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Research article

The effects of weather factors on road traffic casualties: Analysis on provincial panel data of China from 2006 to 2021

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A R T I C L E I N F O

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Road traffic safety
Rainfall
Temperature
ARDL model

A B S T R A C T

Introduction: Road traffic injuries stands as a major concern globally, as they result in significant loss of life, economic impact, and erode trust in government and societal safety. The influence of weather on road traffic safety is undeniable, impacting road conditions, individuals, and vehicles. However, the specific influence of weather on road traffic casualties has seldom been explored.
Method: This study assesses the effect of weather factors on road traffic casualties in China from 2006 to 2021. Vector error correction models (VECM) were utilized to determine the Granger causality between weather factors and covariates. Furthermore, panel autoregressive distribution lag models (ARDL) were applied to quantify the association between weather factors and road traffic casualties.
Results: The findings indicate that rainfall and temperature exert a short-term negative impact on casualty risk, which intriguingly becomes positive in the long term. A standout discovery is the significant role of health investments, which are shown to reduce casualty numbers in both the short and long-terms. In the long run, the gross domestic product significantly enhances casualties, while expressway mileage notably decreases them.
Conclusions: These results demonstrate the significant influence of weather on road traffic casualties and highlight the critical roles played by factors such as gross domestic product, health investment, and expressway mileage. The evidence presented in the study underscores the urgent need for more effective strategies to mitigate road traffic casualties. Thus, some effective measures are proposed to reduce road traffic casualties. This study is conducive to the improvement of traffic in severe weather in China and provides guidance for traffic management departments.

1. Introduction

Road traffic injury has emerged as a pressing global public health concern, as underscored by the United Nations' estimation that road traffic accidents have led to 1.35 million fatalities and 50 million injuries annually [1]. In response to this alarming trend, the United Nations has initiated the Road Safety Action Plan spanning from 2021 to 2030, with the ambitious goal of reducing road traffic

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fatalities and injuries by no less than 50 %. Notably, middle-income countries bear the brunt of this crisis, accounting for approximately 52 % of registered vehicles and 80 % of road traffic deaths, as reported by the World Health Organization (WHO) [2]. Therefore, some middle-income countries, such as China, Brazil, and India, have made significant efforts to implement preventive measures to curb road traffic accidents. Despite China's determined efforts to mitigate such incidents, the number of road traffic casualties (RTCs) in the country continues to stand out as alarmingly high compared to other countries. In fact, in 2022 alone, China witnessed a distressing 61,703 fatalities and 250,723 injuries [3]. The ramifications of RTCs extend beyond the loss of human life, permeating into the domains of social governance distrust and public management crises [4]. Thus, it is necessary to delve into the multifaceted factors that contribute to RTCs.

Extensive studies and practices have been dedicated to understanding the various determinants of RTCs, including human factors [5–7], economic factors [8–10], and road factors [11–13], among others. However, limited research has been paid to the influence of weather-related factors on RTCs. Nevertheless, adverse weather conditions, in particular, exhibit a significant impact on the occurrence of RTCs [14]. USDOT has reported that approximately 21 % of the nearly 6 million vehicle collisions can be attributed to adverse weather conditions [15]. These weather-related collisions include accidents that occur in adverse weather (such as rain, fog, snow, or sleet) or on slick pavement (such as wet, snow, mud, or ice). It is evident that these adverse weather conditions, whether they occur individually or in combination, lead to a surge in the number of RTCs. Therefore, it becomes indispensable to explore the relationship between weather factors and RTCs.

It has been widely acknowledged that severe weather conditions contribute to an increase in RTCs, and numerous studies have substantiated a positive association between severe weather and RTCs. However, certain studies have revealed that the increment of severe weather actually suppresses RTCs [16], owing to the difference between the short-term and long-term impacts of weather. Simultaneously, the geographical location exerts a significant influence on weather patterns [10], and the extent to which weather affects RTCs in China may differ from that in other countries. Therefore, the influence of weather factors on RTCs in China remains unpredictable. Currently, there is a dearth of macro research on the relationship between RTCs and weather factors in China, with most studies focusing on specific provinces, making it difficult to conduct comprehensive analysis and exploration at the national level. Particularly, whether weather factors lead to varying RTCs, whether there exists Granger causality between weather factors and covariates, and whether there are long-term and short-term relationships between RTCs and selected factors.

It is worth noting that existing research predominantly employs a distributed lag nonlinear model (DLNM) to explore the nonlinear and lagged effects of weather factors on RTCs [17,18]. This approach takes into account the temporal dimension and discusses the cumulative impact of weather factors on RTCs based on time series data. However, due to the vast expanse of China, the utilization of DLNM may pose more challenges and result in unreliable results. On the other hand, the vector error correction model (VECM) can determine the causality between selected variables and the direction of causality. Meanwhile, the panel autoregressive distributed lag model (ARDL) incorporates both the temporal and cross-sectional dimensions, thereby overcoming the limitations imposed by small sample sizes and effectively estimating the long-term and short-term relationships between variables [19].

Therefore, this study conducts a descriptive analysis to compare the quantity of RTCs across diverse provinces. VECM is employed to explore the Granger causality between weather factors and covariates. Subsequently, the association between the long-term and short-term is quantified through the utilization of panel ARDL. Finally, this study deliberates upon the results derived from empirical analysis and proffers efficacious measures to reduce RTCs.

2. Literature review

Numerous studies have examined the correlation between the severity of road traffic accidents and weather factors such as rain, fog, wind, and snow [20–23]. Rainfall is regarded as a principal indicator [24]. In comparison to sunlit days, the risk of vehicular collisions, injuries, and fatalities increases significantly on rainy days [25]. Omranian [26] discovered that precipitation enhances the probability of traffic accidents in Texas by 57 %. Rainfall also significantly increases the incidence of traffic accidents in the southern and northern provinces of Thailand [27]. Conversely, scant studies have substantiated the negative connection between traffic accidents and rainfall. Rainfall exhibits a negative correlation with the severity of motorcycle crashes in San Francisco, potentially attributable to riders adopting a more cautious approach [16]. The increment in rainfall likewise reduces the number of traffic accidents in Greece [28]. Therefore, the impact of rainfall on road accidents reflects variability contingent upon the region and country.

The issue of temperature rise has emerged as a significant concern in public health [29]. While numerous studies have focused on precipitation events, the investigation of the correlation between temperature and road traffic accidents remains relatively scarce. Existing research has indicated an increased risk of road collisions associated with increased temperatures [30–32]. In South Korea, Park [33] observed that for each 1 % rise in the daily average temperature, the risk of road injuries increased by 0.59 %. Cheng's findings revealed that rising temperatures amplified the frequency of non-fatal car accidents. Notably, the incidence of fatal car accidents decreased, plausibly attributable to favorable weather conditions prevailing under relatively high temperatures [16]. Some studies have begun to recognize the impact of low temperatures on road accidents. In the context of the first meta-analysis exploring the relationship between ambient temperature and road traffic safety, two studies assessing the connection between low temperature and traffic accident injury were considered [34]. Lee assessed the influence of low temperatures on traffic casualties in Seoul, revealing that for every 1 % decrease in the daily average temperature below the threshold of −5.7 °C, the probability of traffic accidents increased by 2.1 % [35].

In addition to rainfall and temperature, road traffic accidents are influenced by a multitude of factors, including the level of economic development, medical conditions, and the road environment, among others [36]. Table 1 provides a summary of relevant literature [37–43]. Calvo-Poyo employed data from 23 European countries to construct a panel model, incorporating road investment, economic factors, weather variables, and other pertinent factors. The study concluded that increased rainfall, road expenditure, and the proportion of expressways all contributed to a reduction in road mortality [44]. Therefore, considering the action of multiple factors, further study into the impact of weather factors on road traffic safety is necessary.

Studies into the association between weather factors and RTCs in China are scarce and primarily focused on individual provinces. Li [45] determined that factors such as fatigue, adverse road conditions, and complex weather conditions were correlated with traffic

Table 1
An overview of road safety literature.

Authors	Study period	Countries	Variables	Method	Finding
Zhai et al., 2019 [37]	2015	Hong Kong, China	Pedestrian characteristics, driver characteristics (driver age, gender, and contributing factors), vehicle class, road geometry, traffic control type, weather conditions, and crash circumstance.	A mixed logit model	1. High temperatures and rainfall are associated with a higher likelihood of fatal and serious injury (KSI) accidents. 2. The interaction effects of weather conditions on the association between pedestrian crash severity and pedestrian and driver behaviors are significant.
Zou et al., 2021 [38]	2001 −2016	California and Arizona	The fatal traffic accident frequency, social development indicators and climate indicators.	A negative binomial model and log-change model	1. The average temperature and standard precipitation can affect the frequency of fatal traffic accidents. 2. Beer consumption, rural vehicle mileage ratio, and vehicle performance also have a significant impact.
Islam et al., 2023 [39]	2017 −2020	Dhaka, Bangladesh	The number of fatal and non-fatal crashes and the weather-related variables of rainfall, average temperatur, wind speed, relative humidity and specific humidity.	multinomial logit model	1. The increase in specific humidity leads to an increase in the probability of fatal accidents, with a coefficient of variation of 0.2195. 2. Elevated temperatures are associated with an increased risk of fatal accidents. 3. The wind speed is not related to the severity of the accident.
Islam et al., 2019 [40]	2003 −2013	Saudi Arabia,	Traffic accidents, rainfall, temperature, dust/sand storms, total vehicles.	Three static regression models: fixed effect (FE), random effect (RE), and the pooled ordinary least square (POLS) models	1. Temperature, rainfall, sandstorms, and the number of vehicles are the main causes of road accidents in the Saudi Arabian region. 2. Traffic accidents both inside and outside the city have caused significant injuries, but only accidents within the city have caused significant deaths.
Sun et al., 2019 [41]	2004 −2016	China	Traffic accident casualties, GDP, traffic investment, new vehicle ownership, new road mileage and newly increased population.	A panel model	1. An increase in GDP can reduce the number of road traffic casualties. 2. Road mileage is positively correlated with the number of traffic accident casualties.
Myhrmann et al., 2023 [42]	2017 −2020	Copenhagen	The number of bicycle crash, rainfall, wind strength, visibility, temperature.	Palm distributions	1. The risk of bicycle collisions is highly non-linear with air temperature and wind speed. 2. The risk of bicycle collisions increases at both low and high temperatures (0 °C > x, x > 21 °C).
Michalaki et al., 2016 [43]	1993 −2011	England	length of motorways, percentage of young drivers, percentage of vehicle-miles travelled by Heavy Goods Vehicles and precipitation.	A VAR model	1. The frequency of collisions in the main lane is influenced by weather conditions and the presence of Heavy Goods Vehicles. 2. The presence of highway service areas reduces hard shoulder collisions.
Malin et al., 2019 [20]	2014 −2016	Finland	Weather and road condition, road attributes.	The Palm probability approach	1. The adverse road weather conditions increase the risk of road collisions. 2. Compared to two-lane and multilane roads, highways have a higher risk of accidents in adverse weather conditions.

accidents in Sichuan. Gao [46], in the context of Shantou, found that temperature and daylight hours were accountable for the increase in injuries, while wind speed was responsible for their reduction. Similarly, Xing [47] observed that heavy rainfall could impact the severity of road damage in Hong Kong. In Dalian, Liang [34] examined the lag and nonlinear relationship between traffic accidents and temperature. High temperature exerted a positive influence on premature deaths in Wuhan, thereby imposing a burden on the healthcare system and the population [48]. As far as we know, no research has been conducted including weather factors to assess their impact on RTCs across all 31 provinces and cities in China.

As an econometric method, ARDL can overcome the limitations posed by small sample sizes and estimate the long-term and short-term relationships between variables [19]. In road traffic safety, this model is primarily employed to assess the short-term and long-term relationship between economic performance and road safety, but it can also be applied to weather factors. Rezaei and Akinyemi, respectively, determined the short-term and long-term effects of economic development on road safety in Iran and Nigeria using ARDL [49,50]. Li employed this model to explore whether socio-economic fluctuations had a differentiated impact on road traffic accident indicators in China [51]. Ali analyzed the causality and elasticity of road traffic deaths in upper-middle-income countries and high-income countries across three continents, with rainfall being considered in the study of upper-middle-income countries [19,52]. Subsequently, Ali explored the relationship between the health power density index, temperature, rainfall, road length, and road traffic deaths in Pakistan from 1985 to 2016. The results indicated that temperature and rainfall contributed to an increase in road deaths [53].

Therefore, this study employed panel data spanning the years 2006–2021 in China to explore the impact of weather factors on RTCs. Specifically, the annual mean rainfall and temperature were adopted as two weather indicators. Simultaneously, it is necessary to acknowledge the indispensable influence of economic and road-related factors on RTCs. Therefore, this study employed VECM to explore the Granger causality between weather factors and covariates. Subsequently, the ARDL approach was employed to explore the long-term and short-term relationships between RTCs and the selected factors. Finally, based on the empirical findings, a set of recommendations for reducing RTCs is proffered.

3. Data selection

The variables utilized for the empirical analysis included the number of RTCs, rainfall, temperature, regional gross domestic product (GDP), health investment, and expressway mileage. The provincial panel data from 2006 to 2021 in China, procured from diverse sources, constituted the dataset employed in this study. Table 2 presents the chosen variables, including units, abbreviations, and descriptions. Meanwhile, Table 3 lists the descriptive analysis results.

3.1. Road traffic casualties data

The number of road traffic fatalities and injuries served as a reference for casualties, as reported in the China National Statistical Yearbook [3]. Fig. 1 shows the spatial distribution of RTCs in China from 2006 to 2021, with Guangdong having the highest annual RTCs, followed by Zhejiang. According to the aforementioned statistics, the average number of RTCs from 2006 to 2021 amounted to 10,620, with figures ranging from 495 (Tibet, 2016) to 76,465 (Guangdong, 2006). Notably, the count of RTCs exhibited significant differences across different provinces and cities throughout the years under consideration. Fig. 2 (a, b) illustrates the trend of RTCs across 31 provinces and cities in China from 2006 to 2021. Most provinces, especially Guangdong and Zhejiang, have shown the most significant downward trend in RTCs. Meanwhile, an increasing trend in RTCs has been observed in a small number of regions in recent years, such as Guizhou, Hubei, and Jilin.

3.2. Rainfall data

The original rainfall data was obtained from China's surface climate data daily dataset v3.0. Utilizing the latitude and longitude coordinates of meteorological stations, this study employed the inverse distance weight interpolation technique to acquire nationwide daily average rainfall grid maps. By utilizing administrative boundary data and rainfall grid maps of prefecture-level cities, the mean annual precipitation for 31 provinces and cities was computed. In comparison to different provinces and cities, the spatial distribution of precipitation in China exhibited a general decline from the southeast to the northwest, with the most abundant precipitation observed in the southeastern coastal region and the least in the northwestern area. On the whole, the average annual rainfall in China showed an increasing trend from 2006 to 2021.

Table 2
List of variables of data used.

Data	Unit	Abbreviation	Description
Road traffic casualties	person	RTC	Number of road traffic casualties
Rainfall	millimeter	RF	Annual average rainfall
Temperature	Centigrade	TEM	Annual average temperature
Regional gross domestic product	RMB100mn	GDP	An estimated value obtained by dividing gross domestic product and state population.
Health investment	RMB100mn	HI	Local medical and health expenditure
Expressway Mileage	10000 km	Road	Reflects the intensity of highway construction.

Table 3
Descriptive statistics of variables.

Variable	Observation	Mean	Std.Dev.	Minimum	Maximum
RTC	496	10620.169	9270.388	495	76465
RF	495	947.633	527.492	125.162	2358.91
TEM	496	13.762	5.467	2.582	26.05
GDP	496	21097.8	20113.07	290.76	124369.7
HI	496	313.197	278.851	7.01	1857.1
Road	496	0.345	0.218	0.007	1.1

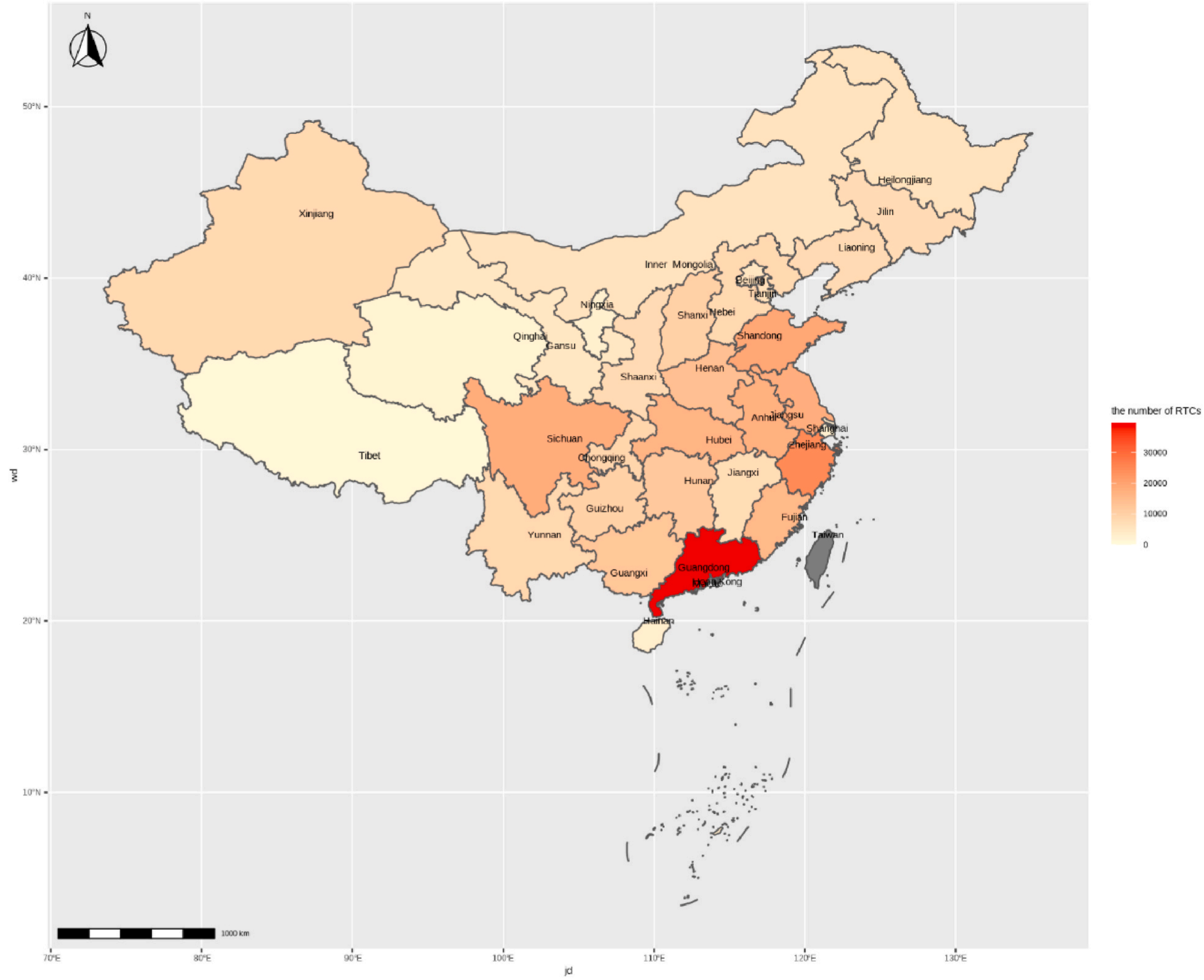

Fig. 1. Map of the RTCs by China, 2006–2021. (Due to the temporary inability to obtain data from Taiwan, it was not included in the study).

3.3. Temperature data

The annual average temperature was determined using a dataset sourced from the National Center of the United States for Environmental Information. Considering that the original data consisted of daily measurements from meteorological stations, the annual temperature was derived using the same methodology as that employed for rainfall. A significant temperature difference was observed between northern and southern China. When compared to various provinces and cities, Heilongjiang experienced the lowest annual average temperature during the period of 2009, measuring a mere 2.58 °C. Conversely, Hainan recorded the highest annual average temperature in 2019, reaching 25.83 °C.

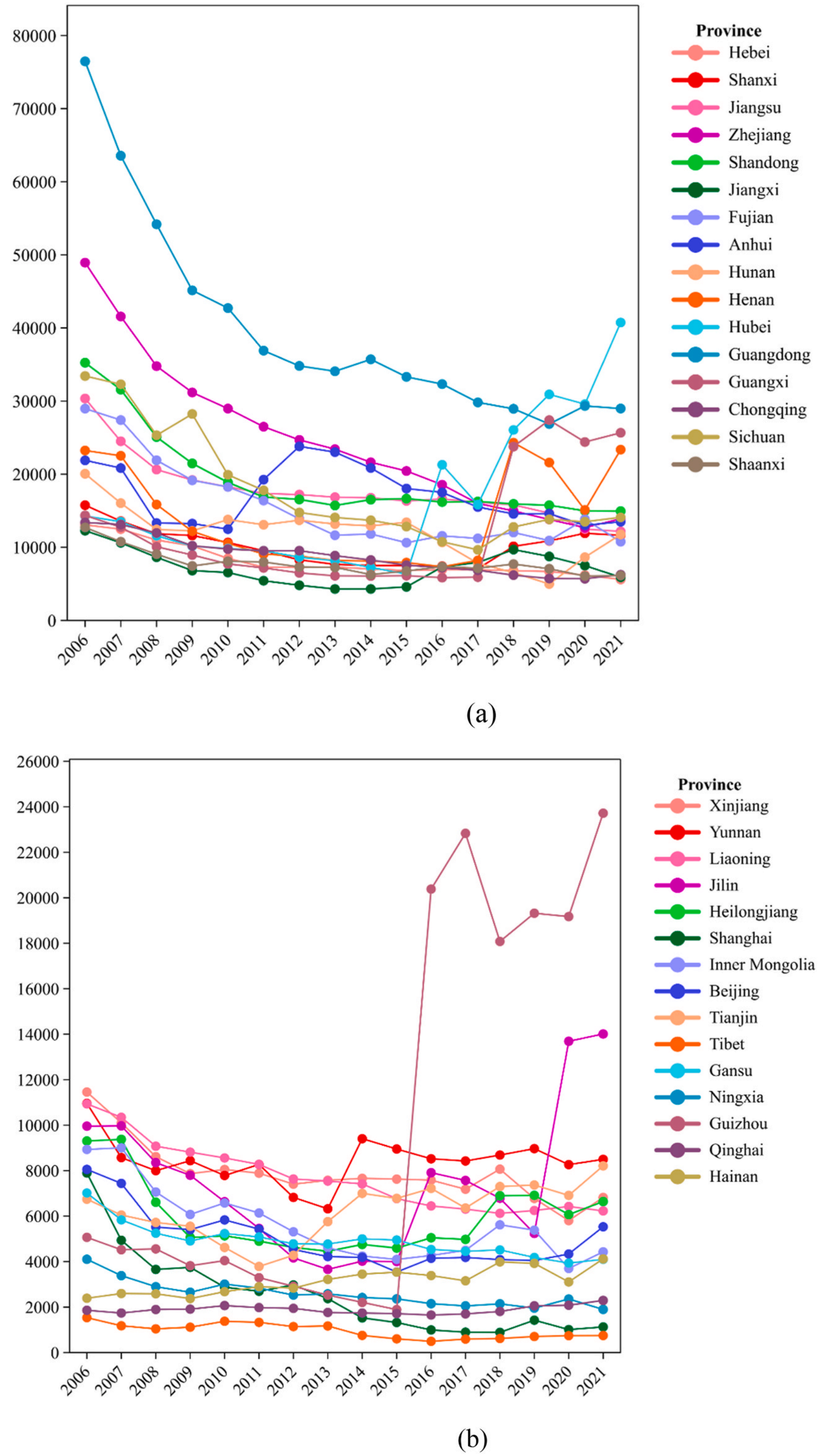

Fig. 2. Trend of RTCs changes in provinces. 2006–2021. (The difference in the vertical spacing between Figures a and b is to better reflect the trend of casualties in different provinces).

3.4. Gross domestic product data

The GDP data was from the China Statistical Yearbook [3]. China's economy experienced rapid growth, and the overall economic performance of each province and city exhibited a consistent upward trend. Over the period from 2006 to 2021, the average GDP stood at 2109.78 billion yuan, with values ranging from 290.76 billion yuan (Tibet, 2006) to 124369.7 billion yuan (Guangdong, 2021). These figures indicate an imbalance in economic development among provinces and cities.

3.5. Health investment data

The database used as a reference for this variable was the China Statistical Yearbook [3]. By analyzing panel data at the provincial level, it was observed that Ningxia recorded the lowest health investment in 2006, amounting to a mere 701 million yuan. Conversely, Guangdong exhibited the highest health investment during the study period, reaching an impressive 185.71 billion yuan in 2021. Overall, health investment in different provinces exhibited an upward trend in tandem with the improvement of the economic development level. However, significant differences in health investment were evident among provinces.

3.6. Expressway mileage data

The expressway mileage data was obtained from the China Statistical Yearbook [3]. As transportation investment increased, the mileage of highways experienced rapid expansion. From 2006 to 2021, the total highway mileage ranged from 0.007 km (Tibet, 2006) to 1.1 km (Guangdong, 2021). Notably, there were significant variations in the total mileage of highways across different provinces and cities in different years.

4. Empirical analysis

4.1. Multicollinearity test

It is challenging to separate respective influences on the various explanatory factors when there is multicollinearity. Therefore, five variables are subjected to multicollinearity analysis to avoid high correlation. A higher variance inflation factor (VIF) indicates a greater probability of collinearity between independent variables.

$$VIF = \frac{1}{1 - {R_i}^2}$$

where R_i is the negative correlation coefficient for regression analysis of other independent variables.

Table 4 presents the results of the multicollinearity analysis, revealing that the tolerance of each variable exceeds 0.1, and the VIF remained below 10. These findings indicate the absence of severe collinearity among the five variables.

4.2. Model specification

This study used the model [54], adjusting the selected variables:

$$RTC_{it} = A_0 RF_{it}^{\alpha 1i} TEM_{it}^{\alpha 2i} GDP_{it}^{\alpha 3i} HI_{it}^{\alpha 4i} Road_{it}^{\alpha 5i} \in^{it}$$

Reducing the heteroscedasticity problem by natural logarithms:

$$In(RTC_{it}) = \alpha_0 + \alpha_{1i} In(RF_{it}) + \alpha_{2i} In(TEM_{it}) + \alpha_{3i} In(GDP_{it}) + \alpha_{4i} In(HI_{it}) + \alpha_{5i} In(Road_{it}) + \varepsilon_{it}$$

where, "i" reflects 31 provinces and cities; "t" reflects time (2006–2021); $\alpha_0 = \ln(A_0)$ shows the constant; the symbols $\alpha_{1,}$ $\alpha_{2,}$ $\alpha_{3,}$ $\alpha_{4,}$ α_5 show the coefficients of explanatory ariables; $\in$ shows the error term.

4.3. Econometric method

This study used five econometric steps, including the Pesaran CD test, unit root analysis, long-term cointegration analysis, VECM

Table 4
Multiple collinearity test.

Variable	VIF	1/VIF
HI	6.87	0.146
GDP	4.38	0.228
TEM	3.60	0.278
RF	3.49	0.287
Road	2.87	0.348

Granger causality analysis, and RTCs's short-term and long-term elastic estimation of explanatory variables. Excel, STATA16, and eviews11 were used for empirical analysis.

4.3.1. Pesaran CD test

Due to the nature of panel data, certain factors may impact all provinces, thereby giving rise to the occurrence of cross-sectional correlation, such as the financial crisis. For short panels ($N > T$) where the cross-sectional count exceeds the number of time periods, the panel ARDL model necessitates a cross-sectional dependence test, commonly referred to as the CD test, as proposed by Pesaran [55].

4.3.2. Panel unit root tests

Traditional panel unit root tests like the ADF (Augmented Dickey-Fuller) test, PP (Phillips-Perron) test, and KPSS (Kwiatkowski-Phillips-Schmidt-Shin) test are invalid when there is a cross-sectional correlation. In the event of cross-sectional correlation, the Pesaran-CADF panel unit root test, which accounts for cross-sectional correlation variables, is employed [56].

4.3.3. Panel cointegration test

In the presence of cointegration, there is at least a one-way causal relationship between variables. The Kao test and Pedroni test represent the two primary methodologies for panel cointegration testing. Kao [57] tested the null hypothesis of no cointegration relationship and employed the residuals of static panel regression to construct statistics. The null hypothesis of the Pedroni [58] test pertains to the absence of cointegration relationship in dynamic multivariate panel regression. In this study, the Kao test and Pedroni test were utilized to assess the potential cointegration relationship between variables.

4.3.4. Panel VECM granger causality test

The identification of the direction of the causal relationship remains elusive through cointegration analysis, as it solely signifies the presence of a causal relationship between variables. Therefore, the Engle and Granger test is commonly employed to identify causal relationships between variables. Hossain (2011) observed that when there is cointegration between variables, utilizing the first difference form of Engel and Granger causality test will give incorrect results. Hence, Hossain introduced the ECM into the Vector Autoregressive (VAR) model to determine the long-term correlation between variables. By incorporating the ECM into the multivariate p-order VECM, an enhanced Granger causality test was employed and adapted based on the selected variables:

$$\begin{bmatrix} \Delta lnRTC_{it} \\ \Delta lnRF_{it} \\ \Delta lnTEM_{it} \\ \Delta lnGDP_{it} \\ \Delta lnFI_{it} \\ \Delta lnRoad_{it} \end{bmatrix} = \begin{matrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{matrix} + \sum_{K-1}^{P} \begin{bmatrix} \beta_{11k} & \beta_{12k} & \beta_{13k} & \beta_{14k} & \beta_{15k} & \beta_{16k} \\ \beta_{21k} & \beta_{22k} & \beta_{23k} & \beta_{24k} & \beta_{25k} & \beta_{26k} \\ \beta_{31k} & \beta_{32k} & \beta_{33k} & \beta_{34k} & \beta_{35k} & \beta_{36k} \\ \beta_{41k} & \beta_{42k} & \beta_{43k} & \beta_{44k} & \beta_{45k} & \beta_{46k} \\ \beta_{51k} & \beta_{52k} & \beta_{53k} & \beta_{54k} & \beta_{55k} & \beta_{56k} \\ \beta_{61k} & \beta_{62k} & \beta_{63k} & \beta_{64k} & \beta_{65k} & \beta_{66k} \end{bmatrix} \begin{bmatrix} \Delta lnRTC_{it} \\ \Delta lnRF_{it-k} \\ \Delta lnTEM_{it-k} \\ \Delta lnGDP_{it-k} \\ \Delta lnFI_{it-k} \\ \Delta lnRoad_{it-k} \end{bmatrix} + \begin{matrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \end{matrix} ECM_{it-1} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \\ \varepsilon_{4it} \\ \varepsilon_{5it} \\ \varepsilon_{6it} \end{bmatrix}$$

where $I = 1, 2, 3, \ldots, n$; $t = p+1, p+2, p+3, \ldots, T$. C_i, β_i, λ_i represent the estimated parameters. Δ indicates first-order difference. ECM_{it-1} is a periodic lag Error term derived from cointegration vector. ε_{it} were a sequence independent Error term with zero mean and finite covariance matrix. The coefficient of ECM shows the speed of convergence towards the long-run equilibrium.

4.3.5. Panel ARDL bound cointegration tests

The following is the ARDL equation used in this study:

$$\Delta Y_{it} = \theta_i \left[Y_{i,t-1} - \lambda_i' X_{i,t} \right] + \sum_{j=1}^{p-1} \xi_{ij} \Delta Y_{i,t-j} + \sum_{j=0}^{q-1} \beta_{ij}' \Delta X_{i,t-j} + \varphi_i + e_{it}$$

where:

$\theta_i = -(1-\delta_i)$; group-specific speed of adjustment coefficient (expected that $\theta_i < 0$); $ECT = [Y_{i,t-1} - \lambda_i' X_{i,t}]$, the error correction term; λ_i'

Table 5
Results of the Pesaran CD test.

Variable	CD-test	p-value
lnRTC	28.659	0.000***
lnRF	20.2	0.000***
lnTEM	52.101	0.000***
lnGDP	82.704	0.000***
lnHI	85.282	0.000***
lnRoad	78.004	0.000***

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

show vector of long-run relationships; ξ_{ij}, $\dot{\beta}_{ij}$ are the short-run dynamic coefficients; Y_{it} was $lnRTC_{it}$, X_{it} shows the vectors of $lnRF_{it}$, $lnTEM_{it}$, $lnGDP_{it}$, $lnHI_{it}$, $lnRoad_{it}$.

5. Results and discussion

5.1. Pesaran CD test

According to Table 5, the CD statistical values for the number of RTCs, rainfall, temperature, GDP, health investment, and road were 28.659, 20.2, 52.101, 82.704, 85.282, and 78.004, respectively, all of which were statistically significant at the 1 % level. Therefore, the panel data utilized in this study exhibited a cross-section correlation.

5.2. Panel unit root test

According to the results of the CD test, the panel data selected for this study exhibited cross-section dependence, rendering the traditional unit root tests invalid. Therefore, the Pesaran CADF panel unit root test was employed in this study.

Table 6 reports the stationarity characteristics of each variable at level I(0). After the first-order difference, all variables exhibited stability at the 1 % significance level, thereby rejecting the assumption of a unit root at the 1 % level. Therefore, all variables were stationary in the first difference form I(1), aligning with the condition for utilizing the ARDL model for estimation.

5.3. Panel cointegration test

To examine the possibility of a cointegration relationship between variables, the Kao test and Pedroni test were employed. Tables 7 and 8 report the results. Cointegration exists among all variables, allowing the use of panel VECM model to estimate Granger causality.

5.4. Panel VECM granger causality test

Granger causality test explores whether variable x leads to variable y. In this study, the panel VECM was employed to establish Granger causality among variables and explore the short-term and long-term causal associations between RTCs, rainfall, temperature, GDP, health investment, and the total mileage of highways. Table 9 is the result. If the ECM coefficient is both significant and negative, it indicates the presence of a long-term causal relationship for the dependent variable.

Based on the results, all explanatory variables exhibit a lasting impact on RTCs. In addition, long-term causal relationships are also observed in rainfall, temperature, GDP, and health investment. In the short run, causality is bidirectional between RTCs and health investment, GDP and health investment, as well as GDP and highways. Additionally, there exists a bidirectional causal relationship between rainfall and temperature, signifying the interdependence of weather factors. Unidirectional causality is observed from the total mileage of highways to RTCs and temperature.

5.5. Panel ARDL bound cointegration tests

5.5.1. Results in the short term

The application of the PMG estimation method necessitates the fulfillment of cointegration relationships. The main advantage of PMG estimation is that it can reduce the impact of endogenous problems, such as reverse causality or being affected by other variables.

Table 10 presents the results of the short-term correlation analysis, revealing the significant associations between rainfall, temperature, and health investment with RTCs. Rainfall and temperature exhibit short-term negative correlations with RTCs, and these correlations attain statistical significance at levels of 10 % and 5 % correspondingly. Specifically, the average annual rainfall increased by 1 mm and RTCs decreased by 0.103. It is notable that the short-term impact of rainfall contradicts the findings of Xing's study on Hong Kong [47]. On one hand, rainfall has the potential to modify traffic volumes and patterns, thereby reducing the occurrence of accidents [59]. Road users may opt to postpone or cancel their journeys on rainy days, thereby reducing their exposure to potential risk. This pattern has been corroborated by Cheng [16] in the context of injury accidents in San Francisco, where it was observed that the number of motorcyclists was limited under adverse weather conditions. On the other hand, the presence of slippery road surfaces

Table 6
Results of the Pesaran CADF panel unit root test.

	P value	Results	Diff_Pvalue	Results
InRTC	0.024**	stability	0.000***	stability
InRF	0.001**	stability	0.000***	stability
InTEM	0.000***	stability	0.000***	stability
InGDP	0.885	unstability	0.001**	stability
InHI	0.520	unstability	0.000***	stability
InRoad	0.214	unstability	0.000***	stability

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 7
Results of the Kao cointegration test.

KaoTest	Statistic	P value
Augmented Dickey-Fullert	4.9199	0.000***

*p < 0.05, **p < 0.01, ***p < 0.001.

Table 8
Results of the Pedroni cointegration test.

Pedronitest	Statistic	P value
Modified Phillips-Perron t	6.601	0.000***

*p < 0.05, **p < 0.01, ***p < 0.001.

Table 9
Results of the panel VECM Granger causality test.

Variables	d.lnRTC	d.lnRF	d.lnTEM	d.lnGDP	d.lnHI	d.lnRoad	ECM
d.lnRTC		−0.063 (0.163)	−0.029 (0.865)	−0.034 (0.740)	−0.385** (0.0002)	−0.1006* (0.017)	−0.186* (0.032)
d.lnRF	0.009 (0.707)		−0.628*** (0.000)	0.062 (0.705)	−0.071 (0.435)	−0.030 (0.158)	−1.024*** (0.000)
d.lnTEM	0.0143 (0.206)	−0.065** (0.005)		−0.120 (0.106)	0.0142 (0.786)	−0.036* (0.026)	−0.642*** (0.000)
d.lnGDP	−0.008 (0.469)	−0.028 (0.263)	−0.047 (0.586)		0.190** (0.003)	0.089*** (0.000)	0.161** (0.003)
d.lnHI	−0.129** (0.003)	−0.015 (0.763)	−0.198 (0.182)	0.738*** (0.0006)		0.016 (0.853)	−0.383*** (0.000)
d.lnRoad	−0.043 (0.052)	0.021 (0.232)	−0.121 (0.170)	0.301** (0.019)	0.043 (0.414)		−0.159 (0.086)

p value in parentheses, *p < 0.05, **p < 0.01, ***p < 0.001.

Table 10
Results of short-run estimations.

	Coef.	Std.Err.	z	P>|z|
ECT	−0.256	0.056	−4.61	0.000***
lnRF	−0.103	0.058	−1.76	0.079*
lnTEM	−1.004	0.461	−2.18	0.029**
lnGDP	−0.277	0.241	−1.15	0.249
lnHI	−0.494	0.130	−3.81	0.000***
lnRoad	−0.176	0.169	−1.04	0.299

*p < 0.05, **p < 0.01, ***p < 0.001.

and reduced visibility prompts drivers to exercise greater caution, thereby minimizing the risk of accidents [60]. Therefore, it is necessary for the government to enhance the deployment of warning signs for severe weather conditions, to raise the awareness of vulnerable populations and advocate for a reduction in travel under severe weather.

Meanwhile, temperature exhibits a negative correlation with RTCs, with a 1 % increase in temperature resulting in more than a 1 % decrease in RTCs. This finding diverges from the findings of Ali's study conducted in Pakistan [53]. One plausible explanation for this phenomenon is that temperature also curtails the exposure of road users and reduces traffic flow on major roads and highways. In addition, the provision of a comfortable temperature in vehicles can enhance driving performance [61]. Presently, vehicle configurations have been upgraded to include air conditioning systems, enabling drivers to adjust the temperature in the vehicle to a comfortable level, thereby mitigating driving fatigue induced by heat. Therefore, it is necessary to optimize automotive intelligent

Table 11
Results of long-run estimations.

	Coef.	Std.Err.	z	P > z
lnRF	0.103	0.047	2.17	0.030**
lnTEM	2.858	0.136	21.01	0.000***
lnGDP	0.359	0.098	3.67	0.000***
lnHI	−0.355	0.045	−7.83	0.000***
lnRoad	−0.476	0.071	−6.75	0.000***

*p < 0.05, **p < 0.01,***p < 0.001.

systems, which can automatically regulate the temperature to align with the human body's comfort range.

Finally, in this study, a significant negative correlation was observed between local health investment and RTCs at a 1 % level of significance. The estimation coefficient indicated that RTCs decreased by 0.494 % in response to a 1 % increase in health investment. Therefore, enhancing health investment can effectively curb RTCs and ensure the safety of road users. This finding is consistent with the research conducted by Boniface [62], thereby reinforcing its validity. Therefore, it is necessary for the government to optimize medical facilities and enhance the capabilities of healthcare professionals in order to reduce the mortality and disability rates among severely injured individuals [63]. Razzak [64] confirmed that trauma centers and efficient trauma teams can reduce the death of injured people.

The results of long-term estimations are shown in Table 11. Over the long term, a 1 % increase in rainfall was found to correspond to a 0.103 % increase in RTCs. This positive relationship between rainfall and RTCs aligns with the findings of Villarini [25]. Prolonged periods of rainfall can lead to road erosion and associated infrastructure damage [65]. Simultaneously, inadequate response from the transportation department during rainfall events can easily result in road congestion and a series of accidents. Therefore, it is necessary to optimize the road management system to reduce RTCs, which can be achieved through measures such as traffic flow control [41].

Temperature leads to an increase in RTCs over the long term, consistent with previous studies [33]. The estimated coefficient revealed that a 1 % increase in temperature led to a more than 2.858 % increase in RTCs. To enhance the environment and improve traffic safety, the government can implement additional measures to mitigate global warming in the future, such as expanding forested areas. Over the long term, extreme heat not only affects the physical condition of drivers but also contributes to the deterioration of road infrastructure, potentially increasing the risk of collisions [66]. Moreover, continuous exposure to extremely high temperatures can result in increased tire pressure and subsequent tire ruptures [31], thereby elevating the risk of collisions. In order to reduce the risk of road damage, we recommend increasing the exploration of roads and related infrastructure at high temperatures.

Remarkably, with each 1 % increase in GDP, the occurrence of RTCs experienced a significant rise of 0.359 %. This finding reveals a counterintuitive relationship between the level of economic development and the state of road safety, which diverges from the conclusions drawn in a previous study conducted in China [41]. De la Fuente [67] discovered that, during periods of economic prosperity, while the number of fatalities resulting from accidents was effectively suppressed, the incidence of injuries increased. This phenomenon can be attributed to two factors. Firstly, the prevalence of reckless driving tends to surge amidst economic growth [68], thereby elevating the risk of accidents. Secondly, economic progress fosters urbanization and enhances the mobility of road users, thus burdening the road traffic system [69]. To mitigate the occurrence of RTCs, it is necessary to enhance collaboration among various governmental ministries, including those responsible for transportation, public health, and information dissemination.

In contrast, there exists a negative correlation of 0.1 % between the total mileage of highways and RTCs, which aligns with the findings of Besharati's study conducted in Iran [70]. Specifically, a 1 % increase in the total mileage of highways corresponds to a 0.476 % reduction in RTCs. One plausible explanation for this phenomenon is that highways possess superior technical characteristics and exhibit greater traffic capacity. Calvo-Poyo [44] highlighted that the fatality rate on expressways is lower than that on conventional roads, thereby underscoring the road safety advantages associated with expressway construction. Therefore, it is necessary to expand the national highway network and optimize the road management system. Notably, the implementation of measures such as enhancing traffic warning signs and intensifying inspections of accident-prone roads can significantly contribute to the reduction of RTCs [13].

There appears a negative correlation between health investment and RTCs in the long term. A 1 % increase in health investment results in a reduction of RTCs by 0.355 %. This finding is corroborated by Sun's study on China [71]. Similarly, Castillo-Manzano [72] analyzed data from 27 EU countries and identified health expenditure as a pivotal factor in mitigating traffic fatalities. Therefore, it is necessary for governments to continue to enhance medical expenditure and implement advanced rescue procedures to appropriately allocate medical resources. Kasem [73] examined the characteristics of traffic fatalities and the allocation of medical services, revealing that the establishment of a triage system can alleviate overcrowding during post-rescue operations for injured patients.

6. Conclusions

Over the past decade, severe weather events have occurred with increasing frequency, warranting attention to the influence of weather factors on RTCs. To improve the environment and improve traffic safety, the Chinese government actively formulated environmental policies to reduce the occurrence of adverse weather. At the same time, China's investment proportion in healthcare expenditure and transportation construction is constantly increasing. However, despite these efforts, China's RTCs remain higher than other Western countries. By utilizing panel data from China spanning from 2006 to 2021, this study delves into the impact of weather factors on RTCs in China. The objective is to expand the literature on road traffic safety in China, provide a basis for traffic control, and provide guidance for road safety improvement strategies under adverse weather conditions. In addition, the findings pertaining to the effects of weather are generalizable and can be applied to other regions with comparable climatic conditions.

The VECM was employed to determine the long-term causal relationship of RTCs. Short-run unidirectional causality was observed from the total mileage of highways to RTCs; and the total mileage of highways to temperature. Long-run causality was bi-directional between RTCs and health investment; GDP and health investment; GDP and the total mileage of highways; rainfall and temperature. The ARDL approach was utilized to analyze the long-term equilibrium and short-term interactions among these variables. Notably, the short-term and long-term effects of weather factors exhibited differences, indicating a lag in the impact of weather factors on RTCs [33]. Specifically, rainfall and temperature were found to reduce RTCs in the short term, which deviates from previous studies conducted in China [42–44]. This discrepancy may be attributed to reduced travel during inclement weather conditions and increased vigilance among road users. Based on these findings, the government can formulate pertinent road policies, such as enhancing early warning systems for severe weather events. In the long run, it was confirmed that both rainfall and temperature contribute to an increase in RTCs, which aligns with previous research [45]. Specifically, a 1 % increase in rainfall and temperature led to a corresponding increase in RTCs by 0.103 % and 2.858 %, respectively. Therefore, the government should devise comprehensive environmental policies aimed at mitigating the occurrence of severe weather, such as expanding forested areas. Additionally, optimizing the road traffic safety risk management system and bolstering road maintenance efforts are necessary. The rise in GDP promotes an increase in RTCs, whereas health investment serves to reduce them. Hence, it is crucial for the government to foster coordination among various departments, including transportation and public health, and allocate medical resources appropriately. Moreover, expanding the total mileage of highways can effectively curb the number of RTCs. To ensure road safety, it is necessary to expand the highway network and strengthen the construction of road network management systems, such as increasing the deployment of speed cameras and fluorescent warning signs.

The caveat of this study is that the raw data used was from meteorological stations. Usually, these weather stations may be located in remote areas. Therefore, the measured precipitation and temperature values may have some differences from the standard values of the province. In addition, this study had some limitations. (a) Despite the extensive collection of macro data to support the study, the analysis only considered a limited number of indicators. (b) The study solely relied on annual data, neglecting the inclusion of more subtle data such as monthly or annual data. (c) The data collected spanned from 2006 to 2021, which only captures 16 years of changes in China. (d) There may exist unobserved confounding factors, including but not limited to severe weather conditions and legal factors. Accounting for these confounding factors could potentially change the obtained results.

The number of road accidents and resulting casualties can be affected by various factors. To further explore the impact of weather factors on fatal traffic accidents, it is necessary to gather additional data from other countries. This will enable a comprehensive analysis of the differential effects of weather factors on the number of road traffic accidents, casualties, and direct economic losses. Subsequently, a comparative analysis can be conducted to compare the differences between China and other countries.

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Data availability statement

The raw data for this study came from different public databases, and all research data will be made available on request. The data of temperature was from the National Center of the United States for Environmental Information https://www.ncei.noaa.gov/data/global-summary-of-the-day/archive/, the rainfall data came from the Meteorological Data Center of the China Meteorological Administration http://data.cma.cn/, and other data can be found at China Statistical Yearbook https://www.stats.gov.cn/sj/ndsj/.

Ethics statement

This study was reviewed and approved by School of Management, Chongqing University of Technology.

Review and approval by an ethics committee was not needed for this study because it used publicly available data, did not involve animal or human clinical trials, and was not unethical.

Informed consent was not required for this study because the data used in this study is from publicly available databases and is legally obtained without causing harm to the subjects, and does not involve sensitive personal information or commercial interests.

CRediT authorship contribution statement

Xiping Zou: Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Lilu Sun:** Writing – review & editing, Writing – original draft. **Tian Lan:** Methodology. **Chengpeng Fan:** Data curation. **Shan Liu:** Data curation. **Hui Zhao:** Writing – review & editing. **Jinlong Qiu:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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