Review Article

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# Meteorological Factors Associated with Crash Severity and Injury Severity in Road Traffic Crashes: A Scoping Review

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## ABSTRACT

**Objective:** This scoping review aimed to identify and map the evidence on meteorological factors directly associated with road traffic crash severity and injury severity.
**Methods:** The review followed PRISMA-ScR guidance. PubMed/MEDLINE, Web of Science Core Collection, Scopus, and Embase were searched from inception to September 29, 2025, with supplementary searches conducted in ProQuest and Google Scholar. Original empirical studies were eligible if they directly examined associations between meteorological factors and crash severity or injury severity. Findings were synthesized descriptively, and the Haddon Matrix was used as a conceptual framework.
**Results:** Of 2,098 records identified, nine studies met the final eligibility criteria. Five studies examined crash-level severity and four examined injury-severity outcomes. Meteorological exposures included precipitation, wet-road conditions, snow and ice, visibility, dust, sun glare, temperature, relative humidity, wind, and solar radiation. Associations were heterogeneous. Rainfall, adverse road-surface conditions, poor visibility, dust, sun glare, high humidity, certain temperature ranges, and wind were associated with greater severity in some settings, whereas inverse or context-dependent associations were also reported. Effects varied according to road-user, vehicle, roadway, and temporal characteristics. No included study directly evaluated meteorological effects on post-crash emergency response, transport, trauma care, or subsequent survival.
**Conclusion:** The available evidence suggested that meteorological influences on road traffic crash severity and injury severity were heterogeneous and context-dependent rather than uniformly adverse. Differences in severity definitions, meteorological exposure measures, analytical approaches, and contextual factors limited direct comparability across studies. Future research should employ standardized severity outcomes, high-resolution meteorological data, and analytical methods capable of addressing interactions, confounding, and nonlinear relationships across diverse road-traffic and climatic settings.

**Keywords:** Meteorological factors; Crash severity; Injury severity; Road traffic crashes; Scoping review

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## Introduction

Road traffic crashes constitute a major global public health challenge and remain among the leading causes of mortality and morbidity worldwide, contributing substantially to premature death and long-term disability across diverse populations and settings. Despite sustained prevention efforts, the global burden of road traffic injuries continues to fall disproportionately on low- and middle-income countries, reflecting enduring inequalities in road safety outcomes [1, 2].

Meteorological factors, such as precipitation, snow, fog, temperature, visibility, and wind, are widely recognized as environmental influences that affect road traffic crashes. These variables have been examined in relation to traffic safety across a wide range of geographical and climatic contexts [3, 4]. Variations in meteorological conditions can alter road-surface friction, visibility, traffic flow, and vehicle dynamics, thereby influencing both crash-level severity and the severity of injuries sustained by individual road users [5, 6].

Recent studies have directly examined associations between meteorological conditions and crash and injury severity using diverse analytical approaches, including econometric and probabilistic models designed to address unobserved heterogeneity and class imbalance [5, 7]. However, the findings remained heterogeneous, with considerable variation in the operationalization of meteorological indicators, the definitions and classifications of crash and injury severity, and the geographical and road-traffic contexts investigated.

While previous reviews have addressed broader questions regarding weather–crash occurrence, injury-rate, or road traffic mortality, evidence specifically addressing crash severity and injury severity remains dispersed across disciplines and study designs [8, 9]. To date, the scope, methodological characteristics, and the findings of studies directly examining meteorological factors in relation to these two severity outcomes have not been comprehensively mapped.

The Haddon Matrix, originally developed by William Haddon Jr. in the 1970s, is a widely used conceptual framework in injury prevention and road safety research that systematically organizes risk factors across temporal phases (pre-crash, crash, and post-crash) and system domains (human, vehicle, and environment). By integrating epidemiological principles with systems thinking, the matrix enables researchers to move beyond single-factor explanations and to consider the dynamic interactions among host, agent, and environmental determinants of injury [10]. In road traffic research, the Haddon Matrix has been extensively applied to identify preventive interventions at multiple levels, ranging from behavioral adaptations and vehicle safety mechanisms to infrastructural and environmental modifications. Its multidimensional structure is particularly valuable for interpreting meteorological influences, as weather conditions may affect crash and injury severity through pathways operating in the pre-crash, crash, and post-crash phases. Accordingly, the Haddon Matrix was used in this review as a conceptual framework to organize weather-related mechanisms and their potential interactions with human, vehicle, road, and post-crash factors [10].

Scoping reviews are particularly well suited for synthesizing broad and heterogeneous bodies of literature, identifying key concepts, and highlighting research gaps without formally assessing effect sizes or study quality [11]. Accordingly, this scoping review aimed to identify, categorize, and systematically map the available evidence on meteorological factors directly associated with road traffic crash severity and injury severity. Crash severity refers to classifications assigned to the crash as a whole, such as property-damage-only, injury, and fatal crashes, whereas injury severity refers to classifications of injury harm among crash-involved road users, including fatal/nonfatal, serious/non-serious, and KABCO-derived categories. This review also aimed to identify methodological heterogeneity and evidence gaps relevant to future road-safety research.

## Materials and Methods

This scoping review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines [11].

PubMed/MEDLINE, Web of Science Core Collection, Scopus, and Embase were searched from inception to September 29, 2025, with supplementary searches conducted in ProQuest and Google Scholar. Search terms were developed around three main concepts: road traffic crashes, injury or trauma outcomes, and meteorological exposures. Controlled vocabulary and database-specific free-text terms were used as appropriate. The road traffic crash concept included "Accidents, Traffic," "Traffic Accident," "Traffic Crash," and "Traffic Collision." The injury and trauma concept included "Wounds and Injuries", "Trauma", "Wounds and Injury", "Injuries and Wound", "Research-Related Injuries", "Damage", "Physical Trauma," and "Physical Injury". The meteorological concept included "Extreme Weather", "Weather", "Climate", "Meteorological Concept", "Meteorological Factor", "Meteorologic Factor", "Temperature", "Humidity", "Atmospheric pressure", "Gaseous Composition", "Solar Radiation", "Cloud Properties", "Wind", "Precipitation", "Aerosols", and "Particulate Matter". The complete database-specific search strategies, including the exact search syntax, controlled vocabulary and free-text terms, field tags, Boolean operators, search dates, and numbers of retrieved records, are presented in Supplementary Table 1.

**Table 1.** Characteristics and meteorological factors associated with road traffic crash severity

| Author, year (country) | Study design/ sample | Crash severity outcome | Meteorological factor(s) | Crash severity-related findings | Key covariates/ contextual factors |
|---|---|---|---|---|---|
| Lankarani *et al.,* 2014 (Iran) [6] | Cross-sectional analysis of Traffic Police records; 542,863 RTCs | Non-injured vehicular crash; injury crash; death at scene | Clear, foggy, snowy, rainy, stormy, cloudy, and dusty weather | Compared with clear weather, dusty weather was associated with higher odds of injury (OR=1.45, 95% CI: 1.07–1.96) and death at the scene (OR=9.27, 95% CI: 5.02–17.13). Foggy, snowy, rainy, and cloudy conditions were associated with lower odds of injury. Rain was not significantly associated with death at the scene. | Scene lighting, crash location, roadway geometry, road surface, and roadway defects |
| Xu *et al.,* 2016 (USA) [12] | Quasi-induced exposure and multiple correspondence analysis; Las Vegas, 2004–2008; 77,250 crashes, including 550 responsible-pedestrian crashes | PDO; injury; fatal crash | Clear, cloudy, rain, and snow/ crosswind/ other conditions | Weather conditions significantly differentiated crash patterns. Injury crashes clustered with rainy conditions, whereas PDO crashes were more commonly associated with clear weather. Fatal crashes clustered primarily with off-peak nighttime/ weekend conditions rather than a specific adverse-weather category. | Time of day, day of week, lighting conditions, pedestrian and vehicle characteristics |
| Zeng *et al.,* 2017 (USA) [13] | Generalized nonlinear mixed multinomial logit modelling of Washington State Interstate freeway data, 2011–2014; 47,657 crashes after data-quality filtering | Fatal; injury; PDO crash | Road-surface condition: dry, wet, snow/ ice/slush; visibility: good/bad | Road-surface condition and visibility were significant contributors to severity. Snow/ice/slush had greater impact intensity for injury and fatal crash densities than dry or wet conditions. Poor visibility also showed greater impact intensity across crash-severity levels than good visibility. | Traffic volume, roadway geometry, shoulder characteristics, median characteristics, and speed limit |
| Lee *et al.,* 2018 (South Korea) [14] | Structural equation modelling; Seoul, 2007–2015; 534 crashes and 590 casualties; 517 wet/dry crash observations used in analysis | Latent accident-severity construct based on fatality rate, number of casualties, and number of damaged vehicles | Rainfall intensity, water depth on roadway | The rain and water-depth factors were significantly and positively associated with accident severity (standardized coefficient=0.12, z=2.234, $p$<0.05). | Drainage length; road slope and curvature; vehicle type; driver age and sex; time of day |
| Najafi Moghaddam Gilani *et al.,* 2021 (Iran) [15] | Logistic regression and ANN; 738 urban crashes in Rasht, March 2019–March 2020 | Injury/fatal crash versus PDO | Sunny and rainy weather | Because only seven fatal crashes occurred, fatal and injury crashes were combined. In the logistic model, rainy weather was associated with substantially greater odds of injury/fatal crash severity (OR=15.658, $p$=0.017), whereas sunny weather was associated with lower odds (OR=0.087, $p$=0.002). | Time of crash, season, driver sex, attention, collision type, vehicle type, and lighting |

ANN: Artificial neural network; CI: Confidence interval; MCA: Multiple correspondence analysis; OR: odds ratio; PDO: Property-damage-only; RTC: Road traffic crash; SEM: Structural equation modelling

All records retrieved from the database and supplementary searches were imported into EndNote X9 (Clarivate, UK), and duplicate records were removed. Three reviewers (M.J., M.M., and M.A.) independently screened the titles and abstracts against the eligibility criteria. The full texts of potentially eligible articles were subsequently retrieved and independently assessed. At the full-text stage, studies were included only if they directly examined the association between at least one meteorological factor and crash severity or injury severity. Studies assessing only crash occurrence, crash or injury frequency, incidence, counts, admission volume, or transport-related burden were excluded. Disagreements at either stage were resolved through discussion and, when necessary, consultation with the corresponding author (K.J.). The study selection process is presented in the PRISMA flow diagram (Fig 1).

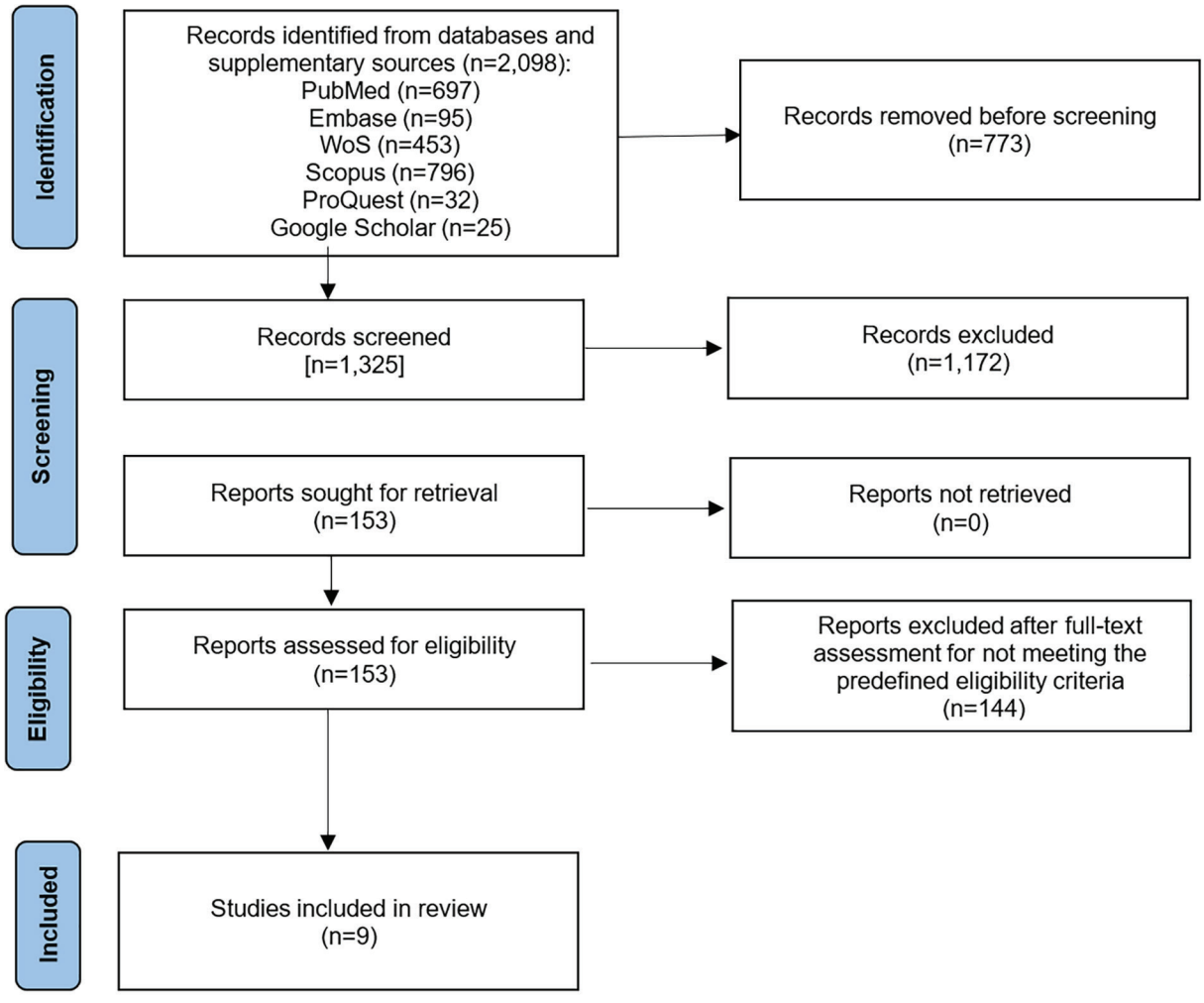



**Fig 1.** PRISMA flow diagram of the study selection process

Studies were eligible for inclusion if they:
• were original empirical studies;
• examined road traffic crashes involving any type of road user or vehicle;
• assessed at least one meteorological or weather-related exposure;
• directly evaluated the association between meteorological conditions and either crash severity or injury severity;
• used a clearly defined crash-severity or injury-severity outcome;
• were conducted in any road setting, including urban, rural, interurban, or highway environments; and
• were published in English or Persian.

Studies were excluded if they:
• examined only crash occurrence, frequency, incidence, risk, or counts without directly evaluating crash severity or injury severity;
• examined only injury, fatality, trauma-admission, or other outcome counts or rates stratified by weather conditions without modelling or otherwise directly assessing severity;
• evaluated meteorological factors only in relation to crash occurrence while crash or injury severity was analyzed solely in relation to non-meteorological factors;
• included weather and severity as separate descriptive, qualitative, spatial, or risk-assessment components without directly examining the association between them;
• were systematic reviews, meta-analyses, narrative reviews, editorials, letters, conference abstracts, or other non-original publications; or
• did not provide sufficient information to determine a direct association between meteorological conditions and crash or injury severity.

For this review, crash severity was defined as the level of severity assigned to a crash as the analytical outcome, including categories such as property-damage-only, injury, serious-injury, or fatal crashes. Injury severity was defined as the level of harm sustained by crash-involved road users, including individual-level fatal/nonfatal or serious/non-serious outcomes, as well as KABCO-based injury-severity classifications recorded in crash datasets. Studies reporting only the frequency or incidence of crashes, injuries, or fatalities within severity categories were not considered direct severity studies.

Data from the included studies were extracted using a standardized data-charting form developed in Microsoft Excel. The extracted information included author and year of publication, country, study design and setting, study period, data source and sample size, unit of analysis, meteorological exposures, definition and classification of the severity outcome, analytical method, covariates, and potential confounding or effect-modifying factors considered in the original analysis, as well as the principal findings concerning the association between meteorological factors and crash or injury severity. Severity outcomes were additionally classified as crash-severity or injury-severity outcomes according to the operational definitions used in this review. Data extraction was performed independently by two reviewers (M.J. and E.K.), and discrepancies were resolved through discussion and, when necessary, consultation with the corresponding author (K.J.).

The extracted data were synthesized using descriptive mapping and narrative synthesis. Studies were first classified according to the level of the severity outcome as either crash severity or injury severity. Meteorological exposures were then grouped into conceptually related categories, including precipitation and wet-road conditions, snow and ice, visibility-related conditions, wind, temperature, and solar-related exposures, as applicable to the included studies. For each exposure, the direction and nature of the reported association with severity were summarized together with the analytical approach and relevant covariates, confounders, or effect modifiers reported by the original study. Due to substantial heterogeneity in study populations, meteorological exposure definitions, severity outcomes, and analytical methods, no quantitative pooling was undertaken. The Haddon Matrix was used as a conceptual framework to organize the identified weather-related mechanisms across the pre-crash, crash, and post-crash phases, while distinguishing meteorological exposures from contextual human, vehicle, and road-related factors.

## Results

The study selection process is summarized in the PRISMA flow diagram (Fig 1). A total of 2,098 records were identified through database and supplementary searches. After the removal of 773 duplicate records, 1,325 records were screened by title and abstract, of which 1,172 were excluded. The full texts of 153 reports were assessed for eligibility. Following full-text assessment according to the predefined eligibility criteria and operational definitions of crash severity and injury severity, nine studies met the eligibility criteria and were included in the final synthesis.

### *Characteristics of Included Studies*

Of the nine included studies, five studies directly examined meteorological factors in relation to crash severity outcomes, whereas four studies examined injury severity outcomes based on road user injury classifications or KABCO-derived injury severity categories. The crash-severity studies used heterogeneous outcome definitions, ranging from binary injury/fatal versus property-damage-only classifications to multinomial and latent severity constructs. The characteristics and findings regarding meteorological factors for studies addressing crash severity are presented in Table 1, and those addressing injury severity are presented in Table 2.

The four remaining studies evaluated meteorological factors in relation to injury-severity outcomes, ranging from fatal versus nonfatal injury to serious/non-serious and KABCO-based severity classifications (Table 2).

Across the nine included studies, the direction and magnitude of meteorological associations with severity varied according to the type of meteorological exposure, severity definition, road user group, and analytical approach. Accordingly, the findings were synthesized separately for crash severity and injury severity to reflect differences in outcome definition and level of analysis across the included studies.

### *Crash Severity Findings*

Five studies evaluated meteorological factors in relation to crash severity. Weather-related effects were heterogeneous across studies. In Iran, Lankarani *et al.,* reported particularly high odds of death at the scene under dusty conditions, whereas rainy weather was associated with lower odds of injury and was not significantly associated with death [6]. Xu *et al.,* found that injury crashes tended to cluster with rainy conditions, whereas fatal pedestrian crashes were more strongly characterized by nighttime and weekend conditions than by a specific adverse weather category [12]. Zeng *et al.,* identified road-surface condition and visibility as significant contributors to crash severity, with snow, ice, slush, and poor visibility showing greater impact intensity across severity levels [13]. Lee *et al.,* demonstrated a significant positive association between the latent rain-and-water-depth factor and accident severity [14], while Najafi Moghaddam Gilani *et al.,* reported substantially greater odds of injury/fatal crashes under rainy conditions and lower odds under sunny conditions [15]. Together, these findings indicated that precipitation-related conditions, weather-related road-surface states, visibility, and dust might influence crash severity, although the direction and magnitude of the associations were not consistent across settings.

### *Injury Severity Findings*

Four studies directly evaluated meteorological factors in relation to injury-severity outcomes.

**Table 2.** Characteristics and meteorological factors associated with injury severity in road traffic crashes

| Author, year (country) | Study design/ sample | Injury severity outcome | Meteorological factor(s) | Injury severity-related findings | Key covariates/ contextual factors |
|---|---|---|---|---|---|
| Ma *et al.,* 2019 (Taiwan) [16] | Population-based case-control study; Taiwan, 2003–2016; 100,411 pedestrians involved in crashes | Fatal versus nonfatal pedestrian injury | Sun glare | Fatal injury occurred in 2.46% of glare-related crashes versus 1.83% of non-glare crashes. Sun glare remained significantly associated with pedestrian fatality in the mixed logit model (β=0.527, t=3.21). | Pedestrian and driver age/sex, driver intoxication, roadway setting, overtaking manoeuvre, pedestrian travel direction |
| Dong *et al.,* 2024 (USA) [7] | CRSS database, 2016–2020; 3,895 bicycle–motor vehicle crashes; latent-class clustering and Bayesian-network modelling | Non-serious versus serious/fatal cyclist injury | Clear, cloudy, rain/snow and other adverse weather | Weather effects varied across crash clusters. Rain/snow increased the serious-injury probability by 5.7% in the controlled-intersection cluster and was also associated with greater serious-injury probability in another crash cluster. Conversely, clear weather increased serious-injury probability by 3% in the non-intersection cluster, indicating heterogeneous weather effects. | Cyclist/driver sex, yielding behaviour, distraction, vehicle characteristics, roadway characteristics, lighting, time period |
| Pathivada *et al.,* 2024 (USA) [5] | I-75, Kentucky, January 2016–April 2021; 21,127 crashes; 17,013 complete cases; MXL, CMXL and CMXLHM models | KABCO-based crash injury severity: fatal/severe injury; minor injury; PDO/ no injury | Air temperature, relative humidity, precipitation, wind speed, solar radiation | In the best-fitting CMXLHM model, relative humidity ≥90% increased fatal/severe-injury probability by 70.53%; wind speed 5–10 mph by 78.17%; and temperature 50–70°F by 12.06%. Solar radiation of 5–200 W/m² decreased fatal/severe-injury probability by 80.34%. | Driver age, DUI, travel speed, traffic volume, vehicle type, roadway geometry |
| Habib *et al.,* 2024 (USA) [17] | Washington State HSIS, 2015–2018; 6,566 large-truck-involved crashes; mixed logit and temporal-stability analysis | No injury; minor injury; severe injury among the driver with the most severe injury recorded in the crash | Snowing | Snowing was a significant random weather-related parameter in the combined 2015–2018 model. Its marginal effects were +0.0009 for no injury, -0.0007 for minor injury, and -0.0002 for severe injury, indicating that snowing did not increase severe-injury probability in the combined model. Similar directions were observed in the 2015 and 2016 models. | Driver behaviour, age, alcohol, restraint use, drowsiness, vehicle characteristics, crash type, roadway geometry, lighting |

CI: Confidence interval; CMXL: Correlated mixed logit; CMXLHM: Correlated mixed logit with heterogeneity in means; CRSS: Crash report sampling system; DUI: Driving under the influence; HSIS: Highway safety information system; KABCO: Police-reported injury severity scale; MXL: Mixed logit; PDO: Property-damage-only

Ma *et al.,* found that pedestrians involved in crashes with sun glare had a higher proportion of fatal injury than those involved in crashes without sun glare, and sun glare remained significantly associated with fatal injury after multivariable modeling [16]. Dong *et al.,* demonstrated heterogeneous weather effects across bicycle–motor vehicle crash clusters: rain or snow increased the probability of serious cyclist injury in some crash contexts, whereas clear weather was associated with higher serious-injury probability in another cluster [7]. Pathivada *et al.,* reported that high relative humidity, moderate wind speed, and certain temperature ranges were associated with increased probabilities of fatal or severe injury, whereas moderate solar radiation was associated with a substantial reduction in fatal or severe-injury probability [5]. In contrast, Habib *et al.,* found that snowing was a significant weather-related parameter in large truck crashes but did not increase severe injury probability in the combined model [17]. These findings further demonstrated that meteorological effects on injury severity were context-dependent and might differ across road user groups and crash environments.

### *Cross-Study Patterns and Contextual Factors*

Overall, precipitation and weather-related surface conditions were the most commonly represented exposures among the included studies, whereas temperature, humidity, wind, solar radiation, sun glare, dust, and visibility were investigated less consistently. Importantly, meteorological exposures were rarely examined in isolation. Driver age, sex, alcohol or drug involvement, speeding, restraint use,

lighting conditions, vehicle type, traffic volume, roadway geometry, and time-related variables were incorporated as covariates, potential confounders, contextual factors, or effect modifiers in several studies. Accordingly, these variables were not considered meteorological risk factors themselves but were retained to characterize the context in which weather–severity associations were observed.

### *Weather-Centered Synthesis Using the Haddon Matrix*

The Haddon Matrix was used to provide a systems-oriented interpretation of the findings regarding severity. Meteorological exposures were treated as the focal factors, whereas human, vehicle, roadway, and temporal characteristics reported in the included studies were considered contextual factors, covariates, or potential effect modifiers rather than independent meteorological risk factors. The resulting weather-centered synthesis is presented in Table 3.

The Haddon Matrix synthesis showed that the available evidence was concentrated primarily on meteorological conditions operating before and during the crash. These conditions were examined in conjunction with human, vehicle, roadway, and temporal characteristics that could influence the observed weather–severity relationship. Importantly, none of the included studies directly evaluated meteorological influences on post-crash processes, including rescue, emergency medical response, transport, trauma care, or subsequent survival. Therefore, the post-crash phase represents a clear evidence gap rather than evidence of an absence of meteorological effects.

## Discussion

This scoping review identified nine studies that directly examined meteorological factors in relation to road traffic crash severity or injury severity. The available evidence was heterogeneous with respect to the definition of severity, meteorological exposures, road-user populations, geographical settings, and analytical methods. Notably, the direction and magnitude of the reported associations were not uniform. Although adverse meteorological conditions were associated with greater severity in several settings, other studies reported weaker, inverse, or context-dependent relationships. These findings suggested that meteorological conditions should not be interpreted as uniformly increasing crash or injury severity; rather, their effects seemed to depend on the specific exposure, crash environment, road-user population, and accompanying human, vehicle, roadway, and temporal characteristics.

Among studies evaluating crash severity, precipitation and weather-related road-surface conditions were the most frequently investigated exposures. Lee *et al.,* reported a significant positive association between a combined rain and water depth factor and crash severity, suggesting that rainfall intensity and water accumulation might contribute to more severe crash outcomes [14].

**Table 3.** Weather-centered Haddon Matrix of meteorological pathways and contextual interactions related to crash severity and injury severity

| Phase | Meteorological exposure/ pathway | Human-related context or interaction | Vehicle/roadway context or interaction | Evidence interpretation |
|---|---|---|---|---|
| Pre-crash | Rain/snow; wet, icy or slushy surfaces; reduced visibility; dusty conditions; sun glare; temperature; relative humidity; wind; solar radiation | Driver and road-user age and sex; alcohol/DUI; speeding or travel speed; distraction/inattention; failure to yield; drowsiness; time-related driving behavior | Vehicle type; roadway geometry; drainage characteristics; road-surface condition; lighting; traffic volume | Meteorological conditions may alter visibility, surface friction, driver perception and behavior, and vehicle controllability before impact. These contextual variables were treated as covariates or modifiers rather than meteorological exposures. |
| Crash | Rain and road-water depth; snow/ice/slush; adverse visibility; dust; wind; temperature/humidity and solar-related conditions were associated with severity | Road-user vulnerability, including pedestrian and cyclist status; age; restraint use; driver characteristics associated with injury severity | Vehicle mass/ type; collision configuration; road-water depth; road geometry; vehicle-control conditions | Included studies demonstrated direct associations between selected meteorological conditions and crash or injury severity, but the magnitude and direction of effects differed across crash environments, road-user groups, and model specifications. |
| Post-crash | No meteorological exposure was directly evaluated in relation to post-crash survival, emergency response, or trauma-care outcomes in the included studies. | Not directly evaluated | Not directly evaluated | Evidence gap: no included study directly examined whether meteorological conditions modified rescue, EMS response, transport, treatment, or post-crash survival. |

Non-meteorological variables are presented as contextual factors, covariates, or potential effect modifiers and should not be interpreted as meteorological exposures. EMS: Emergency medical services; DUI: Driving under the influence

Similarly, Najafi Moghaddam Gilani *et al.,* found substantially higher odds of injury or fatal crashes under rainy conditions and lower odds under sunny conditions [15]. Zeng *et al.,* identified road-surface condition and visibility as important contributors to crash severity, with snow, ice, or slush and poor visibility showing greater impact intensity across severity levels [13]. However, adverse weather did not consistently correspond to greater severity. Lankarani *et al.,* reported lower odds of injury under several adverse-weather categories, while dusty weather was associated with markedly greater odds of death at the scene [6]. Xu *et al.,* likewise found that injury crashes tended to cluster with rainy conditions, whereas fatal crashes were characterized more strongly by nighttime and weekend conditions than by a specific adverse weather category [12]. These inconsistencies might partly reflect differences in driver adaptation, travel behavior, road infrastructure, exposure measurement, and severity classification across study settings.

A similarly heterogeneous pattern was observed among studies of injury severity. Ma *et al.,* found that sun glare was positively associated with fatal pedestrian injury, highlighting the potential importance of visibility-related meteorological exposures even under otherwise clear weather conditions [16]. Dong *et al.,* demonstrated that the effects of weather on serious cyclist injury varied across crash clusters: rain and snow increased serious-injury probability in some contexts, whereas clear weather was associated with greater serious-injury probability in another cluster [7]. Pathivada *et al.,* reported that high relative humidity, moderate wind speed, and certain temperature ranges were associated with increased probabilities of fatal or severe injury, whereas moderate solar radiation was associated with a lower probability of fatal/severe injury [5]. In contrast, Habib *et al.,* found that although snowing was a significant weather-related parameter in large-truck crashes, it did not increase severe-injury probability in the combined model [17]. Taken together, these findings indicated that weather and injury severity relationships might be nonlinear and strongly dependent on road user, vehicle, roadway, and temporal contexts rather than reflecting a simple distinction between favorable and adverse weather.

The findings of the present review should also be interpreted in the context of previous systematic evidence. Qiu and Nixon's systematic review and meta-analysis found that precipitation generally increased crash rates and that snowfall exerted a greater effect than rainfall on crash occurrence and injury rates [8]. However, their synthesis primarily addressed crash occurrence and injury rates, rather than the severity of outcomes conditional on a crash having occurred. This distinction is important since an environmental condition might increase the probability or frequency of crashes without necessarily producing a proportional increase in the severity of each crash. The more heterogeneous severity associations identified in the present review therefore do not necessarily contradict the broader evidence that adverse weather increases the occurrence of crashes.

More directly relevant to severity outcomes, Yousefifard *et al.,* conducted a systematic review and meta-analysis of risk factors for road traffic injury-related mortality in Iran. Their weather-related analysis included seven studies and 51 separate analyses involving more than 1.5 million road traffic victims and found no significant pooled association between mortality and snowy or rainy conditions (OR=0.92, 95% CI: 0.31–2.72) or cloudy or foggy conditions (OR=1.39, 95% CI: 0.96–2.02) [9]. The authors also emphasized the low certainty of the available evidence, substantial inconsistency, retrospective study designs, and incomplete adjustment for important potential confounders. These observations were consistent with the heterogeneity identified in the present review and supported cautious interpretation of individual weather–severity associations.

A recent systematic review by Pathak *et al.,* published after the search period of the present review, further supported the complexity of these relationships. That review examined climate-related weather conditions and road trauma and reported associations between extreme conditions, including heavy rainfall, snow, ice, heatwaves, storms, dense fog, and hail, and increased road trauma outcomes across different geographical settings [18]. However, its scope was broader than that of the present review and encompassed both the incidence and severity of road trauma. The present review therefore complemented this broader evidence by restricting its core synthesis to studies that directly evaluated crash severity or injury severity rather than studies reporting only crash occurrence, injury counts, or trauma rates. Similarly, Theofilatos and Yannis reviewed the effects of traffic and weather characteristics on road safety and reported that precipitation generally increased crash frequency, whereas its effect on crash severity was less consistent. This distinction further supported the need to separate crash occurrence from severity outcomes when interpreting weather-related road-safety evidence [19].

The weather-centered Haddon Matrix provided an additional systems perspective for interpreting these findings. The meteorological exposures identified in the included studies primarily operated through environmental pathways before and during the crash, including changes in road-surface conditions, visibility, vehicle controllability, and driver perception. At the same time, age, sex, alcohol or drug involvement, speeding, distraction, restraint use, vehicle type, traffic volume, lighting, roadway geometry, and other contextual variables

were considered in several studies as covariates, confounders, or potential effect modifiers. These factors should not be interpreted as meteorological exposures themselves; rather, they illustrate the broader context within which weather–severity relationships occur. This distinction is particularly important because the effect of a given meteorological condition might be amplified or attenuated by differences in driver behavior, road-user vulnerability, vehicle characteristics, and road infrastructure.

Methodological heterogeneity also appeared to contribute substantially to the inconsistent findings. Severity was operationalized using a wide range of outcomes, including property-damage-only versus injury or fatal crash classifications, multinomial fatal, injury, property damage-only (PDO) categories, latent crash-severity constructs, binary fatal versus nonfatal injury outcomes, serious versus non-serious injury classifications, and KABCO-based severity categories. Analytical approaches also varied considerably, including conventional logistic regression, multinomial and mixed logit models, structural equation modelling, Bayesian-network approaches, machine-learning techniques, and multiple correspondence analysis. This methodological diversity was consistent with broader reviews of crash-injury severity modelling, which have emphasized the importance of model selection, unobserved heterogeneity, and the increasing use of machine-learning approaches in injury severity analysis [20-22]. Consequently, effect estimates could not be directly compared across all studies, and apparently contradictory findings may partly reflect differences in outcome construction and model specification rather than true differences in meteorological effects.

The geographical distribution of the evidence represented another important limitation of the existing literature. Most included studies were conducted in the United States or selected Asian settings, with relatively limited representation of low- and middle-income countries and regions characterized by different climates, infrastructure, vehicle fleets, driving cultures, and emergency care systems. This geographical concentration limited the generalizability of the findings, as identical meteorological exposures might produce different safety consequences depending on road design, drainage capacity, maintenance practices, vehicle characteristics, driver adaptation, and baseline climatic conditions.

Several evidence gaps were identified. Although precipitation and weather-related surface conditions were relatively well represented in the literature, direct evidence regarding the effects of humidity, wind speed, solar radiation, sun glare, and other meteorological exposures remained limited. Furthermore, none of the included studies directly examined the influence of meteorological conditions on post-crash processes, such as rescue, emergency medical service response, transport time, trauma care, or subsequent survival. The absence of such studies should not be interpreted as indicating that meteorological conditions have no post-crash outcomes; rather, it highlights an important gap in the current evidence base. Future studies should therefore employ clearly defined and standardized severity outcomes, high-resolution meteorological exposure data, and analytical approaches capable of accounting for nonlinear relationships, interactions, confounding, and unobserved heterogeneity. Greater representation of diverse climatic and road-traffic settings, together with explicit investigation of post-crash processes, would further strengthen understanding of how meteorological conditions affect road traffic crash and injury severity.

This scoping review mapped nine studies that directly examined meteorological factors in relation to road traffic crash severity or injury severity. The available evidence indicated that meteorological influences on severity were heterogeneous and context-dependent. Precipitation, weather-related road-surface conditions, reduced visibility, dust, sun glare, temperature, humidity, wind, and solar radiation were associated with severity in different settings. However, the direction and magnitude of these associations were not consistent across studies.

The findings also demonstrated the importance of distinguishing crash severity from injury severity and of considering human, vehicle, roadway, and temporal characteristics when interpreting weather-related effects. Evidence was concentrated on pre-crash and crash-phase conditions, while no included study directly evaluated meteorological influences on post-crash processes, such as rescue, emergency medical response, transport, trauma care, or subsequent survival. Future research should use standardized severity definitions, higher-resolution meteorological data, and analytical approaches capable of addressing nonlinear relationships, interactions, confounding, and unobserved heterogeneity across diverse climatic and road-traffic settings.

## Declaration

**Ethics Approval and Consent to Participate:** The study protocol was approved by the Ethics Committee of Shahid Beheshti University of Medical Sciences (Ethics approval code: IR.SBMU.PHNS.REC.1403.194).

**Consent for Publication:** All authors consent to the publication of this manuscript.

**Conflict of Interest:** The authors declare that they have no conflicts of interest.

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**Authors' contributions:** K.J. contributed to project administration and supervision and approved the final version of the manuscript. M.J., M.M., and M.A. contributed to conceptualization and study selection. M.J., E.K., and M.M. contributed to data extraction and data analysis. All authors have read and approved the final manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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