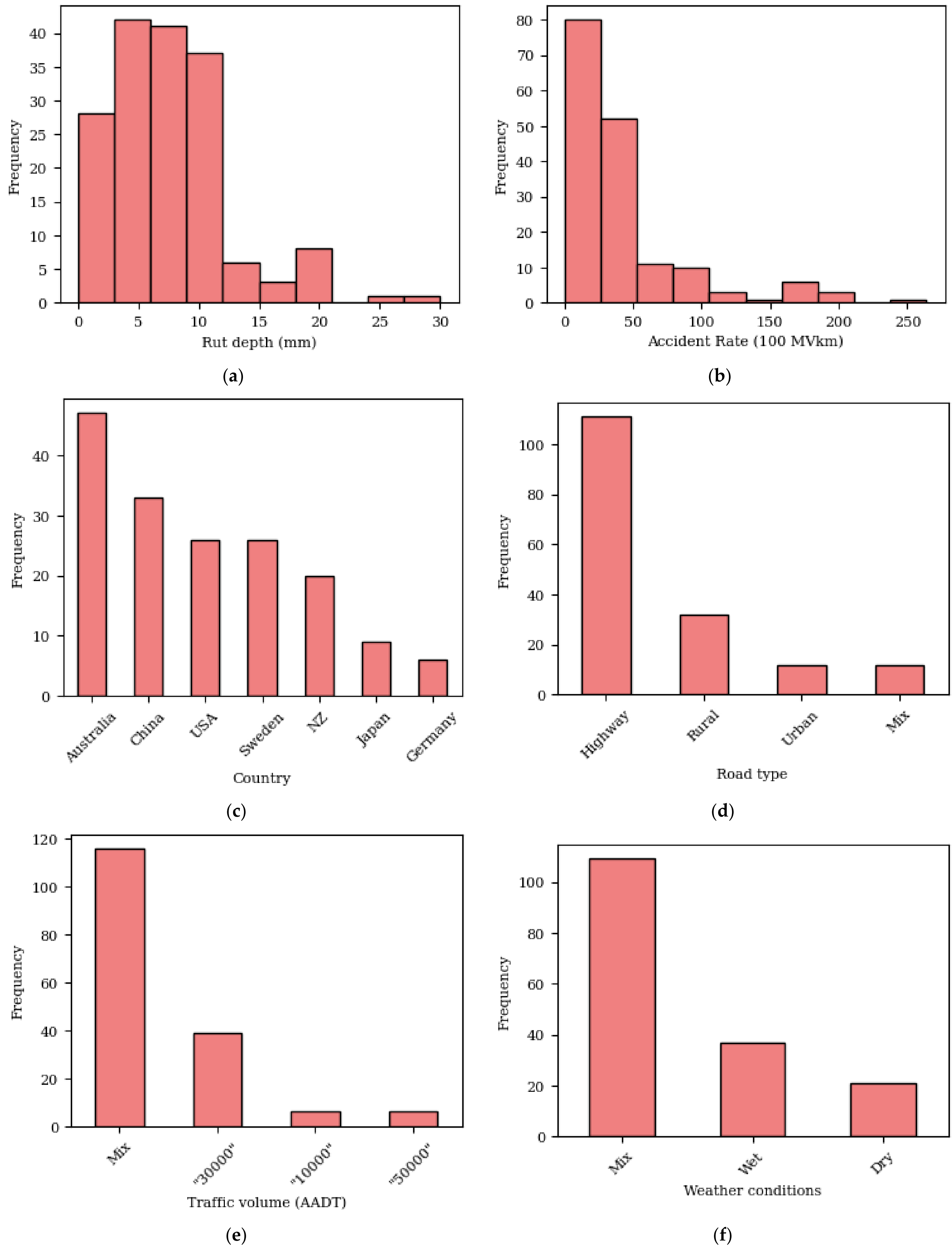
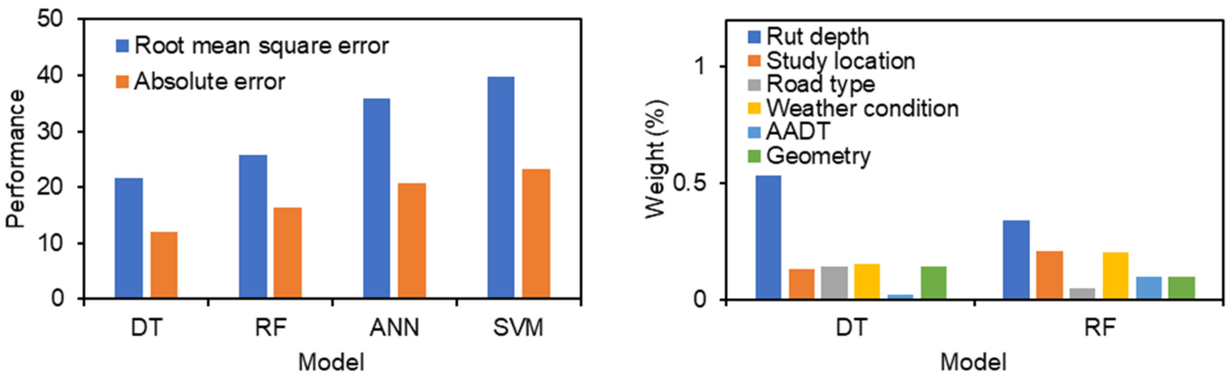


Figure 10. Frequency distribution of the data for (**a**) rut depth, (**b**) accident rate, (**c**) country of the study, (**d**) road type, (**e**) traffic volume, and (**f**) weather conditions.

The dataset was divided into two subsets for model development and testing. The first subset comprised 152 data points, representing approximately 90% of the total dataset, and was used for model development. The second subset included 15 data points, accounting for about 10% of the dataset, and was used for model testing. To minimize the risk of overfitting during model development, ten-fold cross-validation was employed. Four models were developed: DT, RF, ANN, and SVM. The performance of these models was evaluated during both the training/validation phase and the testing phase using root mean square error and absolute error as metrics.

Figure 11a compares the performance of four prediction models: DT, RF, ANN, and SVM. The models' performance was evaluated using root mean square error and absolute error. As shown in Figure 11a, both DT and RF models exhibited fair prediction performance considering the two indicators. The highest performance was attributed to the DT model with root mean square error and absolute error measured as 21.7 and 12.1 accidents per 100 MVkm, respectively. However, it is essential to note that such absolute error may not be acceptable in countries with low accident rates, as discussed earlier. The ANN and SVM models exhibited poor performance, with the ANN model having a root mean square and absolute error approximately double that of the DT model.



(**a**) (**b**)

Figure 11. Evaluation of (**a**) performance of accident rate prediction models and (**b**) relative weights of attributes in the best-performing models.

The superior performance of DT and RF models can be attributed to their ability to handle non-linear relationships and interactions among features, which are common in accident rate prediction. DT is particularly effective in capturing hierarchical and rule-based patterns in the data, while RF further enhances this by reducing overfitting through ensemble learning. In contrast, ANN and SVM models require larger datasets for effective training and often struggle with overfitting and optimization challenges when applied to small datasets, as in this study.

To evaluate the relative importance of different attributes, we analyzed their weights. Figure 11b presents the results for the two best-performing models, DT and RF. Both models assign high relative importance to rut depth values, weather conditions, and study location. Notably, the relative weight of rut depth was considerably higher for DT (53%) compared to RF (34%).

The results demonstrate the potential of employing machine learning algorithms to develop prediction models for accident rates based on rut depth under varying conditions. However, the models were built using a limited and unbalanced dataset, which may raise concerns about their reliability. To enhance reliability, it is essential to create comprehensive and sizable datasets for developing more robust prediction models. The development of such models can enable highway agencies to objectively evaluate pavement safety concerning rutting.

4. Limitations of the Existing Studies and Future Directions

The existing literature on the relationship between rutting and accident rates is constrained by several limitations, which make understanding and explaining the impact of rut depth on traffic safety challenging. The scope of the data used for investigation is often limited. For example, Cairney and Bennett [56] reported that their models were developed based on only 0.5% of the road length and 0.37% of the accidents in Victoria, Australia. Such a small sample size limits the generalizability of their findings. Field observation studies often acknowledge the limitations of their data due to the rarity of roads with deep ruts and the low vehicle mileage on these roads. This results in relatively low accident rates, which complicates the drawing of reliable conclusions. Table 8 presents the average and the maximum rut depth of the datasets utilized by multiple field observation studies. Baskara et al. [8] reported that most roads in their study had good rut depths (0–5 mm), with a smaller percentage having fair rut depths (5–10 mm), and almost none exceeding 10 mm. Chan et al. [9] utilized a database with an average rut depth of 1.2 mm and a maximum of 7.6 mm. Ihs et al. [13] and Cenek et al. [10] highlighted that roads with deep ruts are uncommon, contributing to the low incidence of accidents on such roads. This limited range of rut depths restricts the ability to assess the impact of more severe rutting conditions. Additionally, constructing sizable databases of synchronized rut depth measurements and accident rates may pose significant challenges in some countries.

Table 8. Average and maximum rut depth in the datasets utilized by multiple studies.

Study	Average (mm)	Max (mm)
Chan et al. [19]	1.3	7.6
Alhasan et al. [18] *	4.3	12
Sarwar and Anastasopoulos [22]	4.6	12.3
Christensen and Ragnøy [21]	10.3	>50
Tsubota et al. [15]	7.8	>20

* Estimated using a graph.

Some studies [8,9,11,19] examined the relationship between accident rates and rut depth in isolation or with the consideration of a limited number of potential contributing factors. This approach may present a methodological limitation, as the influence of additional variables is overlooked, particularly when working with small datasets. It is more advisable to investigate the impact of rutting in conjunction with other relevant factors, such as traffic characteristics, environmental conditions, and additional pavement characteristics, including road geometry and skid resistance [22]. This comprehensive approach provides a more accurate understanding of the factors influencing accident rates.

Furthermore, there is a notable gap in leveraging ML techniques to develop predictive models capable of estimating accident rates associated with rutting under diverse conditions. Expanding these models to incorporate additional critical pavement distresses, such as skid resistance and surface roughness, could significantly enhance their applicability and predictive accuracy.

On the other hand, simulation-based studies are crucial for understanding the theoretical impact of rut depth, often identifying conditions that pose the maximum safety risk. Despite their importance, these studies have limitations in modeling the complex relationship between rutting and other factors, particularly those related to human perception and adjustment to rutting. However, it is important to note that simulation models play a critical role in supporting the development of autonomous vehicles. These models help to predict and mitigate potential safety risks, thereby enhancing the reliability and safety of autonomous driving systems.

5. Significance of This Study

This study represents a significant advancement in the objective and data-driven assessment of pavement performance, moving beyond traditional subjective methods. By employing machine learning techniques, it captures the interactive effects of various factors influencing rut depth criticality, thereby improving the accuracy of accident rate predictions. The findings provide actionable insights for highway agencies and policymakers to establish context-specific rut limits and maintenance guidelines tailored to diverse environmental and traffic conditions.

Additionally, this study emphasizes the importance of integrating these findings into the development of autonomous vehicle algorithms, ensuring their capability to handle varying rutting scenarios effectively. Furthermore, the research underscores the need for comprehensive field studies with larger datasets that account for a wider range of rut depths and influencing factors. This approach not only enhances the reliability of pavement condition assessments but also supports the development of safer, more efficient road networks.

6. Conclusions

Researchers have long strived to enhance the assessment of pavement conditions, aiming for automation, quantification, and objectivity. While the detection of pavement distresses has increasingly become automated and quantified, assessing the impact of these distresses remains largely subjective. Consequently, there is a pressing need to quantify the impact of pavement distresses for a more objective assessment of pavement performance. This study focused on understanding the impact of rutting on traffic safety using 38 field observations and simulation-based literature.

Multiple studies have examined the influence of rutting on traffic safety, yet there remains a lack of consensus on its impact. Therefore, this study investigates the sources of discrepancies in reported results regarding the relationship between rutting and traffic safety. Ten factors were analyzed: study type, weather conditions (i.e., pavement wetness), lighting conditions, road type, driving trajectory, road geometry, speed, traffic volume, vehicle type, and study location. The study type was found to significantly influence the conclusions drawn. Simulation studies generally suggest a higher impact of rutting on safety compared to field observations. This discrepancy is attributed to the limitations of simulation models in capturing human factors, such as drivers' ability to anticipate and adjust their behavior to mitigate risks. Wet conditions, curvature, and the presence of other defects were found to exacerbate the hazards posed by ruts. Moreover, driving across ruts, night-time driving, high speeds, and the use of light vehicles were identified as factors that intensify the severity of rut-related issues.

Additionally, this study involved developing rut depth limits and prediction models for accident rates using rutting depth. This study presents rut depth limits considering different environmental and traffic conditions. Also, four ML-based prediction models were developed for evaluating accident rates using field observation data, with the DT model exhibiting the best performance. The relative weight analysis revealed that study location, weather conditions, road type, and road geometry are important factors for predicting accident rates using rut depth.

This study represents a significant step toward achieving a more objective assessment of pavement conditions, which can improve the cost-benefit analysis of maintenance planning. The findings offer critical insights for highway agencies and policymakers to establish accurate rut limits and maintenance guidelines. They highlight the need for autonomous vehicle systems to address scenarios involving rutting under varying conditions. Furthermore, this study emphasizes the necessity of comprehensive field observation studies with larger datasets that cover a broader range of rut depths and account for diverse environmental and traffic factors. Future research should also address discrepancies between field observations and simulations by incorporating real-world driver behavior into simulation models to enhance their accuracy. Additionally, leveraging ML algorithms in future studies, supported by more comprehensive datasets, can significantly improve the applicability and predictive accuracy of models estimating accident rates influenced by pavement conditions. Overall, this study advances the understanding of rutting's impact on traffic safety, providing valuable insights for both current roadway management practices and future autonomous vehicle technologies.

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