



A scoping review of the impact of temperature and humid environmental conditions on drivers' safety across geographical locations

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Received: 16 March 2025 / Accepted: 17 July 2025
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Abstract

Aim Road traffic incidents are one of the most significant causes of death globally, with previous research showing that many meteorological factors influence road traffic safety. The purpose of this scoping review was to examine the effect of high ambient temperature and humidity on road traffic incidents across various climatic zones.

Subject and methods A search of Ovid MEDLINE, CINAHL, PsycInfo (ProQuest), SafetyLit, and Scopus databases was undertaken to identify studies published between 2002 and 2022, focusing on the association between driver safety, and temperature and humid climate. Available data were extracted and analyzed to evaluate the impact of temperature and humidity on road traffic incidents.

Results Forty-eight studies reported on the influence of temperature on driver safety. Two of four studies conducted in polar and subpolar climates reported negative correlations; nine of 11 studies in tropical and subtropical climates reported positive correlations; and 15 studies in temperate climates reported positive whilst five studies reported negative correlations between temperature and traffic incidents. In addition, only ten reported the influence of humidity, and two reported positive correlations, three reported negative correlations, and four reported no significant association. No characteristic tendency was found in the association between humidity and traffic incidents.

Conclusion There is an association between climate and road traffic incidents, with increases found in both extreme hot and extreme cold environmental conditions; however, the influence of relative humidity is less evident.

Keywords Traffic incident · Climate · Temperature · Humidity · Hot

Introduction

Road traffic incidents are an important cause of mortality and physical disability worldwide (Lozano et al. 2012; WHO 2023). In the most recent report by the Global Burden of Disease study, approximately 1.2 million (95% uncertainty interval [UI], 1.19–1.28 million) road-related deaths were reported in 2017, with age-standardized mortality rates by road injuries increasing between 1990 and 2017 (James et al. 2020).

Climate change is a significant problem worldwide. The global temperature has increased by 0.18 °C per decade since 1981, and the average surface temperature in 2021 was 0.84 °C greater than the twentieth-century average (National Oceanic and Atmospheric Administration 2024). Previously, Gasparrini et al. (2015) reported that mortality rates in cold climates were higher than in hot climates, suggesting that rising temperature could help reduce global mortality. However, due to global warming, the growing frequency of extreme heat events has become an increasingly serious issue worldwide. Recent research has highlighted the impact of the increasing occurrence of heat waves, with resulting increases in mortality (Franklin et al. 2023; Mason et al. 2022; Orru and Åström 2017). Therefore, the influence of hot temperatures will become increasingly important in the future, warranting investigation into the effects of heat and road safety.

There are many known risk factors for road traffic incidents, which can be divided into groups such as host

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(human), agent (vehicle and equipment), physical, or socioeconomic environments (Bachani et al. 2017). Environment is a known factor of traffic accidents (Stoupelet et al. 2009), with one of the most significant physical environmental risk factors being the weather (Andrey et al. 2003). Hot environments have been considered a factor due to an increased rate of traffic incidents and fatal outcomes (Basagaña et al. 2015; Pińskwar et al. 2024; Wu et al. 2018). In the laboratory setting, driving performance in warmer ambient temperatures (35 °C, 50% relative humidity [RH]) was found to be impaired when compared to thermoneutral conditions (20 °C, 50% RH) (Daanen et al. 2003). In addition, simple driving tasks, such as keeping the vehicle on a straight course, were found to deteriorate by up to 50%, while undertaking demanding driving tasks, such as correctly identifying a signal and reacting, were found to decrease by over 75% under the duress of heat stress (Lenzuni et al. 2014). Therefore, it appears that driving performance may be diminished when driving in hot environments, although the underlying mechanism is unclear.

Relative humidity also seems to be a factor impacting driver safety. For example, Xiayou et al. (2021) explored cognitive performance in hot-dry (39 °C and 50% RH) and hot-humid (39 °C and 70% RH) conditions and showed that cognitive performance was lower in the hot-humid condition. Xiayou et al. (2021) postulated that the combination of heat and humidity may hamper driving skills due to impaired cognitive performance. Interestingly, Gao et al. (2016) reported no correlation between RH and traffic incidents in Shantou City in China, where the average temperature and RH were 22.6 °C and 75.0%, respectively, which was notably cooler than the laboratory environmental conditions set by Xiayou et al. (2021). Moreover, there are countries situated within or in proximity to the tropics which can reach temperatures and RH similar to or exceeding that investigated by Xiayou et al. (2021). Furthermore, the effect of the tropical (high temperature and RH) environment on road traffic safety is predicted to increase due to climate change (National Oceanic and Atmospheric Administration 2024). Therefore, clarifying the association between hot and humid environments and driver safety is increasingly important.

Liang et al. (2022) conducted a systematic review and meta-analysis on the influence of temperature on traffic incidents. In this review, 34 studies reported that higher ambient temperatures increased traffic incident injuries, whilst only two studies reported increased traffic incident injuries in lower ambient temperatures. In their meta-analysis, the risk of traffic incidents was significantly associated with increased temperature, with an overall relative risk of road traffic injuries of 1.025 (95% confidence interval [CI] 1.014–1.035). However, almost all of the studies in the review were conducted in temperate zones,

and nothing was reported for subtropical, tropical, subpolar, or polar areas, where the ambient temperatures can be more extreme. Furthermore, Liang et al. (2022) did not report on studies that examined the impact of RH on traffic incidents, despite prior evidence suggesting RH as an environmental factor influencing driving performance (Xiayou et al. 2021). Therefore, we conducted a systematic literature review aimed at exploring the impact of ambient temperature and RH on traffic incidents across various climatic zones.

Materials and methods

A systematic review was undertaken, following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement 2020 guidelines (Page et al. 2021). To the authors' knowledge, there are currently no published review protocols suitable for investigating how temperature and relative humidity influence traffic incidents across various climatic zones.

Literature search

A search of Ovid MEDLINE, CINAHL, PsycInfo (ProQuest), SafetyLit, and Scopus databases was conducted for all related studies published from 1 January 2004 to 1 June 2024. To identify articles that met our aim, we used the keywords “automobile driving”, “climate”, “extreme weather, humidity or temperature”, and “traffic accident” as free text in all databases.

Eligibility criteria

The inclusion criteria for this review were as follows: (i) published within the last 20 years (2004 to 2024), (ii) peer-reviewed articles, (iii) original research paper, (iv) full text available, and (v) mentioned the relationship between hot and/or humid climate and road traffic injuries or deaths. Studies were excluded for the following: (i) non-peer-reviewed journal or other type of publication, or (ii) did not mention the impact of hot or humid temperature on road traffic injuries or deaths.

Data collection process

The abstracts extracted from the search were screened by two authors (SK and KD) using the inclusion and exclusion criteria, and any conflicts arising during this initial screening process were resolved by consulting the other authors (WS and RF). This screening procedure was also applied for full original articles, with emphasis on ensuring that full-text articles reported on data regarding the impact of hot or humid climates on driver safety. Available data from

all selected studies were extracted and stored in an Excel spreadsheet. An overview of the data collection process is shown in Fig. 1.

We extracted data on geographic location (i.e., city and country), climatic zone (i.e., tropical, subtropical, subpolar, and polar), study period, definition of temperature and RH, and outcome measures reporting on the association between hot and humid environments and traffic incidents. Climatic zone was categorized based on a previous definition (Feng et al. 2014), and we distinguished the climatic zone from cities or countries included within these studies.

Data quality assessment

The methodological quality of studies reporting on the impact of ambient temperature and/or humidity on road traffic incidents was assessed using the Joanna Briggs Institute (JBI) critical appraisal checklist for prevalence research designs (Munn et al. 2020). To evaluate the overall quality of included studies, JBI checklist scores of 7/9, 6/9, 5/9, and 4/9 were classified as excellent, good, fair, and poor, respectively, for the prevalence checklist.

Results

Following the removal of duplicates, 2926 abstracts were identified across the databases. Once screened, 2820 abstracts were excluded. After full-text screening, 48 studies

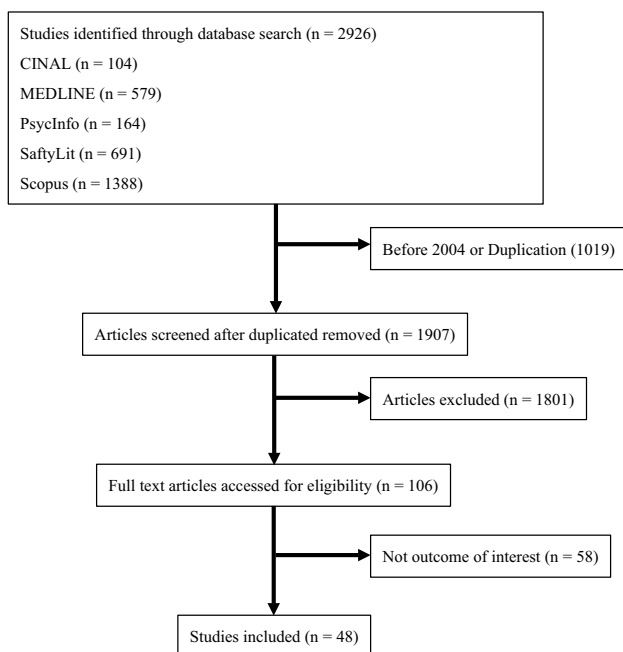


Fig. 1 Flowchart of assessment of studies

met our inclusion criteria (Fig. 1). The summary of 48 articles is presented in Table 1.

The characteristics of epidemiological studies

The geographical characteristics and foci of studies included in the review are summarized in Table 1. Of the 40 studies that reported on the impact of hot and humid environments on traffic incidents between 2004 and 2024, geographical locations included the USA ($n=13$), China ($n=11$), Canada ($n=3$), Japan ($n=2$), Iran ($n=2$), Pakistan ($n=2$), Finland ($n=1$), Australia ($n=1$), Kuwait ($n=1$), Saudi Arabia ($n=1$), England and Wales ($n=1$), France ($n=1$), Greece ($n=1$), Italy ($n=1$), Korea ($n=1$), the Netherlands ($n=1$), Romania ($n=1$), and Malaysia ($n=1$; Table 1).

Four studies were conducted in polar and subpolar areas, seven were conducted in dry areas, seven were conducted in tropical and subtropical areas, and 30 were conducted in temperate areas (Table 1 and Fig. 2). Twenty-eight studies focused on road traffic accidents, 11 on road traffic injuries, seven on road traffic deaths, three on road traffic injuries and deaths, and three on road traffic injury severity (Table 1).

The impact of temperature on traffic incidents

The impact of temperature on traffic incidents is summarized in Table 2. All 48 studies reported that temperature influenced traffic incidents. Nineteen studies focused on daily mean temperature, eight focused on monthly mean temperature, seven on hourly temperature, and six on heat wave days or extreme heat events (Table 2). When comparing high temperatures and traffic incidents, 31 studies reported positive correlations, seven reported negative correlations, and five reported no significant relationships. In five studies, traffic incidents increased in both hotter and colder conditions (Table 2 and Fig. 2).

The relationship between the impact of temperature on road traffic incidents and climatic zone

A summary of the relationship between the impact of temperature on road traffic incidents and climate zones is presented in Table 2. Of the four studies in polar and subpolar areas, two studies reported negative correlations between temperature and traffic incidents (Brubacher et al. 2016; El-Basyouny et al. 2014), one study reported a positive correlation (Perrels et al. 2015), and the other study reported no significant correlation (Kamel and Sayed 2021). Conversely, five of seven studies conducted in dry areas and six of seven conducted in tropical and subtropical areas reported

Table 1 Study characteristics (N = 48)

Reference	Study years	City/state/province	Country	Climate zone	Source of crash data	Source of meteorological data	Outcome
El-Basyouny et al. 2014	2006–2010	Edmonton	Canada	Polar and subpolar	City of Edmonton's Motor Vehicle Collision Information System (MVCIS)	National Climate Data and Information Archive	Road traffic accidents
Brubacher et al. 2016	2003–2012	British Columbia	Canada	Polar and subpolar	Police reports and insurance claims	UA	Road traffic accidents
Kamel and Sayed 2021	2009–2013	Vancouver	Canada	Polar and subpolar	Insurance Corporation of British Columbia (ICBC)	Environment and Climate Change Canada	Cyclist-vehicle crash
Perrels et al. 2015	2000–2010	NA	Finland	Polar and subpolar	Finnish Motor Insurers' Centre	Finnish Meteorological Institute (FMI)	Road traffic accidents
Li et al. 2023	2021–2021	Adelaide	Australia	Dry	Road Crash Database	Scientific Information for Land Owners	Road traffic accidents
Dastoorpoor et al. 2016	2008–2015	Ahvaz	Iran	Dry	Police force of Khuzestan province	Meteorological organization of Khuzestan province	Road traffic accidents
Zare et al. 2022	2011–2017	Sabzevar	Iran	Dry	Emergency department and pre-hospital emergency system	Sabzevar meteorological station	Road traffic accidents
Al-Harbi et al. 2012	2000–2010	Kuwait	Kuwait	Dry	Ministry of Interior for the State of Kuwait	Weather station at the Kuwait International Airport	Road traffic accidents and deaths
Hammad et al. 2019	2011–2016	Punjab	Pakistan	Dry	Punjab Emergency Service	Pakistan Metrological Department Lahore	Road traffic accidents
Ali et al. 2020	1985–2016	NA	Pakistan	Dry	Government of Pakistan	The Climate Change Knowledge Portal (TCKKP)	Road traffic deaths
Islam et al. 2019	2003–2013	NA	Saudi Arabia	Dry	UA	UA	Road traffic accidents
Chen et al. 2023	2019–2021	Chongqing	China	Subtropical and tropical	Chongqing Emergency Dispatch Center	National Climatic Data Center	Road traffic injuries
Gao et al. 2016	2003–2015	Shantou	China	Subtropical and tropical	A tertiary-level hospital in Shantou city	China Meteorological Data Sharing Service System	Road traffic injuries
Zeng et al. 2022	2014–2014	Guangdong Province	China	Subtropical and tropical	Highway Maintenance and Administration Management (HIMAM) platform	Three county-level weather stations: (i) Kaiping Station, (ii) Enping Station, and (iii) Yangjiang Station	Road traffic accidents

Table 1 (continued)

Reference	Study years	City/state/province	Country	Climate zone	Source of crash data	Source of meteorological data	Outcome
Zhan et al. 2020	2010–2016	Shenzhen	China	Subtropical and tropical	Shenzhen center of pre-hospital care	National Oceanic and Atmospheric Administration (NOAA)	Road traffic injuries and deaths
Lio et al. 2019	2001–2016	Macao	China	Subtropical and tropical	Statistics and Census Service of the Macao government	Macao Meteorological and Geophysical Bureau	Road traffic accidents
Xing et al. 2019	2015–2015	Hong Kong	China	Subtropical and tropical	Traffic Information System (TIS)	Hong Kong Observatory	Road traffic accidents
Junus et al. 2017 Cheng 2023	2001_2012 2013–2019	NA NA	Malaysia China	Subtropical and tropical Temperate	UA China Cause of Death Reporting System	UA ERA5 (European Centre for Medium-Range Weather Forecasts [ECMWF] Reanalysis v5)	Road traffic accidents Road traffic deaths
Song et al. 2019	2008–2012	Beijing	China	Temperate	Tertiary hospitals in Haidian District	National Scientific Data Sharing Platform for Population and Health	Road traffic injuries
Liang et al. 2021	2015–2017	Dalian	China	Temperate	China Center for Disease Control and Prevention	National Meteorological Information Center	Road traffic injuries
Zhu et al. 2024	2006–2021	NA	China	Temperate	National Injury Surveillance System	ERA5	Road traffic injuries
Li et al. 2024	2011–2021	Jinan	China	Temperate	Shandong Provincial Death Registration Information Reporting System	China Meteorological Data Sharing Service System	Road traffic deaths
Jones et al. 2008	1995–2000	NA	England, Wales	Temperate	Police-collected STATS19 crash reports	British Atmospheric Data Centre Land Surface Data set	Road traffic injuries and deaths
Bergel-Hayat et al. 2013	1975–2005	NA	France, Netherlands, Greece	Temperate	Police record	UA	Road traffic injuries
Theofilatos 2017	2006–2011	Athens	Greece	Temperate	Greek accident database SANTRA	Hydrological Observatory of Athens (HOA)	Road traffic accidents
Gariazzo et al. 2021	2013–2015	NA	Italy	Temperate	National Institute of Statistics (ISTAT)	Advanced Research Weather Research and Forecasting (WRF-ARW)	Road traffic accidents
Abe et al. 2008	2005–2005	Tokyo	Japan	Temperate	Ambulance transport records of the Tokyo Fire Department	Japan Meteorological Agency	Road traffic injuries

Table 1 (continued)

Reference	Study years	City/state/province	Country	Climate zone	Source of crash data	Source of meteorological data	Outcome
Pan et al. 2022	1979–2015	NA	Japan	Temperate	Ministry of Health, Labor and Welfare of Japan	Japan Meteorological Agency	Road traffic deaths
Park et al. 2021	2012–2017	Seoul-Incheon, Busan, Daegu, Daejeon, Gwangju	Korea	Temperate	Road Traffic Accident Database (DB) of KoROAD	UA	Road traffic accidents
Brijis et al. 2008	2001–2001	Utrecht, Dordrecht, Haarlemmermeer	Netherlands	Temperate	UA	Royal Netherlands Meteorological Institute	Road traffic accidents
Drosu et al. 2020	2011–2014	NA	Romania	Temperate	UA	UA	Road traffic accidents
Pathivada et al. 2024	1990–2014	NA	Spain	Temperate	UA	UA	Road traffic injuries and deaths
Basagaña et al. 2015	2000–2011	Catalonia	Spain	Temperate	Catalan Traffic Authority	Spanish Meteorological Association	Road traffic accidents
Basagaña et al. 2015	2013–2019	NA	Spain	Temperate	General Direction of Traffic	European Climate Assessment and Datasets (ECA&D) database	Road traffic accidents
Wu et al. 2018	2001–2011	NA	USA	Temperate	Fatality Analysis Reporting System (FARS)	North American Land Data Assimilation System (NLDAS-2)	Road traffic accidents
Robertson 2018	2014–2015	NA	USA	Temperate	Fatality Analysis Reporting System	Local airport and weather station	Road traffic deaths
Pathivada et al. 2024	2016–2021	Kentucky	USA	Temperate	Interstate 75	Kentucky Mesonet Center	Road traffic injury severity
Naik et al. 2016	2009–2011	Nebraska	USA	Temperate	Nebraska Department of Roads Office of Highway Safety (NDOR-OHS)	National Climatic Data Center (NCDC)	Single-vehicle truck crush injury severity
Malyshkina and Mannering 2009	2003–2006	Indiana	USA	Temperate	UA	UA	Road traffic injury severity
Ma et al. 2016	2010–2010	Colorado	USA	Temperate	Colorado State Patrol	Weather station	Road traffic accidents
Liu et al. 2017	2000–2012	Maryland	USA	Temperate	Maryland State Police through their Maryland Automated Accident Reporting System (MAARS)	UA	Road traffic accidents
Cheng et al. 2017	2008–2013	San Francisco	USA	Temperate	Transportation Injury Mapping System (TIMS)	Weather Underground	Road traffic accidents
Hou et al. 2022	2016–2020	Los Angeles, New York, Chicago, Seattle	USA	Temperate	Traffic collision dataset hosted by the City of Los Angeles	Meteorological station	Road traffic accidents

Table 1 (continued)

Reference	Study years	City/state/province	Country	Climate zone	Source of crash data	Source of meteorological data	Outcome
Wu 2022	2009–2018	Alabama	USA	Temperate	Alabama Department of Transportation (ALDOT)	North American Land Data Assimilation System (NLDAS-2)	Road traffic accidents
Zou et al. 2021	2001–2006	California, Arizona	USA	Temperate	Fatality Analysis Reporting System (FARS)	USA	Road traffic deaths
Tamerius et al. 2016	2002–2012	Iowa	USA	Temperate	University of Iowa Injury Prevention Research Center (IPRC)	Road Weather Information System (RWIS)	Road traffic accidents
Zhao et al. 2019	2011–2015	Connecticut	USA	Temperate	Connecticut Transportation Crash Data Repository	National Centers for Environmental Information (NCEI)	Road traffic accidents

NA not applicable, UA unavailable

a positive correlation between temperature and traffic incidents (Table 2).

In addition, 30 studies were conducted in a temperate zone, with 19 reporting positive correlations (Table 2), five reporting negative correlations (Brijs et al. 2008; Cheng et al. 2017; Ma et al. 2016; Wu 2022; Zhao et al. 2019), and three reporting no relationship (Izquierdo et al. 2013; Jones et al. 2008; Theofilatos 2017). Five studies reported that traffic incidents increased in both hot and cold conditions; of these, three studies were conducted in a temperate zone (Hou et al. 2022; Liang et al. 2021; Tamerius et al. 2016), one in a dry area (Zare et al. 2022), and the other in a subtropical area (Xing et al. 2019).

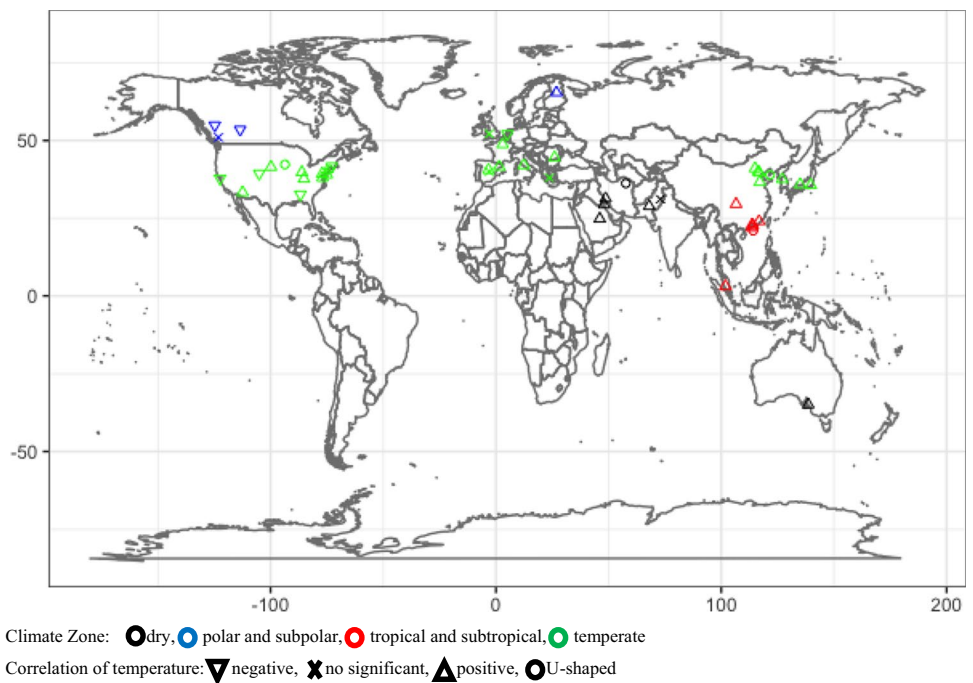
The impact of humidity on traffic incidents

Compared to temperature, there were fewer studies investigating the association between RH and driver safety, with only ten studies reporting the impact of humidity on driver safety (Table 3). All studies reported the influence of RH, whilst none addressed the influence of absolute humidity. Two studies each focused on monthly mean RH (Datoorpoor et al. 2016; Gao et al. 2016), daily mean RH (Al-Harbi et al. 2012; Cheng et al. 2017), and hourly mean RH (Pathivada et al. 2024; Theofilatos 2017). Three studies reported negative correlations between RH and traffic incidents (Datoorpoor et al. 2016; Lio et al. 2019; Naik et al. 2016), and two reported a positive correlation (Pathivada et al. 2024; Song et al. 2019), whilst four studies reported no significant relationships (Al-Harbi et al. 2012; Gao et al. 2016; Theofilatos 2017). One study (Xing et al. 2019) reported that the relative risk of road traffic accidents was 1.32 in dry (RH < 43%) and 1.14 in humid (RH > 97%) environments.

Other meteorological factors

Twenty-one studies considered meteorological risk and protective factors other than heat and RH (Abe et al. 2008; Ali et al. 2020; Bergel-Hayat et al. 2013; Brijs et al. 2008; Cheng et al. 2017; El-Basyouny et al. 2014; Gao et al. 2016; Islam et al. 2019; Junus et al. 2017; Lio et al. 2019; Malyshkina and Mannering 2009; Naik et al. 2016; Pathivada et al. 2024; Perrels et al. 2015; Song et al. 2019; Tamerius et al. 2016; Xing et al. 2019; Zeng et al. 2022; Zhan et al. 2020; Zhao et al. 2019; Zou et al. 2021) (Table 4). Seventeen studies reported a relationship between precipitation and traffic incidents, and 15 of those studies reported that precipitation was a significant risk factor for traffic incidents (Abe et al. 2008; Ali et al. 2020; Bergel-Hayat et al. 2013; Brijs et al. 2008; Islam et al. 2019; Junus et al. 2017; Malyshkina and Mannering 2009; Naik et al. 2016; Perrels et al. 2015; Song et al.

Fig. 2 Summary of study characteristics



2019; Tamerius et al. 2016; Xing et al. 2019; Zeng et al. 2022; Zhan et al. 2020; Zou et al. 2021). The effect of wind speed on traffic incidents was equivocal. Specifically, four studies reported positive correlations between wind speed and road traffic incidents (Pathivada et al. 2024; Malyshkina and Mannering 2009; Naik et al. 2016; Perrels et al. 2015), but two studies reported negative correlations (Gao et al. 2016; Zhao et al. 2019). Three studies examined the influence of sunshine duration, with all of these studies reporting positive correlations with traffic accidents (Gao et al. 2016; Lio et al. 2019; Song et al. 2019). Two studies explored the association between barometric pressure and road traffic incidents, with both studies reporting negative correlations (Lio et al. 2019; Song et al. 2019).

Methodological quality

The results of the data quality assessment are summarized in Tables 2 and 3. Forty-eight studies met the criteria for addressing target population, identification of condition, the method of measuring temperature or humidity, and appropriate statistical analysis, although the criteria of sufficient coverage and response rate were not met. In 11 studies, the source of traffic incident data and meteorological data were not reported, and thus these studies did not meet the JBI criterion for appropriate sampling. Additionally, 14 studies did not report the total number of traffic incidents, and thus the JBI criterion for adequate sample size was not met.

Discussion

This systematic scoping review aimed to explore the influence of ambient temperature and RH on traffic incidents in different global climates. Of the 48 studies reviewed, most (31, 65%) found a positive link between temperature and traffic incidents, especially in temperate (20, 66%), dry (9, 86%), and tropical/subtropical (5, 71%) climates, with one study in polar/subpolar regions. On the other hand, seven studies (15%) showed a negative relationship between temperature and RH, but only in temperate (5) and polar/subpolar (2) areas. Four studies also noted more traffic incidents in both extreme hot and cold conditions across various climates. These findings suggest a U-shaped relationship between temperature and traffic incidents, with incidents rising at both temperature extremes.

Baars (1997) proposed the global workspace theory, which posits that multiple neuronal networks cooperate and compete in cognitive problem-solving at the conscious level. The author suggested that external stimuli, such as heat and RH, might impede this process. With specific reference to environmental conditions, some studies show that heat and RH may impair human cognitive skills and compromise driving performance (Daanen et al. 2003; Xiaoyu et al. 2021), thereby increasing the risk of road traffic incidents. Furthermore, given the forecasted increases in global temperatures via increasing extreme weather events in both intensity and duration (National Oceanic and Atmospheric Administration 2024), a consideration of the impact of heat and RH on road traffic incidents will be needed to reduce future incidents.

Table 2 The impact of temperature across climatic zones

Reference	Country	No. reported	Definition of temperature (°C)	Outcome	The impact of temperature	Change per degree Celsius	Relative risk	Data quality
Subpolar and polar climates								
El-Basyouny et al. 2014	Canada	UA	Daily mean temperature	Road traffic accidents	Negative	-4.1%	UA	Good
Brubacher et al. 2016	Canada	1,820,565	Maximum monthly mean temperature in winter (Dec to Feb)	Road traffic accidents	Negative	-5.3%	UA	Good
Kamel and Sayed 2021	Canada	UA	Daily mean temperature	Cyclist-vehicle crash	Nonsignificant	NA	NA	Good
Perrels et al. 2015	Finland	UA	Daily mean temperature	Road traffic accidents	Positive	UA	UA	Good
Dry climate								
Li et al. 2024	Australia	64,597	Daily mean temperature	Road traffic accidents	Positive	UA	Moderately high: 1.012 (95% CI 0.994–1.030) Extremely high: 1.168 (95% CI 1.010–1.351)	Excellent
Dastoorpoor et al. 2016	Iran	76,006	Monthly mean temperature	Road traffic accidents	Positive	UA	1.01213 (95% CI 0.99967–1.02475)	Excellent
Zare et al. 2022	Iran	36,079	Daily mean temperature	Motorcyclist injuries	U-shaped	UA	Extremely cold: 1.20 (95% CI 1.11–1.30) Cold: 1.02 (95% CI 0.99–1.05) Hot: 1.11 (95% CI 1.03–1.20) Extremely hot: 1.27 (95% CI 1.14–1.41)	Excellent
Al-Harbi et al. 2012	Kuwait	505,801	Daily mean temperature	Road traffic accidents and deaths	Positive	UA	UA	Good
Hammad et al. 2019	Pakistan	UA	Monthly max and min temperature	Road traffic accidents	Nonsignificant	NA	NA	Good
Ali et al. 2020	Pakistan	UA	Daily mean temperature	Road traffic deaths	Positive	+3.28% due to a 1% increase in temperature	UA	Good
Islam et al. 2019	Saudi Arabia	30,619	Mean temperature	Road traffic accidents	Positive	UA	UA	Good
Subtropical and tropical climates								
Cheng et al. 2023	China	49,265	Hourly mean temperature	Road traffic injuries	Positive	UA	1.346 (95% CI 1.167–1.552)	Excellent
Gao et al. 2016	China	11,263	Monthly mean temperature	Road traffic injuries	Positive	UA	UA	Good
Zeng et al. 2022	China	UA	Annual mean temperature	Road traffic accidents	Positive	UA	UA	Good
Zhan et al. 2020	China	137,458	Hourly temperature	Road traffic injury and deaths	Positive	+0.87%	UA	Excellent
Lio et al. 2019	China	393,176	Daily mean temperature	Road traffic accidents	Positive	UA	UA	Excellent

Table 2 (continued)

Reference	Country	No. reported	Definition of temperature (°C)	Outcome	The impact of temperature	Change per degree Celsius	Relative risk	Data quality
Xing et al. 2019	China	16,170	Hot (above 33), cold (below 12)	Road traffic accidents	U-shaped	UA	Extremely hot: 1.11 (95% CI 0.96–1.30) Extremely cold: 1.14 (95% CI 1.03–1.26) UA	Excellent
Junus et al. 2017	Malaysia	UA	Daily maximum temperature	Road traffic accidents	Positive	UA	UA	Fair
Temperate climate								
Cheng et al. 2023	China	300,664	Hourly mean temperature	Road traffic deaths	Positive	UA	Odds ratio: 1.37 (95% CI 1.16–1.40) UA	Excellent
Song et al. 2019	China	6295	Weekly mean temperature	Road traffic injuries	Positive	UA	UA	Excellent
Liang et al. 2021	China	5197	Hot (above 24.9), cold (below –2.3)	Road traffic injury	U-shaped	UA	Hot: 1.198 (95% CI 1.017–1.411) Cold: 1.017–.95% CI 1.001–1.035) UA	Excellent
Zhu et al. 2024	China	1,031,082	Heat wave (daily maximum temperature above 92.5th percentile for 3 or more consecutive days)	Road traffic injuries	Positive	+3.61% (95% CI 1.97–5.29) in heat wave	UA	Excellent
Li et al. 2024	China	9794	Daily mean temperature	Road traffic deaths	Positive	UA	Odds ratio: 2.09 (95% CI 1.66–2.63) NA	Excellent
Jones et al. 2008	England, Wales	1,490,230	Daily mean temperature	Road traffic injury and deaths	Nonsignificant	NA	NA	Excellent
Bergel-Hayat et al. 2013	France, Netherlands, Greece	UA	Monthly mean temperature	Road traffic injury	Positive	+0.4% (main roads) +2% (motorways)	NA	Fair
Theofilatos 2017	Greece	UA	Hourly mean temperature	Road traffic accidents	Nonsignificant	NA	NA	Good
Gariazzo et al. 2021	Italy	588,517	75th to 99th percentiles (hot) and from 25th to first percentile (cold) of temperature	Road traffic accidents	Positive	UA	Hot: 1.12 (95% CI 1.09–1.16) Cold: 0.93 (95% CI 0.91–0.96) NA	Excellent
Abe et al. 2008	Japan	643,849	Hourly mean temperature	Road traffic injury	Positive	+0.025	NA	Excellent
Pan et al. 2022	Japan	438,365	Daily mean temperature	Road traffic deaths	Positive	UA	1.60 (95% CI 1.35–1.90) UA	Excellent
Park et al. 2021	Korea	305,268	Daily maximum temperature	Road traffic accidents	Positive	+0.59%	UA	Good
Brijis et al. 2008	Netherlands	UA	Daily mean temperature	Road traffic accidents	Negative	UA	UA	Good

Table 2 (continued)

Reference	Country	No. reported	Definition of temperature (°C)	Outcome	The impact of temperature	Change per degree Celsius	Relative risk	Data quality
Drosu et al. 2020	Romania	UA	Monthly mean temperature	Road traffic accidents	Positive	+2.42%	UA	Fair
Aparicio et al. 2013	Spain	UA	Monthly mean temperature	Road traffic injury and deaths	Nonsignificant	NA	NA	Fair
Basagaña et al. 2015	Spain	118,489	Heat wave days	Road traffic accidents	Positive	+2.9% (95% CI 0.7–5.1)	UA	Good
Basagaña et al. 2015	Spain	1,908,406	Daily mean temperature	Road traffic accidents	Positive	UA	1.15 (95% CI 1.11–1.20)	Excellent
Wu et al. 2018	USA	261,125	NA	Road traffic accidents	Positive	+3.4% (95% CI 0.9–5.9)	UA	Good
Robertson 2018	USA	23,634	Daily mean temperature	Road traffic deaths	Positive	UA	UA	Excellent
Pathivada et al. 2024	USA	21,127	Hourly mean temperature	Road traffic injury severity	Positive	+12.06% (10–21.1)	UA	Excellent
Naik et al. 2016	USA	1721	NA	Single-vehicle truck crush injury severity	Positive	UA	UA	Good
Malyshkina and Mannering 2009	USA	811,720	NA	Road traffic injury severity	Positive	UA	UA	Fair
Ma et al. 2016	USA	542	Daily mean temperature	Road traffic accidents	Negative	UA	UA	Excellent
Liu et al. 2017	USA	1,281,226	Extreme heat event	Road traffic accidents	Positive	+1% (95% CI 1.00–1.02)	UA	Good
Cheng et al. 2017	USA	2141	Daily mean temperature	Road traffic accidents	Negative	UA	UA	Excellent
Hou et al. 2022	USA	2,198,806	Daily mean temperature	Road traffic accidents	U-shaped	+1.58% (95% CI 0.36–2.79) above 26.1	UA	Excellent
Wu 2022	USA	493,829	Heat wave days	Road traffic accidents	Negative	+11.59% (95% CI 5.17–16.43) below –4.8	UA	Excellent
Zou et al. 2021	USA	UA	Monthly mean temperature	Road traffic deaths	Positive	–1.4% (95% CI 0.4–3.1)	UA	Fair
Tamerius et al. 2016	USA	85,466	Hourly temperature	Road traffic accidents	U-shaped	UA	UA	Excellent
Zhao et al. 2019	USA	UA	Monthly mean temperature	Road traffic accidents	Negative	UA	UA	Good

NA not applicable, UA unavailable, U-shaped: the event occurred more in both hot and cold conditions

Table 3 The impact of humidity across climatic zones

Reference	Country	No. reported	Definition of humidity	Outcome	The impact of humidity	Relative risk	Quality
Dry climates							
Dastoorpoor et al. 2016	Iran	76,006	Monthly mean relative humidity	Road traffic accidents	Negative	0.98939 (95% CI 0.98283– 0.99598)	Excellent
Al-Harbi et al. 2012	Kuwait	505,801	Daily mean relative humidity	Road traffic accidents and deaths	No significant association	NA	Excellent
Subtropical and tropical climates							
Gao et al. 2016	China	11,263	Monthly mean relative humidity	Road traffic injury	No significant association	NA	Excellent
Lio et al. 2019	China	393,176	Relative humidity	Road traffic accidents	Negative	UA	Excellent
Xing et al. 2019	China	16,170	Dry (below 43%), wet (97%)	Road traffic accidents	U-shaped	Dry: 1.32 (95% CI 1.15–1.51) Wet: 1.14 (95% CI 1.03–1.26)	Excellent
Temperate climate							
Song et al. 2019	China	6295	Weekly mean relative humidity	Road traffic injuries	Positive	UA	Excellent
Theofilatos 2017	Greece	NA	Hourly mean relative humidity	Road traffic accidents	No significant association	NA	Good
Pathivada et al. 2024	USA	21,127	Hourly mean relative humidity	Road traffic injury severity	Positive	+70.53%	Excellent
Naik et al. 2016	USA	1721	Relative humidity	Single-vehicle truck crush injury severity	Negative	UA	Good
Cheng et al. 2017	USA	2141	Daily mean relative humidity	Road traffic accidents	No significant association	NA	Excellent

NA not applicable, UA unavailable. U-shaped: the event occurred more in both wet and dry situation

Interestingly, the association between temperature and traffic incidents reported in this review revealed both positive ($n = 31$) and negative ($n = 7$) correlations, suggesting that the relationship between temperature and traffic incidents is not linear. Supporting this notion, five studies that collected data on traffic incidents in both extreme hot and cold environments reported a U-shaped association (Hou et al. 2022; Liang et al. 2021; Tamerius et al. 2016; Xing et al. 2019; Zare et al. 2022). Additionally, this relationship is supported by research conducted in environmentally controlled laboratory studies, which reported that driving performance in both cold and hot environments deteriorated when compared to thermoneutral conditions (Daanen et al. 2003).

Unfortunately, only a few studies have focused on the influence of RH on traffic incidents, with results being relatively inconsistent. One study (Xing et al. 2019) reported that both elevated RH and dry conditions increased traffic accidents, suggesting that humidity may influence traffic incidents similarly to air temperature (U-shaped relationship). Furthermore, all studies indicated the influence of RH on the observed outcomes. Most studies included in

this review reported RH, presumably because many climate stations from which climate data were extracted primarily recorded RH, whilst absolute humidity data were often unavailable. Given that RH is significantly affected by temperature fluctuations, future research should consider evaluating both variables concurrently.

Some studies reported on the temperature and RH variations inside vehicle cabins in a hot climate (Lenzuni et al. 2014; Zhang et al. 2020; Zhou et al. 2019). Those studies reported that the temperature inside the cabin dropped faster and plateaued more quickly with the administration of cooling methods such as driving with the window open (Lenzuni et al. 2014) or turning on the air conditioning (Zhang et al. 2020; Zhou et al. 2019). Also, all three studies reported that RH increased, with the change attributed to changes in temperature, as the absolute humidity appeared stable inside the cabin.

The results reveal a clear distinction in temperature between vehicle cabins and the ambient environment, which is moderated by cooling methods implemented by drivers. Therefore, to correctly evaluate the impact of hot and humid

Table 4 Other meteorological risk and protective factors

Risk factor/protective factor	Definition	Zones				References
		Subpolar and polar	Dry	Subtropical and tropical	Temperate	
Risk factor						
Precipitation	Where there is more rain, there is a greater probability of traffic incidents	Yes	Yes	Yes	Yes	Abe et al. 2008; Ali et al. 2020; Bergel-Hayat et al. 2013; Brijs et al. 2008; Islam et al. 2019; Junus et al. 2017; Malyshkina and Mannering 2009; Naik et al. 2016; Perrels et al. 2015; Song et al. 2019; Tamerius et al. 2016; Xing et al. 2019; Zeng et al. 2022; Zhan et al. 2020; Zou et al. 2021
Wind speed	Where the wind speed is high, there is a greater probability of traffic incidents	Yes	No	No	Yes	Malyshkina and Mannering 2009; Naik et al. 2016; Perrels et al. 2015; Pathivada et al. 2024
Sunshine duration	Where the sunshine duration is long, there is a greater probability of traffic incidents	No	No	Yes	Yes	Gao et al. 2016; Lio et al. 2019; Song et al. 2019
Snow	Where there is more snow, there is a greater probability of traffic incidents	Yes	No	No	No	El-Basyouny et al. 2014
Fog	Where there is fog, there is a greater probability of traffic incidents	No	No	No	Yes	Zhao et al. 2019
Protective factor						
Precipitation	Where there is more rain, there is a lower probability of traffic incidents	No	No	No	Yes	Cheng et al. 2017; Zhao et al. 2019
Wind speed	Where the wind speed is high, there is a lower probability of traffic incidents	No	No	Yes	Yes	Gao et al. 2016; Zhao et al. 2019
Barometric pressure	Where the barometric pressure is high, there is a lower probability of traffic incidents	No	No	Yes	Yes	Lio et al. 2019; Song et al. 2019

climates on driver safety, future research should consider assessing the actual temperature and RH inside vehicle cabins in a hot and humid climate.

For example, activating air conditioners before driving may effectively reduce the temperature inside cars, thereby protecting drivers from heat stress and reducing the risk of road traffic incidents in hot climates. Additionally, reducing absolute humidity in cars may improve the environment inside vehicles and potentially reduce road traffic incidents, minimizing the impact of high RH on impairing human cognitive skills (Lenzuni et al. 2014; Zhang et al. 2020; Zhou et al. 2019). However, further research is warranted to confirm the impact of humidity (both absolute and relative) on driver behavior and traffic incidents, given the limited number of studies and conflicting findings to date.

The included studies also reported other meteorological factors as risk or protective factors. Given that humidity is higher on rainy or snowy days, the influence of humidity

on drivers' safety should also be considered when investigating rainy or snowy weather conditions. Interestingly, two studies reported high barometric pressure as a protective factor against traffic incidents (Lio et al. 2019; Song et al. 2019). Considering that barometric pressure is lower with rainy and snowy weather conditions, it is reasonable to assume that higher barometric pressure would result in lower traffic incidents, albeit indirectly. Also, three studies reported positive correlations between the duration of sunshine and traffic incidents (Gao et al. 2016; Lio et al. 2019; Song et al. 2019), possibly because ambient temperature can increase with longer periods of sunshine. However, the correlation between wind speed and traffic incidents was conflicting. For example, four studies reported positive correlations (Pathivada et al. 2024; Malyshkina and Mannering 2009; Naik et al. 2016; Perrels et al. 2015) while two studies reported negative correlations (Gao et al. 2016; Zhao et al. 2019). A study conducted by Zhang et al. (2024) reported

that aerodynamic interference had an important role in traffic incidents. Thus, to evaluate the effect of wind speed, we need to explore constant wind speed in conjunction with wind turbulence. Therefore, further studies are needed to clarify the effects of wind speed, barometric pressure, and duration of sunshine on traffic incidents.

Road type may also be important when we evaluate the influence of hot and humid climate on driving safety. For example, moisture on unpaved roads greatly influences driving performance (Rada et al. 1989). Therefore, changes in ambient temperature and humidity may have a greater safety impact for driving on unpaved than on paved roads. Additionally, heat stress may promote the degradation of road pavement (Nemry and Demirel 2012), so insufficient road maintenance may increase traffic incidents in hot climates. Given that maintenance of paved roads incurs a financial cost, the effect of temperature and humidity on traffic incidents may be higher in lower-income countries or rural areas with poorer road conditions.

Strengths and limitations

A strength of this review was that no limits were applied to the search regarding the country that the data were extracted from, which enables a global perspective regarding the impact of climatic conditions on traffic incidents. Furthermore, results identified that only a few studies examined the impact of humidity on traffic incidents, warranting further research in this area. In addition, our review focused on the effect of temperature across climatic zones, demonstrating that the association between heat, humidity, and cold environmental conditions and traffic incidents are more apparent in subtropical, tropical, subpolar, and polar countries.

In addition to the strengths of this paper, some limitations should also be noted. Firstly, all studies checked ambient temperature and RH, but they did not explain the temperature and humidity (absolute or relative) inside the vehicle cabins, the point of exposure for drivers, and therefore potentially have a greater influence on driving performance. From some laboratory studies, the temperature inside vehicle cabins changed by opening a window(s) or activating an air conditioning system, so the rate of opening a window or switching on an air conditioner may influence results, and may contribute to the discrepancies among results in this review. Secondly, half of the included studies were conducted in the USA or China, which may introduce reporting bias. Interestingly, only one study regarding the impact of temperature and humidity was reported from Australia, even though Australia is a continent considered to exhibit extreme weather conditions, particularly with regard to heat and RH in the northern and central regions. Thus, additional research is warranted to explore the impact of a hot and humid climate on traffic incidents in northern Australia. Finally, there

were inconsistencies regarding the definition of temperature and RH across the studies. The ambiguity in the definitions of these key terms may have arisen because some studies focused on these effects as secondary measures.

Conclusion

Temperature impacts traffic incidents, with contrasting positive and negative correlations reported. Positive correlations were more evident in subtropical and tropical climates, whilst negative correlations were clearer in subpolar and polar climates. Thus, the influence of temperature is U-shaped. With the limited number of studies including the influence of humidity (absolute or relative) on driving performance, further research is needed to clarify the significance of humidity with respect to road traffic incidents.

Acknowledgements None.

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Soonho Koh. The first draft of the manuscript was written by Soonho Koh and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Data availability Not applicable.

Code availability Not applicable.

Declarations

Consent for publication Not applicable.

Consent to participate Not applicable.

Ethics approval This research does not require ethical approval as it is based on publicly available information.

Conflict of interest The authors declare that they have no conflict of interest.

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