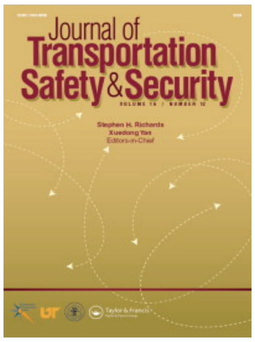

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Unraveling the complex relationship between weather conditions and traffic safety

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ABSTRACT
Understanding the impact of different weather conditions on crash frequency and crash severance is essential for developing effective strategies and interventions to mitigate road crashes. Extensive research has been conducted worldwide over the past few decades to investigate the relationship between weather conditions and traffic crashes. By synthesizing this collective body of work using the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), this paper seeks to provide a valuable resource for practitioners, policymakers, and researchers in their quest for evidence-based strategies to enhance traffic safety and minimize the adverse effects of weather conditions on road users. This systematic literature review establishes eligibility criteria for selecting relevant studies that span diverse geographical regions, climates, and methodologies. The objective is to present a comprehensive analysis of the intricate relationship between weather conditions and traffic safety, shedding light on the direct influence of weather phenomena like rain, snow, fog, winter, and extreme temperatures, as well as the underlying mechanisms and contributory factors. This study contributes to the advancement of transportation safety research, leveraging a credible foundation for evidence-based decision-making and guiding strategic development to safeguard road users and promote traffic safety amidst diverse weather challenges.

KEYWORDS
Safety; traffic crash; inclement weather; snow; systematic review

1. Introduction

Roadway crashes result in millions of serious injuries and deaths leading to significant financial losses annually, making traffic safety a major global concern. According to the World Health Organization's Global Status Report on Road Safety, a total of 1.19 million people died in traffic crashes in 2021 (Global Status Report on Road Safety 2023, n.d.). Among the many factors that contribute to traffic crashes, weather conditions play a significant and complex role (Hammad et al., 2019; Perrels et al., 2015).

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Weather-related crashes are not only more frequent but often more severe due to the unpredictable nature of weather phenomena, such as rain, snow, fog, and extreme temperatures, which can impact roadway conditions (Pisano et al., 2008; Qian et al., 2016) and affect driver behavior (Chakrabarty & Gupta, 2013; Druta et al., 2020; Elyoussoufi et al., 2023). This makes it crucial to understand the extent of the impact that various weather conditions have on traffic safety. Despite technological advancements in vehicle safety and traffic management, weather continues to be a major contributing factor to road crashes. By identifying specific weather-related risks and patterns, it is possible to inform policy decisions, improve road designs, and enhance driver education programs.

The influence of inclement weather on transportation safety has long captured the attention of policymakers, researchers, and practitioners worldwide. Recognizing the potential risks associated with adverse weather conditions and their impact on traffic safety is paramount in developing effective strategies to mitigate these risks and enhance the overall resilience of the roadway network. This study aims to contribute to the existing body of knowledge by presenting a comprehensive review of studies that have explored the relationship between weather conditions and various parameters of traffic safety, placing particular emphasis on crash occurrences and frequency.

A systematic review of the literature on the relationship between weather conditions and traffic safety is essential for several reasons. First, existing studies often vary in their methodologies, data sources, and geographical contexts, leading to inconsistent findings that make it difficult to draw broad conclusions. By synthesizing these studies systematically, this review will provide a more comprehensive understanding of the topic and identify gaps in current research. Second, a thorough examination of past interventions and strategies aimed at mitigating weather-related crashes will help inform future safety measures, ensuring that they are grounded in evidence. Lastly, given the increasing frequency and intensity of extreme weather events due to climate change (M. S. R. Amin et al., 2014; Leard & Roth, 2016), the findings of this review are more pertinent than ever, as they will help prepare transportation systems to adapt to changing environmental conditions.

Extensive research has been conducted worldwide in recent decades to investigate the relationship between weather parameters and traffic crashes. By synthesizing this collective body of work, this paper aims to provide a valuable resource for practitioners, policymakers, and researchers in their quest for evidence-based strategies to enhance traffic safety and minimize the adverse effects of weather conditions on road users. Therefore, in order to ensure a comprehensive and methodical investigation of the available literature, this study utilized the PRISMA guidelines that facilitate a systematic search and thorough review of relevant studies, thereby enhancing the rigor and reliability of the research process. By adhering to these guidelines, this paper aims to provide a robust analysis of the correlation between weather conditions and transportation safety parameters, contributing to the existing knowledge base and informing future research endeavors.

2. Study design

This study utilized the PRISMA guidelines to analyze the available literature systematically and comprehensively, focusing on the relationship between weather conditions and traffic safety factors. The adoption of the PRISMA framework ensured a rigorous and dependable research process, involving a meticulous search and thorough evaluation of relevant studies. The PRISMA guideline is a widely recognized set of recommendations designed to enhance the transparency and reporting quality of meta-analyses and systematic reviews. Developed in 2009, these guidelines aim to ensure adherence to a standardized approach when conducting systematic reviews, thereby facilitating replication and critical appraisal of the work. It consists of 27 checking items and a flow chart that guides researchers in conducting a comprehensive literature search, selecting eligible studies, extracting data, assessing study quality, and synthesizing the results (Moher et al., 2009). The PRISMA guidelines enable the improvement of the rigor and reproducibility of the systematic reviews, promoting the synthesis of reliable evidence to inform decision-making and policy formulation. Additionally, the correlation between weather and traffic safety parameters was examined by analyzing studies that meet the eligibility criteria defined using the SPIDER framework. Cooke et al. (2012) developed a tool-SPIDER framework - that assists in establishing eligibility criteria for systematic reviews with a focus on qualitative and mixed-methods research designs. This framework defines the Sample, Phenomenon of Interest, Design, Evaluation, and Research Type criteria, and provides a systematic approach to defining the key components for inclusion and exclusion criteria, ensuring that relevant studies are selected based on the research question and objectives. Given its compatibility with qualitative research and its ability to accommodate limited resources and time constraints (Methley et al., 2014), the SPIDER method was chosen as the preferred approach for conducting this systematic review on weather-related traffic safety. The following are the SPIDER criteria employed in this study:

- *Sample:* The review included studies that investigated the effects of different weather parameters on traffic safety with a focus on crash occurrence, frequency, and severity. The sample included studies from various geographic locations, road types, and users.

- *Phenomenon of Interest:* The review focused on studies examining the impact of adverse weather (e.g., rain, snow, fog, winter, etc.) on traffic safety. To target the most up-to-date studies on the subject, the study period from 2010 to 2023 was considered.
- *Design:* The review employed quantitative, qualitative, and mixed-methods research designs, and included experimental, observational, and case studies on the impact of weather conditions on traffic safety.
- *Evaluation:* The review evaluated the studies assessing weather's impact on traffic safety. Studies presenting statistical analysis, modeling, or qualitative findings were also examined.
- *Research Type:* All types of publications, including peer-reviewed journal articles, conference papers, white papers, reports, dissertations, and books from all over the world related to weather conditions and traffic safety have been covered in this review. The studies were selected based on predefined inclusion/exclusion criteria, as listed in Figure 1.

The research team employed several databases, namely TRID, Google Scholar, PubMed, Scopus, and Web of Science (WoS), to carry out a comprehensive literature search. To ensure extensive coverage of relevant literature pertaining to weather's impact on traffic safety, a combination of search terms was used such as "weather condition(s)," "weather," "crash(es)," "accident(s)," "traffic safety," and "weather hazard," along with

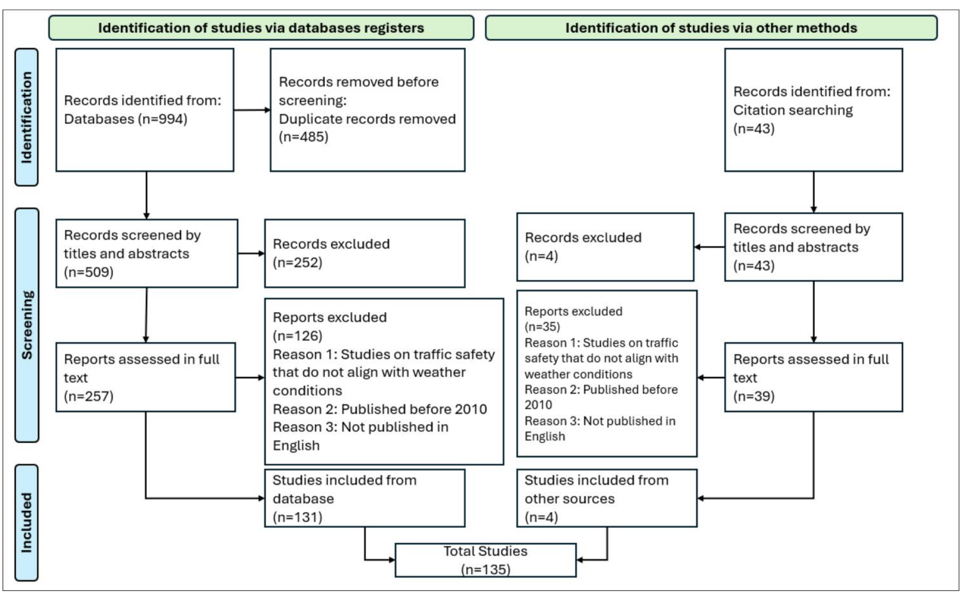

Figure 1. Flowchart for systematic review on relationship between weather conditions and traffic safety using PRISMA guideline.

their variations. For the systematic review, the PRISMA approach was employed, as depicted in Figure 1. Initially, the study team screened the titles and abstracts of the retrieved literature to assess their alignment with the SPIDER framework's criteria.

PRISMA's structured stages—identification, screening, eligibility, and inclusion—in acquiring systematically filtering studies, enhancing transparency and replicability in the search methodology. The process started with an expansive search using broad terms like "weather condition(s)," "weather," "crash(es)," "accident(s)," "traffic safety," and "weather hazard," along with their variations, to maximize the retrieval of potentially relevant studies on weather-related crashes. After the initial identification phase, the SPIDER framework was applied to refine the selection criteria and align them with the specific focus on weather-related traffic safety. Each SPIDER component was customized to address critical aspects of the research question. The Sample criterion targeted studies that examined the effects of adverse weather conditions on crash outcomes, covering diverse geographic locations and crash types. The Phenomenon of Interest centered on studies that analyzed how various weather conditions (e.g. snow, rain, fog) affect crash frequency, severity, and other safety-related factors. By focusing on these specific elements, the SPIDER framework narrowed down the dataset to the most relevant studies, which were subsequently assessed in line with PRISMA's eligibility and inclusion phases. This combined approach—utilizing PRISMA's structured process for systematic reviews and SPIDER's targeted criteria for study selection—allowed for a robust and efficient selection process. Titles and abstracts were initially screened for alignment with SPIDER-defined criteria, ensuring that studies with the relevant focus were selected for a deeper evaluation. Full-text articles of potentially relevant studies were then assessed in detail to confirm their eligibility based on both PRISMA and SPIDER guidelines. Ultimately, this fusion of frameworks facilitated a comprehensive, relevant, and focused literature set, improving the reliability and applicability of the review findings in understanding weather's impact on traffic safety.

The full texts of potentially relevant studies were evaluated to determine their eligibility for inclusion in the systematic review. The search focused on literature published in English from all countries within the 14-year period from 2010 to 2023. Through database searches, a total of 994 records were identified and extracted, while 43 additional records were obtained from other sources. After eliminating duplicate records, screening process was performed, leading to 552 studies that underwent further evaluation to identify those meeting the eligibility criteria set by the SPIDER framework. This resulted in a final selection of 552 studies for full-text screening. Following the full-text screening, 421 articles were excluded based on predefined exclusion criteria, leaving the team with 135 records eligible for inclusion in the final systematic review.

This study introduced a two-step conceptual framework based on reactive and proactive categories. Reactive studies focus on examining correlations between weather conditions and traffic safety outcomes, providing insights into how adverse weather correlates with crash frequency and severity. These studies largely align with sections on crash frequency analysis, crash severity analysis, and context-specific safety studies, helping to understand situational impacts and vulnerabilities. Proactive studies, in contrast, address countermeasures and technological interventions intended to mitigate weather-related crash risks, emphasizing preventative actions to enhance road safety. This includes research on sensor technologies and countermeasures specifically designed to improve safety in adverse weather conditions. The structure of the key topics was selected based on an analysis of counts and observed trends (47 records on crash frequency, 15 on crash severity, 48 on context-specific studies, 12 on sensor technologies, and 13 on countermeasures). This structure aligns with the landscape of existing studies and provides a comprehensive framework for understanding key themes in weather-related crash studies. Additionally, this approach—proactive versus reactive—further enhances the framework, facilitating a clearer understanding of how studies contribute either to understanding the impact of weather on crashes (reactive) or to developing solutions (proactive). This inclusive categorization is illustrated in Figure 2, showing how multiple studies intersect across categories based on their scopes and contributions to weather-related safety literature.

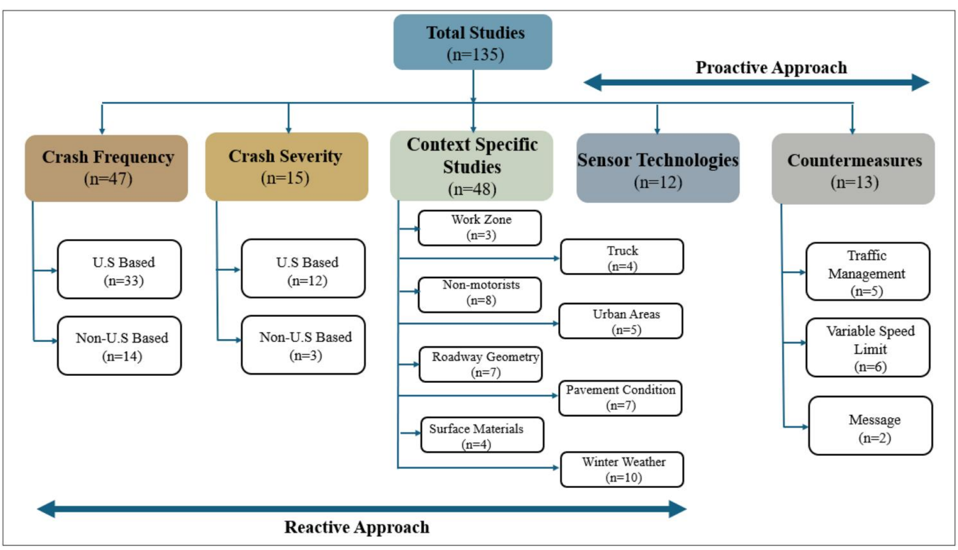

Figure 2. Systematic classification of studies into relevant categories.

3. Key topics

3.1. Crash frequency analysis

Traffic safety is a complex domain influenced by various factors, including weather conditions. Understanding the impact of different weather conditions on crash frequency and crash occurrence is crucial for devising effective strategies and interventions aimed at mitigating road crashes. Over the past few decades, extensive research has been conducted worldwide to investigate the relationship between different weather conditions and traffic crashes. This section aims to provide a comprehensive review and analysis of 135 articles focused on crash frequency and crash occurrence in relation to various weather conditions. To ensure a comprehensive coverage of the topic, these articles have been categorized based on their geographic origin. The review presents a rigorous examination of the literature, highlighting key findings, trends, and gaps in knowledge. By synthesizing the collective knowledge from both U.S. and non-U.S. studies, this review aims to contribute to a deeper comprehension of the correlation between weather variables and crash occurrences.

3.1.1. U.S. based studies

Several studies provided valuable insights into the impact of rainfall and rainy weather conditions on road safety. Sharif et al. (2011) found that adverse weather conditions, particularly rainfall and flooding, significantly contributed to motor vehicle-related flash flood fatalities in Texas, with all age groups at risk and fatalities concentrated in urban areas. Focusing on the highway type and location, Xiaoduan et al. (2011) revealed that rural freeways exhibited higher crash-risk ratios, with spatial analysis linking highway geometrics to crashes, while injury severity and single-vehicle run-off-roadway crashes increased during rainy hours. Zhao et al. (2019) revealed that weather variation significantly contribute to fluctuations in monthly traffic crashes on freeways while Saad and Chien (2018) identified patterns related to crashes on New Jersey freeways, including speed variances and weather conditions. Additionally, J. Yuan et al. (2018) focused on urban arterials and found rainy weather to significantly affect crash occurrence.

Focusing on the crash type in adverse weather, Das and Sun (2014) provided insights into specific risk factors of run-off crashes for single vehicle. While, Das et al. (2020) highlighted the prevalence of run-off road crashes of single vehicle during rainy weather in Louisiana, Jung et al. (2011) demonstrated the safety impact of rainy weather on multivehicle crash frequency to validate its effects on traffic operations. Jung et al. (2013) further studied factors influencing vehicle-to-vehicle crashes in rainy weather in

Wisconsin, finding that higher traffic volumes, speed limit changes, and off-ramp presence increased crash frequency, while wider shoulders and greater rainfall reduced it. Although, roadside barriers effectively reduced severe and run-off roadway crashes, increased the total number of crashes, varying with weather conditions, and time of day (Park et al., 2016). J. Xu et al. (2014) revealed that crash frequencies and fatality rates increased with higher population, and rainfall intensity, while speed limits and hospital distance were inversely related to crash rates but positively associated with fatality rates.

Spatial and temporal variability in relative crash risk during rain was investigated by Omranian et al. (2018), revealing higher risk variability in rural counties and more crashes in urban areas. Temporally, crash risk fluctuated with seasonal precipitation patterns and increased with rising rainfall intensity. Malin et al. (2019) highlighted the increased crash risks to be associated with icy rain and slippery roads. Proactive road weather safety audit processes were introduced to address weather influences on highway safety (Qin et al., 2013). High wind and fog were associated with higher fatality rates during crashes (Tarefder & Zhang, 2018). Strong et al. (2010) synthesized existing research and estimated changes in speed and crash frequency in winter, while also developing a severity index for compacted snow. On the other hand, M. M. Ahmed et al. (2014) demonstrated the feasibility of using real-time airport weather data to predict increased highway crash risk during fog and reduced visibility, with poor visibility and higher traffic exposure both significantly raising crash likelihood. Furthermore, Das et al. (2017) confirmed the expected correlation between low visibility and increased crash likelihood. In another study, Chung et al. (2018) found rain and snow to have stronger correlation with crash than fog. Moreover, Chen et al. (2018) examined the correlation between snow and lane-change-related crashes, finding that lane-specific traffic factors, such as flow into the target lane and flow ratio, significantly influenced crash likelihood, especially during snowy conditions. Finally, Das et al. (2021) analyzed operating speeds and identified specific speed metrics useful for assessing safety risks, finding higher variability in hourly and monthly operating speeds across the year correlated with an increased number of crashes under various weather conditions.

In addition, reduced visibility under hazy weather conditions was found to significantly increase car-following crash risk and affect drivers' behavior (Gao et al., 2018). Hazy weather also amplified crash risk and impaired car-following performance (Gao et al., 2020). On mountainous highways, there were weak correlations between the subjective and objective risk of adverse weather conditions, highlighting the need to enhance overall perception competence (Xue et al., 2022). Hazardous factors related to crash occurrence on mountainous freeways were identified, emphasizing the need to study crashes by season (Yu & Abdel-Aty, 2013). The study highlighted that temperature had varying effects on crash risk during snow and dry seasons. Factors such as lower temperatures, increased snowfall, heavy fog days, and lower wind speed were correlated with higher monthly crashes on freeways (S. Zhao et al., 2018). Rain and mist/fog had an impact on freeway crash risks and including weather information improved prediction accuracy (C. Xu et al., 2018). Different longitudinal driver assistance systems (LDAS) varied in their effectiveness for reducing the likelihood of multi-vehicle rear-end (MVRE) crashes during minor adverse weather (Y. Li et al., 2017).

El-Basyouny, Barua, Islam, and Li (2014) highlighted that adverse weather increased various types of crashes, with the highest run-off-the-road crashes. Gårder (2014) observed that All wheel drive (AWD) vehicles were underrepresented in winter-condition crashes while overrepresenting certain 4WD vehicles. Yu, Xiong, et al. (2014) established significant correlations between visibility, and precipitation in mountainous freeway crashes, and visibility and precipitation were found to significantly interact with geometric factors like steep downgrade slopes and curves, increasing crash risk. Michalaki et al. (2016) identified the influence of weather conditions and heavy vehicles on motorway collisions. Lastly, Leard and Roth (2016) revealed the association between warmer temperatures and increased traffic fatalities, particularly among pedestrians, bicyclists, and motorcyclists, estimating substantial costs related to climate change impacts on traffic crashes.

3.1.2. Non-U.S. based studies

Numerous international studies also have investigated the connection between weather conditions and crashes, uncovering significant insights. Haque et al. (2022) found that weather conditions in Bangladesh significantly impacted road crashes, with higher fatality rates during rainy and foggy weather, and identified districts more vulnerable to weather-related crashes through spatial hotspot analysis. Theofilatos (2019) discovered that rainfall intensity had a strong linear impact on crashes on an urban motorway in Athens. Furthermore, Theofilatos (2017) found that weather parameters did not directly affect crash likelihood. For example, El-Basyouny, Barua, & Islam (2014) identified that temperature and snowfall significantly impacted crashes, with higher temperatures reducing crashes and snowfall increasing them, while rainfall was mostly insignificant. Major snow or rain events following dry conditions showed a strong association with specific crash types, such as follow-too-close, stop-sign-violation, and ran-off-road crashes.

Focusing on the temporal characteristics, Karim et al. (2012) identified a negative association between collision frequency and daylight hours, whereas the number of snowfall hours exhibited a positive correlation in Edmonton, Canada. In contrast, El Esawey et al. (2019) evaluated weather-related collisions on highways in rural British Columbia, Canada, and demonstrated a reduction in serious collisions during the winter. Furthermore, Jaroszweski and McNamara (2014) highlighted the importance of using a weather radar to analyze rainfall's impact on road traffic crashes in urban areas. Redelmeier and Manzoor (2019) found that alcohol-related crashes were more frequent and life-threatening during adverse weather. Xing et al. (2019) highlighted the importance of considering non-linear exposure-response relationships and lag effects in assessing the impact of weather on crash risk.

In tropical countries like Malaysia, while weather conditions may not be as extreme as in regions with snow or typhoons, significant precipitation remains a key contributor to road crashes (Zulhaidi et al., 2010). Rain, in particular, has emerged as the most prominent weather-related threat, second only to crashes in fine conditions. Bergel-Hayat et al. (2013) demonstrated correlations between weather variables and a total number of injury crashes on a monthly basis, emphasizing the value of considering within-the-month variability of weather for road safety monitoring. Adverse weather conditions in India, such as rain, fog, and temperature changes, increase traffic crash risk, with drivers facing challenges in making safe decisions despite adaptive behaviors like slower speeds and longer headways (Chakrabarty & Gupta, 2013). Conference of European Directors of Roads (2021) provided insights into the measures adopted by national road authorities to mitigate wet weather driving risks. At last, Bakircioglu et al. (2015) emphasized the impact of adverse weather on various aspects of transportation and the need for integrating weather conditions into transport models. Table 1 shows a summary of the studies on crash frequency associated with weather conditions.

3.2. Crash severity analysis

The systematic review presents an analysis of crash severity with a focus on weather conditions. The studies discussed encompass both U.S. and non-U.S.-based research, offering valuable insights into the factors influencing crash severity under various weather conditions. The U.S. studies explore the attributes associated with rainfall-involved crash fatality and injury severities, with the impact of other weather parameters on crash severity. The findings collectively underscore the complexity of weather-related crash severity and the need for comprehensive strategies to enhance road safety.

Table 1. Summary of studies on traffic safety (crash frequency) associated with weather conditions.

Authors and year	Key findings/summary
(Leard & Roth, 2016)	Warmer temperatures lead to a higher number of fatal traffic crashes, particularly for pedestrians, bicyclists, and motorcyclists.
(Becker et al., 2022)	Snow: more single truck crashes, rain: more single-car crashes, high wind speeds: more single-truck crashes.
(Sharif et al., 2011)	Motor vehicle-related fatalities pertaining to flash floods were higher in Texas compared to other states.
(Haque et al., 2022)	Crashes during rainy and foggy weather had higher fatality rates.
(Theofilatos, 2019)	Crash showed a robust linear correlation with rainfall intensity, while average flow exhibited a nonlinear relationship.
(Jaroszweski & McNamara, 2014)	The stricter rain event criteria used with weather radar resulted in an increased Rainfall Accident Ratio (RAR) in Manchester, while the RAR decreased in Greater London.
(Chung et al., 2018)	Utilizing weather station data along with vehicle-miles-traveled is a cost-effective method to create geospatial crash risk analysis models.
(Das et al., 2017)	Confirmed the expected relationship between low visibility and increased crash likelihood during inclement weather. Identified key factors associated with inclement weather crashes.
(Das et al., 2017)	Driving during periods of low visibility increases the likelihood of a crash, highlighting the importance of considering visibility in road safety measures.
(Strong et al., 2010)	Inclement weather adversely affected crash frequencies and vehicle speed while reducing fatal crashes.
(J. Yuan et al., 2018)	Rainy weather indicators had significant effects on crash occurrence on urban arterials.
(M. M. Ahmed et al., 2014)	Real-time weather data from airports can effectively predict increased risk on highways.
(Xiaoduan et al., 2011)	Crash and injury risk escalated with rainfall, exhibiting fluctuations based on the time of day.
(Das et al., 2020)	Single-vehicle run-off road crashes are prevalent during rain
(Chen et al., 2018)	Rural single-vehicle crashes in rain are more likely to cause fatality due to slippery roads and limited visibility.
(Jung et al., 2011)	Daily rainfall and wind speed are significant factors in crash frequency and severity estimation.
(J. Xu et al., 2014)	Crash frequencies and fatality rates increased with rainfall.
(Redelmeier & Manzoor, 2019)	Adverse weathers were significantly more frequent during alcohol-related crashes, increasing the relative risk by 19%.
(Omranian et al., 2018)	Crash rates varied depending on the precipitation patterns and geographical locations
(Das & Sun, 2014)	Temperature, snowfall, and major snow or rain events following dry weather had significant impacts on crash types.
(Zhao et al., 2019)	Single vehicle run-off, property damage only, and sideswipe crashes in the same direction were significant during rain.
(Saad & Chien, 2018)	Monthly crashes were influenced by lower temperatures, and increased heavy foggy days.
(Das et al., 2021)	Weather parameters did not directly affect crash likelihood or severity.
(Gao et al., 2020)	Reduced visibility significantly increased car-following crash risk and affected drivers' behavior, including decreased headway distance and increased speed variances.

(*continued*)

Table 1. Continued.

Authors and year	Key findings/summary
(Jung et al., 2013)	Hazy weather increased collision risk and impaired car-following performance.
(C. Xu et al., 2013)	Rainfall influenced vehicle-to-vehicle crash occurrences.
(Xue et al., 2022)	Crash experience and injuries in adverse weather increased drivers' perceived risk values.
(S. Zhao et al., 2018)	Temperature and snowfall had significant effects on crash types, while rainfall showed mixed results.
(Bergel-Hayat et al., 2013)	Lower temperatures, heavy fog days, increased snowfall increased crashes.
(Park et al., 2016)	Weather variables showed significant correlations with injury crashes.
(Y. Li et al., 2017)	Rain and mist/fog significantly increased crash risks on the freeway.
(Yu & Abdel-Aty, 2013)	Weather had significant impacts on various aspects of transportation.
(Qin et al., 2013)	Introduced a program that developed practical road weather safety audits to proactively address weather-related highway safety issues.
(Yu et al., 2013)	Daylight hours were negatively correlated with collision frequency, while snowfall hours showed a positive correlation.
(Tarefder & Zhang, 2018)	Weather was found to influence crash occurrence.
(Conference of European Directors of Roads, 2021)	Extreme weather, such as high wind and fog, resulted in higher fatality rates.
(El-Basyouny, Barua, Islam, & Li, 2014)	Abrupt changes in snow or rain were positively correlated to all types of crashes.
(Dell'Acqua, De Luca, Russo, et al., 2012)	Adverse weather increased all crash types, with run-off-the-road having highest crashes.
(Aguilar et al., 2022)	Rainfall intensity had a significant influence on crash frequency, and porous asphalt surfaces led to a reduced crash rate in light rain.
(Chakrabarty & Gupta, 2013)	Weather impacts on passenger vehicle crashes yielded inconsistent results, while consistent results were obtained for freight-involved crashes.
(Zulhaidi et al., 2010)	The study highlighted the challenges of promoting safe travel decisions during adverse weather in India.
(Malin et al., 2019)	AWD vehicles were underrepresented in winter-condition crashes compared to dry roads. Four-wheel drive (4WD) vehicles, particularly pickups and SUVs, showed some overrepresentation.
(Yu, Xiong, et al., 2014)	Icy rain and slippery roads increased the relative crash risks
(Michalaki et al., 2016)	Precipitation and visibility were correlated with crash occurrence.

Furthermore, this section also covers studies grouped into different focus crashes, including work zones, near crashes, non-motorists, etc., and discusses various modeling approaches in a dedicated section to further enhance the understanding of crash severity.

3.2.1. U.S. based studies

Focusing on the roadway surface condition during adverse weather, Tefft (2016) found that adverse weather and roadway surface conditions accounted for a significant portion of crashes, with single-vehicle crashes and younger drivers being more common. Crashes on snow-covered or icy roads resulted in fewer injuries and fatalities compared to those on dry roads. In contrast, Kelarestaghi et al. (2017) found that inclement weather and young drivers tend to reduce crash severity. Ashifur Rahman et al. (2022) identified distinct attribute clusters associated with rainfall-involved crash fatality and associative impacts on injury severities, in Louisiana. The severity of crashes during rainy conditions was found to be significantly influenced by factors like speed limits, roadway alignment, and driver behaviors. Higher speeds and challenging road layouts, such as curves, increased crash risks when roads were wet and slippery. Additionally, driver impairments from intoxication and the nonuse of safety restraints exacerbate these risks. J. Xu et al. (2014) mapped variables in Texas and revealed that crash frequencies and fatality rates increased with local jobs and population densities, as well as rainfall. Z. Li et al. (2019) identified factors that increased the probability of fatal incapacitating injuries in single-vehicle crashes in rain. The studies by Yan et al. (2021), Jung et al. (2011), I. U. Ahmed and Ahmed (2022), and Saad and Chien (2018) highlighted various aspects of crash severity and the influence of weather conditions. Collectively, these studies found that adverse weather conditions, such as rain, snow, and fog, significantly influenced crash severity and frequency. For instance, Yan et al. (2021) linked higher crash severity to overturning crashes and early morning driving. Similarly, I. U. Ahmed and Ahmed (2022) identified temporal instability in rural highway crashes, where factors such as roadway conditions and driver behaviors varied from year to year. Furthermore, Jung et al. (2011) demonstrated that rainfall intensity and wind speed notably impacted crash risk, while Saad and Chien (2018) highlighted how speed variance could predict potential incidents under adverse conditions.

Other studies have explored the correlation between weather conditions and crash severities, providing valuable insights for road safety improvements. Jung et al. (2012) examined factors influencing crash severities during rainfall on high-speed roadways, while I. U. Ahmed and Ahmed 2021 focused on the disaggregate analysis of crash injury severity based on weather on rural two-lane highways. Das et al. (2021) studied the impact of operating speeds and roadway characteristics on crash likelihood to bolster the existing countermeasures to reduce crash severity. The study found that adverse weather conditions and young drivers tend to reduce crash severity. Additionally, studies by Jung et al. (2013), Wang et al. (2017), Mathew and Pulugurtha (2022), Shaheed et al. (2016), and Z. Li et al. (2018) provided insights into various factors that influence crash severity in different weather conditions. For instance, Jung et al. (2013) found that rainy weather increased vehicle-to-vehicle crashes, with factors like speed limits and lack of seatbelt use worsening crash severity. Similarly, Wang et al. (2017)

identified that snow, rain, and fog significantly heightened the likelihood of fatal multi-vehicle crashes, urging the need for greater speed reduction during these conditions. Mathew and Pulugurtha (2022) emphasized that weather events, especially rainfall and low visibility, impacted travel time reliability and crash occurrence, supporting the implementation of weather-responsive traffic management strategies. Meanwhile, Shaheed et al. (2016) highlighted that visibility and pavement temperature in winter weather crashes were key factors affecting occupant injury severity, with significant within-crash correlations.

3.2.2. Non-U.S. based studies

In recent research on weather-related crash severity, Fountas et al. (2020) found that under adverse weather and lighting conditions, factors such as vehicle type, driver age, and speed significantly influenced injury severity. For instance, younger drivers and higher speeds were associated with more severe outcomes, while the presence of roadside lighting helped mitigate injury severity in poor weather, demonstrating the important interplay between these factors. In a similar context, Theofilatos et al. (2017) highlighted factors such as speed, flow, crash type, and wind speed as influential in crash severity on urban arterials. Furthermore, Wei et al. (2021) observed several factors that influenced the severity of single-vehicle crashes differently under foggy and clear weather conditions. In foggy weather, young drivers, non-dry road surfaces, and signal control were significant contributors to crash severity. Additionally, M. S. R. Amin et al. (2014) suggested that climate change could lead to a decrease in crashes during snowy and freezing days, but a holistic approach is needed to mitigate severe road crashes. Meanwhile, El-Basyouny, Barua, Islam, and Li (2014) found that adverse weather conditions contributed to an increase in property-damage-only and run-off-the-road crashes, further underscoring the need for targeted interventions during poor weather conditions. Table 2 shows a summary of studies on crash severity associated with weather conditions.

3.3. Context-specific studies

3.3.1. Work zone

Several studies by Ghasemzadeh and Ahmed (2019, 2017, 2016) explored the impact of weather on crash severity in work zones. Ghasemzadeh and Ahmed (2017) found that adverse weather conditions increased crash severity, with lighting conditions and posted speed limits being key risk factors. In their 2016 study, they observed a rise in weather-related work zone crashes in Washington, where alcohol involvement, angle crashes, and rear-end

Table 2. Summary of studies on traffic safety (crash severity) associated with weather condition.

Authors and year	Key findings/summary
(Ashifur Rahman et al., 2022)	Four distinct clusters of roadways, crash environment, and driver conditions were identified for different injury severities.
(Fountas et al., 2020)	Vehicle- and driver-specific characteristics had varying effects on severities under varying light and weather states.
(Theofilatos et al., 2017)	Speed, traffic flow, crash type, and wind speed as key factors influencing crash severity on urban arterials.
(Yan et al., 2021)	Crash severity determinants demonstrated overall instability, but certain factors showed relative spatial or temporal stability.
(Tefft, 2016)	Crashes in unfavorable weather were less likely to result in fatalities compared to crashes on favorable weather.
(Jung et al., 2011)	Rainfall intensity and wind speed were significant factors in estimating crash frequency and severity in rainy weather.
(J. Xu et al., 2014)	Crash frequencies and fatality rates increased rainfall, while speed limits had negative associations with crash rates.
(Z. Li et al., 2019)	Factors such as curves, on-grade roads, signal control, and alcohol impairment increased the probability of incapacitating injuries and fatalities during rain.
(I. U. Ahmed & Ahmed, 2022)	Temporal instability was observed in most variables, with significant differences in contributing factors between crashes in adverse and clear weather.
(Saad & Chien, 2018)	Speed variances, along with other factors, can serve as signals for impending crashes and help in implementing timely mitigation measures.
(Jung et al., 2012)	Rainy weather significantly correlates crash severities with car following deficiency, wind speed, and vehicle types.
(I. U. Ahmed & Ahmed, 2021)	Significant differences in contributing factors were found between adverse and non-adverse weather.
(Theofilatos, 2017)	Variations in traffic significantly influenced crash occurrence, but weather parameters did not directly affect crash likelihood or severity.
(Das et al., 2021)	Crashes were associated more with higher hourly speed variability within a day and increased monthly speed variability within a year.
(Kelarestaghi et al., 2017)	Adverse weather and crashes involved with heavy trucks, unbelted passengers, and vulnerable road users increased likelihood of severity.
(Jung et al., 2013)	Higher speed limits, poor driver's lateral lane control, and absence of safety belt usage increase likelihood of severe crashes in rainy weather.
(Wang et al., 2017)	Snow or fog increased crashes with over 35 vehicles, while rain raises those with ten or more vehicles.
(Wei et al., 2021)	Effects of driver age, road surface condition, signal control, occupation, and weekends on crash severity vary depending on weather factors.
(Atiquzzaman et al. 2019)	Developed real-time alert system using vehicular network and connected vehicle technology for improved driver safety.
(Mathew & Pulugurtha, 2022)	Adverse weather affects travel time reliability and crash occurrence, providing valuable insights for traffic engineers and planners.
(M. S. R. Amin et al., 2014)	Weather conditions, driver characteristics, and road attributes show significant correlations with hazardous weather-related crashes.
(M. Amin et al., 2014)	Changing weather patterns are associated with increased hazardous weather-related crashes and their severity.
(El-Basyouny, Barua, Islam, & Li, 2014)	Adverse weather states increase property-damage-only crashes and all crash types, with run-off-the-road crashes showing the highest increase.
(Shaheed et al., 2016)	Significant factors influencing occupant injury severity in winter weather crashes include occupant-related factors, crash-level factors, and weather-related variables.
(Z. Li et al., 2018)	Wet road conditions, male drivers, semi-trucks, and young drivers have favorable effects on injury outcomes.

crashes significantly worsened during poor weather. Finally, Ghasemzadeh and Ahmed (2019) emphasized the importance of traffic control devices and lighting in mitigating crash severity under adverse weather, calling for improved lighting and traffic management in work zones.

3.3.2. Truck

Several investigations were conducted to identify the impacts of weather conditions on crash injury severity involving trucks, with a special focus on the manner of collision, and driver behavior. For example, Naik et al. (2016) focused on the effects of weather on single-vehicle truck crash injury severity using detailed 15-minute weather station data along with crash-specific and roadway data. Based on the analysis, several factors that increase the likelihood of severe crash injuries in single-vehicle truck crashes include higher wind speed, rain, and warmer air temperatures. Interestingly, higher levels of humidity were found to be associated with less severe injuries. Another research by Kelarestaghi et al. (2017) conducted a macroscopic analysis to identify the key crash contributing factors associated with adverse weather conditions (e.g. rain, sleet/hall, snow, and fog). The study reported that heavy truck with unbelted passengers increases the odds of severe crashes (OR = 6.04) in adverse weather conditions. Another study investigated the combined effects of traffic volume and meteorological parameters (e.g. precipitation, sun glare, high wind speed) on hourly probabilities of 78 different crash types (Becker et al., 2022). Focusing on trucks, single-truck crashes were found to be associated with high wind speeds, and relative risk increase measures were largest for a posted speed limit of 100 km/h to 130 km/h. In addition, single-truck crashes were found to have a higher relative risk increase measure in snowfall or freezing rain conditions.

Uddin and Huynh (2020) examined factors contributing to the severity of truck-involved crashes under various weather conditions using crash data collected from Ohio (2011-2015). The authors found that weather conditions such as normal, rain, and snow, had varying effects on crash injury severity. Factors that heightened the risk of severe injuries included higher posted speed limits (65 mph or more) during rainy conditions, crashes occurring on curved road segments, and incidents happening between 4 pm and 7 pm in snowy weather conditions. The study also proposed countermeasures such as focusing on drivers, implementing variable speed limit signs during rainy conditions, and restricting trucks on non-interstate roads during inclement weather. Rossetti and Johnsen (2011) examined the influence of adverse weather on the trucking industry and explored the potential implications of climate change for weather-related crashes. They highlighted various weather factors that impacted commercial motor vehicle operations and driver safety and suggested that climate variability and change could increase the frequency or intensity of these events. Their paper emphasized the need for exploring alternative strategies, such as education, training, or technological solutions, by the Federal Motor Carrier Safety Administration to address weather-related safety challenges in the face of climate change. In another study, Xiaoxiang et al. (2022) focused on truck platoon safety during crosswinds and found that the aerodynamics of a platoon differed significantly from a single truck, with the leading truck experiencing the highest maximum lateral displacement.

3.3.3. Non-motorists

Tarko and Thomaz (2015) discovered that warm temperatures and low precipitation, conditions that presumably increased motorcycle traffic, were associated with a higher incidence of crashes. Similarly, Y. Li and Fernie (2010) observed that inclement weather led to less safe road crossing behavior among pedestrians. Klang (2019) further revealed that lower temperatures and precipitation significantly reduced cyclist and pedestrian numbers, while other factors such as darkness, slipperiness, snow, moisture, and high winds had less noticeable effects. Contrasting these findings, Theofilatos and Yannis (2017) investigated real-time data (traffic and weather) from urban arterials in Athens, Greece, finding that Powered 2-wheelers (PTW) are more prone to multivehicle crashes, while weather characteristics had no impact on PTW crashes.

Cheng et al. (2017) showed that weather conditions have a complex relationship with motorcycle crash severity. Higher air temperature decreases the likelihood of fatal crashes while increases crashes at other severity levels. Rainfall, on the other hand, is linked with a decreased crash risk across all severity levels. In a study by Zhai et al. (2019) focusing on pedestrian crashes, it was found that higher temperatures and rain are linked to an increased probability of severe pedestrian crashes. These weather conditions also influenced the effects of convicted driver and pedestrian behaviors on crash severity. The findings emphasized the importance of considering weather and implementing real-time traffic control measures to enhance both motorcycle and pedestrian safety. D. Li et al. (2017) explored factors impacting injury severity of pedestrian under various weather conditions in Great Britain, highlighting the vulnerability of elderly pedestrians and effects of PSL on injury severity. They identified significant predictors of injury severity, including pedestrian age, PSL, roadway lighting, and vehicle movement. Alternately, Q. Yuan et al. (2018) explored high tricycle crash rates in Beijing, China, and found that factors such as speed limitation, time of day, and air quality index influenced the crash fatality rate (CFR), providing valuable insights for improving tricycle driving safety and suggesting measures to mitigate injuries in tricycle crashes.

3.3.4. Urban areas

A few research addressed how weather conditions affect traffic safety in urban settings, mostly conducted outside the US. Focusing on the city of Porto, Portugal as a case study, one of the previous research addressed the influence of daily precipitation, lagged effects of the precipitation accumulated during the previous month, and mean temperature (Lobo et al., 2019). The study suggested that rainy days are associated with the occurrence of road crashes, although the effect may be mitigated by prior precipitation. Using matched pair analysis, another research utilized 3 years (2008–2011) of crash data collected from Manchester and Greater London to investigate the impact of rainfall on road traffic crashes (Jaroszweski & McNamara, 2014). Using Relative Accidents Rates (RAR) as a measure, the study reported that a rain event under the weather radar approach results in an increased RAR in Manchester, while the RAR observed under these rainy weather conditions decreases in Greater London. Driving behavior, traffic volume, speed, and other concurrent meteorological factors were found to be linked to the variations in RAR. Another study, conducted in Toronto and Montreal using a similar matched-pair design, found no discernable change in the relative risk for snow-related casualty rates, but the relative risk of fatality during rains had decreased dramatically (Andrey, 2010). Additionally, the study also reported that weather-related casualty rates remain elevated. A US-based study identified rainfall and snow as significant factors increasing the fatal crash rates in four and six-lane urban interstate freeways in the state of Ohio (Kassu & Hasan, 2020). Another US-based study conducted in Salt Lake City, Utah focused on how weather conditions affect the number and type of crashes (Call et al., 2019). According to the findings, winter is the most dangerous season due to the strong correlation between crashes and monthly snowfall. While most crashes tend to occur during evening rush hours, a larger proportion of weather-related crashes take place between 5 am and 7 am Excessive speed is often a contributing factor in these incidents, although crashes during adverse weather tend to be less severe on average. Roadway slope also plays a significant role, as even slight increases in slope lead to a higher number of crashes.

3.3.5. Roadway geometry

Studies on roadway geometry's impact on traffic safety highlight roundabouts' benefits, and factors affecting crash types on freeways, emphasizing the importance of real-time traffic management during adverse weather to mitigate crash risk.

In recent research on weather-related traffic safety, various studies have explored the impact of environmental and geometric factors on crash occurrences and severity. Yu, Abdel-Aty, et al. (2014) analyzed real-time crash patterns on the I-70 Freeway, finding that single-vehicle crashes were more likely during snowy conditions, moderate slopes, and on three-lane segments, while sideswipe and rear-end crashes differed based on visibility and road characteristics. Similarly, Zhao et al. (2019) highlighted the significant contributions of weather factors in monthly traffic crashes and found that lower temperatures, heavy fog, reduced precipitation, and narrow shoulders were associated with higher crash rates while accounting for time effects improved crash prediction accuracy. In line with these findings, Shangguan et al. (2020) investigated rear-end collision avoidance behavior under foggy weather, focusing on visibility and road alignment using a driving simulator. The study found that reduced visibility led to more dangerous driving behavior, while road alignment, particularly downward slopes. Y. Zhao et al. (2018) found that converting signalized intersections to roundabouts led to a 20% reduction in injury and fatal collisions, though property-damage collisions slightly increased. The study also showed that roundabouts were less sensitive to rainy conditions compared to signalized intersections, where crash risk increased by 4% to 22% during rainfall. Additionally, Tian et al. (2019) aimed to enhance low-grade road safety in adverse weather through appropriate control measures. Yu et al. (2013) emphasized the influence of traffic, weather, and roadway geometry on crash occurrence on a mountainous freeway, while M. M. Ahmed et al. (2012a) highlighted the role of geometric features, and live weather and traffic data on crash occurrences during the snowy season. Focusing on the non-U.S. based studies, Wen et al. (2019) investigated the effects of weather and roadway characteristics on crashes at Kaiyang Freeway in China. They focused on a specific roadway segment and found that interactions of precipitation with curve, wind speed with slope, and visibility with slope increased freeway crash risk, but slope with precipitation decreased crash risk. The findings underscored the need for tailored traffic management strategies based on specific weather and roadway characteristics.

3.3.6. Pavement condition

The impact of pavement conditions on roadway safety has been explored. U.S. studies highlight the significance of implementing safety programs to reduce wet weather skidding crashes, propose simulation models to enhance wet weather driving safety assessment and emphasize the benefits of porous friction courses (PFCs) in reducing crashes during wet weather in Texas. Non-U.S. studies focus on Israel's maintenance policy to mitigate first rain skidding accidents (FRSA) and the correlation between crash rates, weather factors, and asphalt type used in road modernization operations. Understanding how pavement conditions influence road safety is crucial for implementing effective safety measures to reduce crashes during adverse weather.

Several studies have addressed the issue of road safety during adverse weather. According to McCarthy et al. (2021) skid resistance impacted safety of both dry and wet pavements, with a greater impact posed by wet surface. Abohassan et al. (2021) identified the negative impact of weather variables and the positive influence of maintenance operations in the assessment of impact posed by snow and ice control operations. Abohassan et al. (2022) further analyzed the effects of varying pavement friction levels on traffic safety during snowstorms, finding that reduced friction significantly increased collision risks, especially on arterial roads. Collisions decreased when friction was above 0.6 and increased sharply below 0.35. Fwa (2017) proposed a new approach using a simulation model to enhance the understanding of skid resistance performance and improve wet weather driving safety assessment while de Fortier Smit and Prozzi (2013) found that PFCs were advantageous in reducing crashes, injuries, and fatalities on Texas roads during wet weather. McGovern et al. (2011) presented a program aimed at reducing wet weather skidding crashes, offering valuable information to states interested in implementing such programs. Yaron et al. (2011) examined Israel's water blasting treatment policy aimed at reducing FRSA by removing contaminants accumulated during the dry season before the first rains. The study found that water blasting effectively improved skid resistance, reducing the risk of skidding accidents following the first rain.

3.3.7. Surface materials

de Fortier Smit and Prozzi (2013) investigated the safety benefits of PFCs for road surfaces during wet weather in Texas. Their analysis of road sections constructed between 2003 and 2011 revealed that PFCs significantly reduced crashes, injuries, and fatalities during wet weather. However, there was a slight increase in crashes immediately after the construction of porous asphalt surfaces. Similarly, Tong and Li (2015) studied rain and snow's impact on traffic safety parameters. Through simulation analysis, they generated curves for lateral displacement and force, and braking distance for varying friction coefficients of pavement surface, providing insights into car safety performance in various weather states. In contrast, Buddhavarapu et al. (2015) evaluated the safety benefits of a PFC on high-speed roadways in Texas and found that a PFC did not effectively reduce wet weather crashes.

They emphasized the importance of proper usage and interaction with road users to maximize the benefits of safety infrastructure investments.

Dell'Acqua, De Luca, Mauro, et al. (2012) investigated the relationship between asphalt type used pre- and post-modernization operations, crash rates on freeways, and weather factors. They found that crash frequency was significantly influenced by rainfall intensity, regardless of whether dense or porous asphalt was used. The crash rate initially increased with porous asphalt with rainfall intensity up to 0.5 mm/h and then decreased, possibly due to drivers exercising caution during adverse weather. Porous asphalt was also associated with a reduced crash rate in adverse weather and light rain, highlighting its benefits. Additionally, the study emphasized the psychological effect of rainfall on drivers, which had a more significant impact than the reduced surface adherence on wet roads. Similarly, Dell'Acqua, De Luca, Russo, et al. (2012) confirmed the dependence of crash frequency on rainfall intensity for both dense and porous asphalt surfaces. They observed that the crash rate decreased after a rainfall intensity of 0.5 mm/h with porous asphalt, indicating cautious driving behavior during adverse weather. Porous asphalt surfaces also led to reduced crashes in inclement weather and light rain, emphasizing the psychological impact of rain on drivers.

3.3.8. Winter weather

This section examines winter weather's impact on traffic safety, encompassing U.S. and non-U.S. based studies. U.S. studies highlight the effects of icy pavements, snowfall, and surface conditions on crash severity, as well as the significance of maintenance operations and calibration for enhanced safety. Non-U.S. studies emphasize correlations between weather elements and crash types, including day-of-the-week variations and vulnerability based on age and gender. Understanding these relationships is crucial for developing effective safety strategies during winter conditions.

Winter weather conditions have a substantial impact on crash severity, particularly during icy and snowy conditions. Anderson et al. (2020) analyzed crash and meteorological data, finding that most winter-weather-related crashes occurred during minimal weather conditions, often due to residual snowfall. The study also revealed that icy pavements increased crash severity, while snowfall and visibility impacted the likelihood of crashes. Similarly, Zhang et al. (2019), while looking at winter storm occurrences, highlighted the significant influence of weather conditions and road surface conditions on crash occurrence. Chen et al. (2018) identified that snow conditions significantly increase the likelihood of lane-change-related crashes on Wisconsin freeways. The study also identified that factors such as traffic flow and speed in specific lanes, combined with snow, contribute to these crashes. Gårder (2014) analyzed crash data and found that AWD and 4WD vehicles had different involvement rates in winter-condition crashes compared to dry-road crashes.

In response to the heightened crash risks during winter, various studies have developed models to better understand and mitigate these risks. Dong et al. (2019) developed safety benefit evaluation models for maintenance operations in winter, including the impact of snowplow parameters. In a subsequent study, Hallmark and Dong (2020) developed a crash frequency model for winter weather conditions to select key variables from datasets on weather, snowplow operations, and traffic. Their findings highlight that increased snowplow operations before winter storms significantly reduce crash rates. Abaza and Ahmed (2018) recalibrated the Highway Safety Manual to an improved version for cold regions by incorporating weather-related variables. Their study found that these weather-related factors, when combined with traffic data, improved the accuracy of safety predictions, particularly in cold regions like Alaska. Usman et al. (2011) highlighted a consistent association between poor road surface conditions and increased crash occurrence during winter seasons, with weather, road maintenance operations, and site-specific characteristics significantly impacting road safety.

Effective winter road maintenance is crucial for reducing crash risks during inclement weather. Hans et al. (2012) revealed that winter weather significantly increases crash frequency and severity on Iowa's rural highways, developing metrics like crash density and severity to identify high-risk locations. Their study emphasized the need for systematic methods to target crash mitigation during winter conditions. Hans et al. (2011, p. 3) further identified sites with potential safety improvements during winter conditions. Shahandashti et al. (2019) recommended consistent appearances of maintenance operations vehicles and the implementation of the Operations Management System in winter for enhanced safety. Additionally, Wong and Kwon (2021) utilized regression kriging to effectively analyze winter collision hot spots in Iowa, demonstrating its robustness for identifying high-risk areas and supporting targeted road safety interventions over five winter seasons.

The role of pavement friction in winter road safety cannot be overstated, particularly during snowstorms. Abohassan et al. (2022) demonstrated the association between pavement friction and collision occurrence during snowstorms, with lower friction levels markedly increasing the likelihood of collisions. Their study emphasized the need to prioritize arterial roads in snow clearing efforts, as these roads experienced a higher incidence of collisions than collectors during adverse winter conditions. Understanding the effects of weather conditions on vehicle dynamics is essential for improving road safety. Tong and Li (2015) explored the ADAMS/Car simulation model to analyze vehicle safety under various road surface conditions, finding that changes in friction coefficients during rainy and snowy weather significantly affect lateral displacement, lateral force, and braking distance.

Focusing on the Non-U.S. based studies, El-Basyouny, Barua, & Islam (2014) explored the correlation of weather elements with crash types, highlighting the significance of temperature and snowfall, while rainfall had minimal impact. The study also revealed the high significance of heavy downpours and extreme snow following dry weather for specific crash types. Karim et al. (2012) analyzed collision frequencies throughout the days of the week, revealing negative correlations between collision frequency and the number of daylight hours and positive correlations with the number of snowfall hours.

3.4. Sensor technologies

This section examines the implementation and impact of sensor technologies on traffic safety. U.S.-based studies showcase the potential of connected vehicle applications in reducing delays and emissions, while RWIS deployment reduces weather-related collisions. Non-U.S. studies demonstrate the effectiveness of Virtual RWIS stations and intelligent wireless traffic safety networks in enhancing road safety through accurate forecasts and real-time incident warnings. These studies emphasize the importance of sensor technologies in improving traffic safety under adverse weather conditions.

Chang et al. (2015) demonstrated the potential of connected vehicle applications in addressing safety, mobility, and environmental challenges in transportation. They found that combined V2I applications in signalized networks resulted in reduced delays, carbon dioxide emissions, and fuel consumption. Additionally, V2I applications in flow management on congested freeways helped mitigate speed differentials and minimize delays caused by major incidents. Their research emphasized the significant potential of intersection-focused safety applications and curve speed warning applications in reducing crashes and fatalities. Researchers have proposed innovative solutions to address the challenges of achieving accurate environment sensing and obstacle detection in adverse weather for autonomous vehicles (Singh & Vegamoor, 2021). The implementation of RWIS has shown significant reductions in weather-related collisions and proved to be cost-effective for winter road maintenance (Sharma et al., 2021). Weather data and Automatic Vehicle Identification (AVI) systems have proven useful in live analysis of crashes, emphasizing the effects of visibility and speed on crash likelihood (I. Ahmed et al., 2011). The deployment of RWIS has resulted in reduced fatalities and improved road conditions (Koeberlein et al., 2015; Jin et al., 2014).

Technologies utilizing floating car data and data mining models have demonstrated effectiveness in predicting weather-related road congestion and improving crash analysis accuracy (M. M. Ahmed et al., 2012; Clements & Cohn, 2016). Secure real-time traffic signal systems adapting to inclement weather have successfully reduced crashes and red-light violations (Abdel-Rahim et al., 2015. Furthermore, Driver assistance systems and the use of different spectral bands for enhanced vision have shown promising results in reducing MVRE crashes during adverse weather (Y. Li et al., 2017; Pinchonp et al., 2016). Overall, these studies highlight the importance of innovative technologies and data-driven approaches in improving traffic safety and mitigating the effects of inclement weather on traffic safety.

Non-U.S.-based studies have also contributed valuable insights into roadway safety under adverse weather conditions. For instance, Hassan and Mcclintock (2020), implemented Virtual RWIS stations along Ontario's Highway 401 to enhance existing infrastructure by identifying colder locations using mobile RWIS and weather forecasting algorithms. This approach provided accurate pavement forecasts in sensitive areas and proved cost-effective by eliminating the need for physical installation and maintenance. Similarly, in the WiSafeCar project, Eloranta and Sukuvaara (2011) developed a service framework and intelligent wireless traffic safety network. The project utilized vehicle-based sensor data and hybrid wireless communication to provide real-time incident/crash warnings, road condition information, and accurate weather updates. Moreover, Bakircioglu et al. (2015) demonstrated that Adaptive Cruise Control (ACC) and Cooperative ACC systems performed more effectively in preventing crashes. This approach improved traffic safety by enhancing the availability of relevant information to drivers, ultimately facilitating informed decision-making, and enhancing overall road safety. Table 3 shows a summary of studies looking at different technologies implemented to improve traffic safety in different weather conditions.

3.5. Crash countermeasures

Different crash countermeasures, including traffic management, VSL, and weather-related messages, have been addressed in past studies. U.S. studies demonstrate the effectiveness of VSL systems in reducing winter crashes and various crash types on rural mountainous freeways. Non-U.S. studies evaluate intelligent transport systems and weather-activated road signs, highlighting their potential to mitigate crash rates during adverse weather conditions.

3.5.1. Traffic management

Alfelor (2011) emphasized the significant role of weather events in highway crashes, injuries, fatalities, and congestion, highlighting the potential for

Table 3. Summary of studies on sensor technologies implemented for traffic safety associated with weather conditions.

Authors and year	Key findings/summary
(Singh & Vegamoor 2021)	Integration of LWIR cameras and radar formed a reliable sensing system for achieving SAE Level 5 autonomy in challenging weather.
(Hassan & Mcclintock, 2020)	Virtual RWIS stations provided cost-effective and accurate pavement forecasts, eliminating the need for installation and maintenance.
(Sharma et al., 2021)	RWIS significantly reduced inclement weather collisions and was a cost-effective solution.
(M. Ahmed et al., 2011)	The most significant factors influencing crash likelihood were the 10-minute average speed and 1-hour visibility before the crash.
(Koeberlein et al., 2015)	RWIS infrastructure and operations lead to a remarkable reduction in winter driving fatalities, with a benefit/cost ratio of 22.
(Clements & Cohn, 2016)	TomTom floating car data enabled accurate weather-related congestion alerts and predictions, improving road safety.
(Eloranta & Sukuvaara, 2011)	WiSafeCar project created a hybrid wireless traffic safety network providing accurate incident/crash warnings and real-time road condition information.
(M. M. Ahmed et al., 2012)	Data mining models outperformed classical models in crash analysis, with Artificial Neural Network and decision trees exhibiting the best accuracy.
(Abdel-Rahim et al., 2015)	The implemented system reduced potential crashes, specifically rear-end crashes, crossing crashes, and lane change crashes during adverse weather.
(Y. Li et al., 2017)	CACC system performed best in crash risks reduction during small-scale inclement weather on freeways.
(Jin et al., 2014)	The proposed method effectively optimized RWIS station locations, enhancing transportation safety in a tri-county region in Texas.
(Pinchonp et al., 2016)	Comparative study highlighted the detection capabilities of various spectral bands in providing enhanced vision during poor visibility conditions.

improved response through advancements in Active Traffic Management and Integrated Corridor Management. Similarly, Becker et al. (2022) found snow and wind speed having the greatest impact on single-truck crashes and rain on single-car crashes, while sun glare increased multi-car crashes. Incorporating meteorological variables improved predictive models, enabling live warning systems and traffic management. In addition, Yu, Abdel-Aty, et al. (2014) identified influences of snowy seasons on traffic management and crashes. Supporting this, Elassad et al. (2020) developed a real-time crash prediction model with MLP, which performed best in various weather conditions. Moreover, Aron et al. (2015) assessed the correlation between crash injuries, traffic conditions, and rain, with a focus on evaluating the safety efficiency of a new traffic management system.

In a distinct study, Wen et al. (2019) found interactions between wind speed and slope, precipitation, and curve, and visibility and slope were positively associated with an increase in freeway crash risk. Additionally, Raddaoui et al. (2020) found that CV's in-vehicle advanced warning systems, delivering real-time weather and work zone notifications, improved safety and driver response in work zones. However, displaying multiple warnings in work zone caused occasional distraction. These findings highlighted the potential of CV technology in improving work zone safety in inclement weather.

Non-U.S.-based studies have also made important contributions to understanding traffic safety in adverse weather conditions. Regarding traffic control devices, Theofilatos (2017) emphasized weather-activated road signs with adjustable posted speed limits to educate drivers and reduce crashes. Besides, Karim et al. (2012) introduced a proactive methodology to address weather-related safety issues by implementing road weather safety audit processes.

3.5.2. Variable speed limit (VSL)

Weather-based VSL systems showed a significant reduction in various crash types (Gaweesh & Ahmed, 2020). Saha and Young (2014) found a notable decline in winter crashes following the implementation of the VSL system, indicating its positive impact on safety. Additionally, Saha et al. (2015) highlighted the influence of adverse weather and crash occurrence on VSL implemented rural freeway corridors in mountainous terrain. Gaweesh and Ahmed (2020) assessed weather based VSL systems on a rural interstate in the mountainous part of Wyoming with a significant reduction in various crash types. Furthermore, Yasanthi et al. (2022) examined drivers' responses to fixed speed limits in various road-weather conditions, proposing a range of reliability-based Weather-Responsive VSL for rural highways. Focusing on the interstate, C. Xu et al. (2018) found that weather-based VSL significantly reduced various types of crashes on the interstates.

Wazirzada (2016) evaluated the effectiveness of an ITS variable speed system on crash rates in wet and dry roadways on the M1 in New South Wales. The study examined crash data, including fatal injury, and non-injury crashes. Furthermore, Crean (2016) introduced VSL with weather-activated live road signs in New Zealand to educate drivers and reduce crash rates during wet weather on State Highway 29.

3.5.3. Message

CTC & Associates LLC and Minnesota Department of Transportation (2019) recommended developing a system to generate and deploy weather-related messages on dynamic message signs (DMS) in Minnesota, as it would improve safety and mobility by enhancing the timeliness, accuracy, and effectiveness of these messages. Moreover, in a prior study, it was found that the implementation of Road Weather Information Systems (RWISs)

Table 4. Summary of studies on traffic management, variable speed limit, message for traffic safety associated with weather condition.

Authors and year	Key findings/summary
(Alfelor, 2011)	Emphasized the significant impact of weather events on highway crashes and congestion
(Becker et al., 2022)	Found that snow and wind had the greatest impact on single-truck crashes, rain on single-car crashes, and sun glare on multi-car crashes.
(Yu, Xiong, et al., 2014)	Identified influences of snowy seasons on traffic management and crashes.
(Elassad et al., 2020)	Developed a real-time crash prediction model
(Aron et al., 2015)	Assessed the correlation between crash injuries, traffic conditions, and rain, with a focus on evaluating safety efficiency.
(Wen et al., 2020)	Found that interactions between wind speed and slope, precipitation and curves, and visibility and slope.
(Raddaoui et al., 2020)	Found that CV in-vehicle warnings improved work zone safety but occasionally caused distraction, highlighting their potential in bad weather.
(Theofilatos, 2017)	Emphasized on weather-activated road signs with adjustable posted speed limits.
(Karim et al., 2012)	Introduced a proactive methodology to address weather-related safety issues
(Saha & Young, 2014)	Significant reduction in winter crashes following the implementation of the VSL system.
(Saha et al., 2015)	Interaction between grades, horizontal curves, and weather variables significantly influenced crash occurrence.
(Gaweesh & Ahmed, 2020)	Weather dependent VSL demonstrated a notable decline in various crash types.
(Wazirzada, 2016)	The system was effective in reducing crash rates in wet and dry conditions.
(Yasanthi et al., 2022)	Proposed range of reliability-based WRVSLs to enhance transportation safety in adverse road-weather conditions.
(CTC & Associates LLC and Minnesota Department of Transportation, 2019)	Generating weather-related messages and deploying them on DMS would enhance the safety and mobility of travelers.
(Crean, 2016)	Speed variances, in conjunction with other factors, could serve as signals for impending crashes.

combined with Variable Message Signs (VMSs) significantly reduced serious winter collisions (El Esawey et al., 2019). Table 4 shows a summary of studies on countermeasures for traffic safety associated with different weather conditions.

4. Conclusions

This systematic literature review project aimed to provide a comprehensive understanding of the impact of weather conditions on various parameters of traffic safety. The review identified 135 relevant studies that examined the correlation between adverse weather parameters and crash frequency, crash severity, and other aspects of traffic safety. By adhering to the PRISMA guidelines and utilizing the SPIDER framework, the research process was systematic and rigorous, enhancing the reliability and validity of the findings.

By synthesizing the collective body of work on the subject, this systematic review serves as a valuable resource for those involved in the road safety profession. Research has highlighted the significant influence of weather conditions on traffic crashes. Adverse weather events, including rain snow, fog, and wind, substantially increase crash risk due to reduced visibility, hazardous road surfaces, and altered driver behavior. Studies indicated that rural freeways, urban arterials, and mountainous areas experience elevated crash rates under these conditions, with rainfall being particularly associated with increased crash frequency. Furthermore, adverse weather exacerbates crash severity, as wet roads, poor visibility, and icy surfaces often result in more serious incidents, such as single-vehicle run-off-road crashes. Contributing factors, such as speed, road design, and driver impairment, further intensify these risks.

Context-based studies examined the influence of weather on traffic crashes in specific scenarios, such as work zones, truck-involved crashes, non-motorist safety, and urban settings. Research showed that work zone crashes increase during adverse weather, particularly when lighting and traffic control measures are insufficient. Truck-involved crash severity is significantly influenced by specific weather conditions such as rain, snow, and high winds, with increased risk observed under these conditions. High-speed limits, curved road segments, and late afternoon to early evening timeframes further exacerbate injury severity, particularly during rainy or snowy weather. Single-truck crashes are especially susceptible to severe outcomes in high winds and warmer temperatures, while elevated humidity tends to reduce injury severity. Trucks with unbelted occupants are at notably higher risk for severe injuries in inclement weather. Additionally, climate variability may amplify the frequency and intensity of these hazardous conditions, highlighting the need for adaptive safety measures like variable speed limits, truck restrictions on certain roads, and improved stability controls in high-wind conditions to reduce crash severity.

Studies on non-motorists, such as pedestrians and cyclists, revealed that inclement weather decreases road safety, especially during low-visibility conditions. Urban studies have found that weather impacts crash risk differently depending on traffic density, road design, and local climate patterns. Various countermeasures have been implemented to mitigate the impact of weather on crash frequency and severity, with technologies like VSL and RWIS playing a prominent role. VSL systems, especially in areas with frequent adverse weather, have successfully reduced crash rates by dynamically adjusting speed limits based on real-time conditions. RWIS provides accurate, real-time weather data to inform drivers and traffic management systems, leading to better decision-making and reduced crash risks. Additionally, weather-responsive traffic control measures, such as weather-activated road signs and intelligent transportation systems, have shown promising results in improving road safety during adverse weather conditions.

This research serves as a fundamental basis for evidence-driven methodologies and the development of policies, aiming to effectively address the complexities brought about by inclement weather conditions on roadways. Promoting safety measures and interventions based on sound research can lead to a safer transportation system, reducing the number of road crashes and mitigating the impact of adverse weather on road users. This systematic review contributes to advancing the knowledge and understanding of the complex correlation between weather and safety parameters in transportation. The findings underscore the importance of considering weather conditions in road safety planning and decision-making, ultimately working toward a safer road environment for all users.

Abbreviation and Acronyms

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SPIDER	Sample, Phenomenon of Interest, Design, Evaluation, and Research Type
WoS	Web of Science
NOAA	National Oceanic and Atmospheric Administration
QCLCD	Quality Controlled Local Climatological Data
VSL	Variable Speed Limit
WRVSL	Weather Responsive VSL
LDAS	Different Longitudinal Driver Assistance Systems
MVRE	Multi-Vehicle Rear-End
RWIS	Road Weather Information System
RAR	Rainfall Accident Ratio
ACC	Adaptive Cruise Control
CACC	Cooperative ACC
PTW	Powered 2-wheelers
MPR	Market Penetration Rates
CV	Connected Vehicle
PSL	Posted Speed Limits
CFR	Crashing Fatality Rate
PFC	Porous Friction Courses
FRSA	First Rain Skidding Accidents
CRW	Contaminant Removal Waterblasting
AVI	Automatic Vehicle Identification
RTI	Road Transportation Infrastructure
SPF	Safety Performance Functions

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