How rainfalls influence urban traffic congestion and its associated economic losses at present and in future: taking cities in the Beijing-Tianjin-Hebei region, China for example?

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Abstract
Traffic congestion is one of serious problems in cities; rainfalls would exacerbate traffic congestion, and thus result in huge economic losses. However, limited studies focused on how rainfalls influenced traffic congestion and its associated economic losses. Based on detailed hourly data, we estimated how traffic congestion index (TCI) changed with different rainfall intensities in the Beijing-Tianjin-Hebei (BTH) region, and we also explored their economic losses. The results illustrated that all cities presented the similar trend of daily traffic congestion, and morning peak occurred 2 h later on holidays than workdays. Rainfall had significant impacts on traffic congestion for most time windows, except midnight. Traffic congestion increased with rainfall intensities, but smaller cities were more vulnerable to rainfall intensity than megacities. Rainfalls led to 0.95 billion yuan of extra economic losses in 2019, 38% of which occurred under heavy rainfalls. Traffic congestion in 2019 caused a total economic cost of 30.08 billion yuan in the BTH region (0.4% of its GDP), including the recurrent cost and economic losses due to rainfalls; besides, the social cost and direct cost contributed the same share of 49.5%, with 1% from the environmental costs. Considering future urban development and climate change, it is beneficial to establish the climate-resilient transportation system for avoiding future serious traffic congestion as well as huge economic losses in future.

Keywords rainfall · traffic congestion · economic losses · climate change · the Beijing-Tianjin-Hebei region (BTH)

1 Introduction
Although global cities only covered 0.63% of global terrestrial area, 55% of global people lived there and 80% of economic activities occurred there (Liu et al. 2018). More convenient conditions attracted a huge number of people immigrating into cities, and thus global urban area has been expanding since last a few decades (Li et al. 2020). This increasing trend has been continuing; it was reported that 68% of global people would live in cities
by 2050 and global urban area would expand to 3.6 million km² by 2100 (Gao and O’Neill 2020). Nevertheless, growing urban area and urban population have resulted in an increase in intra-city commuting distance and commuting population (Yan et al. 2022; Zhu et al. 2022), and thus brought great challenges to local urban transportation system, especially traffic congestion. Consequently, traffic congestion at present turns to be a serious problem in cities, especially in megacities and populated cities (Dadashova et al. 2021).

Traffic congestion can greatly increase travel time and fuel consumption, which lead to a great deal of economic costs (Chen et al. 2020; Litman 2013; Winston and Langer 2006). For example, traffic congestion in the USA led to 8.8 billion more hours and 3.3 billion more gallons of oil consumption in 2017, which totaled to 23.7 billion dollars of economic costs (Schrank 2019); the total economic costs of traffic congestion could amount to 0.9% and 1.3% of their GDPs in Germany and France (Nash 2003).

Besides, traffic congestion can result in serious air pollution and huge greenhouse gas emissions, with about 2–4 folds of CO, HC, and NOx emissions than normal levels (Sjodin et al. 1998; Sun et al. 2022); moreover, traffic congestion at peak hours could lead to 14.3–30.4% of more pollutant emissions (Wen et al. 2020). Therefore, it is of great significance to pay more attention to traffic congestion and its associated economic losses.

Climate conditions would have some impacts on local traffic systems, and bad weather (like rainfall) could cause more serious traffic congestion (Papakonstantinou et al., 2020). Due to slippery roads and worse visibility, drivers have to control car speed and keep larger safe headway on rainfall days in order to avoid traffic accidents (Bi et al. 2022; Zhang et al. 2021), resulting in less traffic capacity (Ivey et al. 1975; Mathew and Pulugurtha 2022); thus, cities tend to be more congested in rainfall days. Meanwhile, people would be undesirable to travel outdoors if not necessary and thus there is a relatively smaller traffic volume on rainy days, especially on holidays (Alhassan and Ben-Edigbe, 2010). Hence, rainfall has a significant impact on traffic congestion within cities. Growing bodies of studies have pointed out that light rainfall can reduce 2–13% of freeway speed and 4–10% of freeway capacity, compared with sunny days; even worse, they could increase to 17% and 30% under heavy rainfalls (Smith et al. 2004). Therefore, heavy rainfalls would cause more serious traffic congestion. Global climate change would bring more intensive extreme events in future (like more heavy rainfalls) (Guhathakurta et al. 2011), and it was estimated that China will face 2–3 times more extreme rainfall events due to climate change (Wang et al. 2020a).

Combined urban development, population increase, and more extreme rainfalls, cities will undoubtedly and inevitably face increased traffic burdens and more serious traffic congestion in future, leading to more economic losses (Kc et al. 2021). Hereby, it is significant to explore how rainfall influences traffic congestion and its associated economic losses, especially considering future climate change.

Previous studies have already achieved a lot on traffic congestion in cities, like their influences, social and economic costs, mitigation practices, and so on (Guo et al. 2015; Sweet 2014). However, these studies were mainly based on field investigation in specific cities (Ali et al. 2014), and it was hard to explore their differences among cities. Thanks to the development of big data, traffic congestion can be evaluated by Taxis’ GPS trajectory data (Kan et al. 2019) and car-sharing data (Sun et al. 2018). Thus, some websites (like AutoNavi Map) provided some valuable traffic congestion information, based on their travel data. Based on data from the AutoNavi Map, Li et al. (2019) explored how urban landscape influenced traffic congestion. In spite of some achievements, limited studies focused on exploring differences of traffic congestion among cities, as well as their associated economic costs. Besides, it is also highly urgent to study how rainfalls influence urban traffic congestion among cities at present and in future.

As a highly populated area, the Beijing-Tianjin-Hebei region (BTH) is facing serious traffic congestion; traffic congestion in Beijing, one of the most congested cities in China, resulted in 58 billion yuan of economic losses in 2010 (Chen et al. 2020; Litman 2013; Winston and Langer 2006). More importantly, rainfall will increase travel time and energy consumption compared with recurrent traffic congestion (Kc et al. 2021), leading to extra socio-economic costs in the BTH region. For example, the extreme rainfall event on July 21st in 2012 caused transportation paralyzed in Beijing, leading to a total economic loss of 10 billion yuan (Su et al. 2015). Consequently, estimating the economic costs of traffic congestion due to rainfall is beneficial for sustainable urban transportation (Fortunato et al. 2014). Thus, it is significant to explore how rainfalls influence traffic congestion and its associated economic losses in the BTH region at present and in future. However, there was no such studies focused on above issues in the BTH region, and thus our study aimed to bridge above gaps, based on detailed hourly traffic congestion data from the AutoNavi Map. More detailed, we aimed (1) to illustrate their differences of urban traffic congestion among cities and among time windows in the BTH region; (2) to explore how rainfall influences traffic congestion there; (3) to estimate the recurrent traffic congestion cost and the extra economic loss due to rainfall in the BTH region, comprising direct economic, social, and environmental costs; (4) and finally to discuss how climate change influences traffic congestion and its associated economic losses in future.
2 Materials and methods

2.1 Study area

The Beijing-Tianjin-Hebei region is located in North China and covers a total area of 0.21 million km² (Fig. 1a, b). It is characterized by the temperate monsoon climate, and its annual rainfall can amount to 300~700 mm, 90% of which is concentrated in summer (Fig. 1c). In the BTH region, there are two megacities of Beijing and Tianjin and 11 prefecture-level cities in Hebei, including Shijiazhuang, Baoding, Cangzhou, Tangshan, Qinhuangdao, Handan, Langfang, Xingtai, Zhangjiakou, and Chengde. The total urban population of the BTH region was 51.44 million, and its total amounts of private cars were 21.59 million. However, there existed great differences among cities in the BTH region (Fig. 1d), considering population, traffic conditions, and so on. Due to the limited data, we only focused on 10 cities in the BTH region, except Xingtai, Hengshui, and Chengde.

2.2 Data and materials

Thanks to the rapid development of big data, websites (like AutoNavi Map) can provide monitoring data to present traffic conditions. In the website of AutoNavi Map, its traffic congestion index (TCI) is defined as the ratio of the travel time in the real flow and the travel time in the free flow; thus, TCI can be used to present traffic congestion, with a higher value being more congested. The AutoNavi Map (https://report.amap.com/diagnosis/index.do) has provided the traffic congestion data of 101 Chinese cities since 2014, and thus we obtained hourly TCI data in 2019 for our study area. Besides, we also obtained the traffic volume from the Beijing Transport Development Report, including daily proportion of private cars on road, daily total time of each car on road, and proportion of cars on road at different time windows.

Hourly rainfall data in 2019 was obtained from China Meteorological Data Service Center, as well as future rainfall data under future scenario of RCP 4.5. According to
China Meteorological Administration, rainfalls were divided into 3 different categories, including sunny (no hourly or daily rainfall), light rainfall (0 ~ 1.5 mm of hourly rainfall or 0 ~ 10 mm of daily rainfall), and heavy rainfall (hourly rainfall > 1.5 mm or daily rainfall > 10 mm). According to human activities in our study area, each day can be divided into five different time windows as follows: the morning peak time of 7:00–9:00 (MP), the working time of 9:00–17:00 (WT), the evening peak time of 17:00–19:00 (EP), the night economic time of 19:00–23:00 (NE), and the midnight time of 23:00–7:00 (MN). Furthermore, we also obtained some socio-economic data, including an employed population of secondary and tertiary industries in the urban area, urban resident gasoline consumption, and car ownership per hundred people. The detailed data source was presented in Table 1.

2.3 Methods

Figure 2 presented our research framework and it included three main steps as follows. (1) Rainfall and traffic congestion: we used the Kruskal-Walls testing method to explore the relationship between rainfall and traffic congestions for different cities in the BTH region, considering different time windows and different rainfall intensities. (2) Costs of traffic congestion: the total economic costs of traffic congestion (excluding new energy vehicles) were compromised by direct economic, social and environmental costs. In our research, the economic cost of traffic congestion on sunny days was defined as the recurrent cost. Rainfall would result in more serious traffic congestion and thus lead to extra economic losses on rainy days; therefore, the total economic costs on rainy days include the recurrent cost and the extra economic losses. (3) Future traffic congestion: future traffic congestion was discussed under future scenario of RCP 4.5, considering its rainfall frequency and rainfall intensity. More detailed methods were illustrated as follows.

2.3.1 Traffic volume

Traffic volume referred to the total commuters on road, and it can be estimated by

\[ V_t = P \times CC \times TP \times TT \times b_t \]  

(1)

where \( V_t \) referred to the traffic volume at time \( t \); \( P \) and \( CC \) were the number of employed workers and private cars per 100 people; \( TP \) was the travel proportion of private cars, and it was 0.77 for workdays and 0.704 for holidays; \( TT \) was the daily frequency on road for each car, and it was 3.33 times on workdays and 3.2 times on holidays; \( b_t \) was hourly proportion of cars on road at the time window of \( t \). The Beijing Transportation Annual Report 2020 (http://www.bjtjc.org.cn/) presented \( TP \), \( TT \) and \( b_t \) in Beijing, and we assumed that these values were the same in other cities of the BTH region. Besides, this report only presented the \( b_t \) on workdays, and we estimated \( b_t \) on holidays, with the help of traffic congestion data and the travel proportion on holidays (more detailed information see SI).

2.3.2 The direct economic cost and its losses due to rainfall

The direct economic cost referred to the expenditure of more gasoline consumed due to rainfalls, compared with the free flow. Thus, we can estimate the direct economic cost by following steps:

| Table 1 The main data and data source in this study |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Data                             | Content                                | Resolution       | Usage                                | Source                                      |
| Traffic congestion               | Traffic congestion index                | Hourly           | Congestion condition                 | AutoNavi Map: https://report.amap.com/diagnosis/index.do |
| Cars on road                     | The daily proportion of private cars on road to all private cars; The total time of each car on road for each day; The proportion of cars on road at different time windows | Statistical data | Traffic volume                        | http://www.bjtjc.org.cn/List/index/cid/7.html |
| Socioeconomic data               | Employed population of secondary and tertiary industries in the urban area Urban resident gasoline consumption; Cars per one hundred people The trade price of carbon | Statistical data | Traffic congestion cost               | China City Statistical Yearbook 2018; Beijing Statistical Yearbook 2018; Tianjin Statistical Yearbook 2018; Hebei Statistical Yearbook 2018; http://www.tanpaifang.com/ |
| Meteorological data             | Hourly rainfall Future rainfall under RCP 4.5                  | Hourly           | Influence of rainfall on traffic congestion Impact of climate change on traffic congestion | China Meteorological Data Service Center: http://data.cma.cn/ National Climate Center, China Meteorological Administration |
(1) The gasoline consumption in workday and holiday

We collected the total gasoline consumption in each city (TGc), but the gasoline consumption differed significantly between workdays and holidays, due to their different travel volumes on road. As a result, the ratio ($R$) of gasoline consumption on workdays and holidays can be estimated based on numbers of holidays or workdays, private car travel proportion, and daily frequency on road for each car between holidays and workdays (Eq. (2)). Therefore, the gasoline consumption on workdays or holidays can be estimated based on the value of $R$:

$$ R = \frac{D_W \times TP_W \times TT_W}{D_h \times TP_h \times TT_h} \tag{2} $$

Here, $D_W$, $D_h$ were the number of workdays and holidays; $TP_W$ and $TP_h$ were the travel proportion of private cars of workdays and holidays; $TT_W$ and $TT_h$ were the daily frequency on road for each car of workdays and holidays.

(2) Daily recurrent gasoline consumption on workdays or holidays

Total gasoline consumption was made up of recurrent gasoline consumption under normal traffic conditions (namely sunny days) and extra gasoline consumption due to rainfalls. Since great variations of the proportion of cars on the road ($b_t$) existed at different times, the hourly recurrent gasoline consumption can be estimated by $DGc \times b_t$, with $DGc$ being daily average recurrent gasoline consumption. Furthermore, extra gasoline consumption due to rainfall can be calculated by $DGc \times b_t \times ITCI_t$, while $ITCI_t$ was the growth percentage of TCI under rainfall. Therefore, gasoline consumption on workdays or holidays (Gc) was the sum of hourly recurrent gasoline consumption and hourly extra gasoline consumption (Eq. (3)), and we can estimate the $DGc$ as Eq. (4) thanks to detailed rainfall data.

$$ Gc = \sum_{t=1}^{24} ((DGc \times b_t) \times (m + ITCI_t \times m_1)) \tag{3} $$

$$ DGc = \frac{\sum_{t=2}^{24} (b_t \times (m + ITCI_t \times m_1))}{Gc} \tag{4} $$

Here, Gc was gasoline consumption on workdays or holidays; DGc was daily average recurrent gasoline consumption, $b_t$ was the hourly proportion of cars on road at $t$ moment, $m$ was the total hours of $t$ moment on workday or holiday and the $m_1$ was the total rainfall hours at $t$ moment.

(3) The direct economic cost and its losses due to rainfall

The recurrent gasoline consumption represented gasoline consumption under normal traffic conditions; therefore, with hourly average TCI under normal traffic conditions and gasoline price, we can estimate the direct economic cost of recurrent traffic congestion (Eq. (5)) and also its direct economic losses due to rainfalls (Eq. (6)).

$$ Dec_t = \frac{DGc \times bt}{TCI_t} \times (TCI_t - 1) \times G \tag{5} $$
of gasoline, $C$ was the carbon trade price in 2019 for each city.

### 2.3.5 The total economic cost and the total economic losses due to rainfall

The total economic cost, namely the recurrent traffic congestion cost, was compromised by the direct economic, social, and environmental costs, and it can be estimated by Eq. (11).

$$\text{Tec}_t = \text{Dec}_t + \text{Sec}_t + \text{Eec}_t$$  \hspace{1cm} (11)

As the same, the total economic losses due to rainfall can be estimated by Eq. (12), including the direct economic, social, and environmental losses:

$$\text{RTec}_t = \text{RDec}_t + \text{RSec}_t + \text{REec}_t$$  \hspace{1cm} (12)

### 2.3.6 Future traffic congestion and their economic costs

The future traffic congestion is estimated by the relationship between traffic congestion and rainfall intensities, as well as their future economic costs. In this research, we collected the rainfall frequency and rainfall intensity in the BTH region for the period of 2080–2098 based on the dataset of high-resolution combined dynamical and statistical downscaling for multivariable. The regional climate model system can be the best dynamical downscaling tool for obtaining long-term climate change data at the regional scale. Therefore, this dataset was developed by a regional climate model system RegCM4.4 and nested five global climate models in CMIP5 including EC-EARTH, CSIRO-Mk3-6-0, MPI-ESM-MR, HadGEM2-ES, and NorESM1-M. Although this dataset has been proved it can well reproduce the mean states of weather conditions variables, all extreme temperature indices, and most of the extreme precipitation indices, their biases of interannual variability were mostly inherited from the regional climate model data (Han et al. 2019).

### 3 Results

#### 3.1 Traffic congestion among cities in the BTH region

All cities presented the similar trend of daily traffic congestion in the BTH region, with two summits at morning peak and evening peak (Fig. 3). For all these cities, their TCIs at midnight were highly similar at around 1.1; however, their traffic congestion presented great differences among cities and among time windows (more detailed information in SI). Serious traffic congestion mainly occurred at morning peak and evening peak, with their TCIs larger than 1.5 in all cities.
of the BTH region. Besides, the morning peak on holidays was about 2 h later (around 10 am) than workdays (around 8 am) in all these cities, while their evening peak on holidays were highly similar with that on workdays. Longer distance and more time were consumed between their home and work-places in Beijing, leading to the highest job-housing balance value (Fig. 3k and SI); thus, more serious traffic congestion occurred in Beijing, and its TCIs can amount to 2.0 at morning peak and evening peak on workdays, much higher than other cities. Despite lower job-housing balance result, both Baoding and Cangzhou also faced serious traffic congestion at morning peak and evening peak on holidays. Beijing and Tianjin presented significant differences of traffic congestion between holidays and workdays, while remaining cities did not present clear differences between holidays and workdays. More detailed, Beijing and Tianjin faced more serious traffic congestion at morning peak and evening peak on workdays than holidays, while their TCIs at other time windows were highly similar both on workdays and on holidays. Qinhuangdao, a hot tourism destination, presented a little more congested on holidays than workdays, especially at the work time, because there were more tourists on holidays.

3.1.1 Rainfall and traffic congestion

Rainfall had a significant influence on traffic congestion for most time windows, and heavy rainfalls lead to more serious traffic congestion (Fig. 4a and Fig-SI 3), especially at morning peak and evening peak. However, traffic congestion at midnight did not present significant differences between rainy days and sunny days, it was mainly because only a

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Fig. 3 The hourly TCI in cities of the BTH region in 2019. (Note: BJ, Beijing; TJ, Tianjin; SJZ, Shijiazhuang; BD, Baoding; CZ, Cangzhou; HD, Handan; LF, Langfang; QHD, Qinhuangdao; TS, Tangshan; ZJK, Zhangjiakou, the red line represents workdays, the blue line represents holidays, k, the relationship between TCI and Job-housing balance)
few cars were on road at midnight. Besides, light rainfalls led to about the TCI increase of 36% on workdays at morning peak and evening peak, while it could amount to 60% under heavy rainfalls. Despite a little smaller, heavy rainfalls on holidays can lead to 8% higher of its TCI than sunny days. Heavy rainfalls had great impacts on traffic congestion in Beijing, especially at evening peak; however, traffic congestion was more vulnerable to rainfalls in some small and medium-sized cities (like Canzhou and Zhangjiakou). More detailed, their TCIs increased by 3% under rainfalls in Beijing and Tianjin, but their increase of TCI could amount to 5% for the remaining cities, even up to 11% under heavy rainfalls in Zhangjiakou. Traffic congestion in Baoding had been mitigated under rainfalls on holidays, and it was probably because there were fewer cars on road then. Since there was no need to arrive on time on holidays, different urban residents tended to commute outdoors at different times, and thus there was no serious morning peak on holidays.

Fig. 4  Traffic congestion index (TCI) under different rainfall intensities in cities of the BTH region (a: the average level of TCI in the BTH region on workdays (a1) and holidays (a2); b. the TCI in cities of the BTH region on workdays (W) and on holidays (H))
especially in small cities. However, most urban residents
tended to back home around 6–7 pm, and thus evening peak
existed most cities on holidays, lower than that on workdays.
Besides, less demand for travel existed on rainy holidays for
some urban residents, and thus no significant traffic peak
existed on rainy holidays.

3.1.2 The economic cost of recurrent traffic congestion

The annual economic cost of recurrent traffic congestion
totaled to 30.08 billion yuan in the BTH region; besides,
the daily economic cost on workdays was about 90.6 million
yuan and it was about 40% higher than holidays (Fig. 5a).
More detailed, both the social cost and direct cost were 29.81
billion yuan (49.5%), due to recurrent traffic congestion. In
spite of being 1%, the annual environmental cost of recurrent
traffic congestion still amounted to 0.27 billion yuan. Beijing
contributed the largest share (66%) to the total economic
cost of recurrent traffic congestion in the BTH region, due to
its higher salaries, larger population, and more serious traffic
congestion; besides, its daily total economic cost on holidays
were only 65% of that on workdays, with about 39 and 60
million yuan, respectively. The recurrent traffic congestion
in Tianjin also resulted in large economic costs, with its
daily costs of 12.2 million yuan on holidays and 16.3 mil-
lion yuan on workdays. Moreover, great differences of total
economic costs existed among different time windows. The
only 2 h of morning peak (7:00–9:00) contributed to 33%
of the total economic costs on workdays, but its percentage
dramatically dropped to 9% on holidays. Traffic congestion
at work time on holidays contributed to the largest share
(53%) of its daily total economic cost, much higher than
that on workdays. Besides, their percentages of remaining
time windows did not present significant differences between
holidays and workdays, but their economic costs decreased a
lot on holidays due to less traffic congestion then.

3.1.3 The economic losses of traffic congestion due
to rainfalls

Traffic congestion due to rainfalls led to a total economic loss
of 950 million yuan in the BTH region; therefore, the total

![Fig. 5](image)

*Fig. 5* The daily economic cost of recurrent traffic congestion in the BTH region in 2019 (the daily recurrent costs on workdays and holidays (a) and their compositions for different cities (b) and different time windows (c))
economic costs of traffic congestion could amount to 31.03 billion yuan, accounting for 0.4% of its GDP in 2019. Rainfalls on workdays totally led to the economic losses of 864.1 million yuan for traffic congestion. Only 27% of rainfalls were heavy rainfalls, but they contributed to 38% of total economic losses due to rainfalls; more detailed, each heavy rainfall event could result in the economic losses of 7–20 million yuan more than each light rainfall event (Fig. 6a and b). If it rained for whole one day, daily economic losses in Beijing could amount to 16–30 million yuan on workdays and 4 million yuan on holidays. Zhangjiakou was highly vulnerable to rainfall and thus rainfalls led to larger portion of its annual total economic costs due to traffic congestion. Therefore, it is of high importance to explore how to mitigate economic losses of traffic congestion due to rainfalls in future, especially for these vulnerable cities.

Heavy rainfalls on workdays had larger impacts on economic losses of traffic congestion than light rainfalls, especially at evening peak (Fig. 6c and d). However, different rainfall intensities did not have significant influences on economic losses at Worktime and at midnight, as well as at morning peak on holidays, since there were limited external activities at these times. Rainfalls at morning peak on workdays could lead to a total economic loss of 12–20 million yuan, following by 7–15 million yuan at evening peak. It was worth noted that rainfalls had much larger influences at night economic time than other time windows, especially under heavy rainfalls; it was because it could turn to be highly congested at night economic time on workdays when it rained. Therefore, it is of high importance to forecast rainfalls in future to avoid serious traffic congestion and its associated economic losses, especially at workdays.

4 Discussion

4.1 Climate change and traffic congestion

This study examined how rainfalls influenced urban traffic congestion and its associated economic losses in the BTH region; our results illustrated rainfalls would significantly increase traffic congestion, whose economic losses amounted to 950 million yuan in 2019. Except Handan and Zhangjiakou, the frequency of light rainfall in most cities of the whole BTH region would drop (about –1.5%) in future, and Tianjin (–7%) and Tangshan (–7%) present larger reductions (Table 2). With the same population and economic level, less light rainfall in future could lead to a decrease of total traffic congestion costs in the BTH region; however, light rainfall in future can still bring in 38–59 million yuan per day of economic losses due to traffic congestion in Beijing. The frequency of future heavy rainfall would increase by 2.4% in the whole BTH region, especially in the cities of Shijiazhuang, Zhangjiakou, and Handan, and their associated traffic congestion cost would be enhanced. However, future heavy rainfalls could keep a stable level in Beijing and present a reduction in Tianjin (–4%), but they can also bring in large economic costs in these two megacities there.

Extreme rainfalls, defined as the 95th percentile rainfall thresholds (Wang et al. 2021), can not only lead to lower car speed or more traffic accidents but also could be significantly harmful for whole traffic system, including traffic signals, road facilities, and map navigation. For example, the extreme rainfall event on August 2017 had destroyed its electric system in Harris County, Texas, which lead to serious regional traffic congestion (Shield et al. 2021). Extreme rainfalls have also destroyed traffic system in the BTH region and led to serious damages. The extreme rainfall event on July 21st 2012 in Beijing led to a total of 76 people death and 10,660 houses damage; this extreme rainfall event totally led to the economic loss of 11.64 billion yuan, which accounted for 56% of the total economic cost of traffic congestion in Beijing (Hu et al. 2015). What’s more, it was estimated that more extreme rainfalls could occur in the BTH region in future (Shi Ying et al. 2019), which could lead to a huge number of economic losses. Therefore, more attentions and measurements should be gained or applied to solve traffic congestion, especially considering future climate change. For example, better road drainage systems, culvert capacity, and more green areas would benefit to reduce runoffs when extreme rainfalls occur and also be conducive to avoid urban waterlog disaster (Kang et al. 2017; Sun et al. 2019); thus, these strategies would be also conducive to avoid serious traffic congestion, thanks to its higher pumping capacity of roads and tunnels (Hodges et al. 2011; Rattanachot et al. 2015; Taylor and Philip 2015). Furthermore, early warning of rainfalls would also be a great way to conduct some strategies ahead and also to avoid economic losses (Wang et al. 2020b).

4.2 Urban development and traffic congestion

Urban development could have great influences on traffic congestion in cities. Higher population and worse traffic system led to more serious traffic congestion (Sarzynski et al. 2006), and our studies presented the similar result with previous studies (Dadashova et al. 2021; Song et al. 2019). Beijing presented more serious traffic congestion than cities in Hebei Province. More developed cities faced more serious traffic congestion, with larger economic losses. The economic cost of traffic congestion could amount to 0.6% of its GDP in Beijing, higher than the average level of 0.4% in the BTH region; however, it was still a little lower than the economic losses of 0.9–1.5% in developed countries, like the USA, the UK, and Germany (Lasley 2019). Vehicles per capita in Beijing were only 60% of the value in Japan and Germany (more detailed information see SI), but it was still higher than in other cities of the BTH region. Future
urbanization in the BTH region could lead to more vehicles on road, and thus these cities could face more serious traffic congestion and more economic losses in future. However, due to lower fuel energy consumption and less air pollution (Bai et al. 2022; Li et al. 2022), new energy vehicles may offset some costs due to traffic congestion in the BTH region.

More than 50% of economic losses of traffic congestion were caused by occasional events (like serious traffic accidents and extreme climate) in developed countries (like the USA and Australia) (Charles 2005; Chen et al. 2012; Zheng et al. 2020). These serious occasional traffic accidents totally resulted in 1.2 million people’s death all over the world.
Based on other big data (like cell phone signaling data) in example, we aim to estimate more accurate traffic volume and discuss these differences and uncertainties in future. For (like Beijing). Thereby, we should explore this information could also lead to some uncertainties in some large cities gasoline consumption were considered in this study, which fic systems. Besides, only employed population and local BTH region, with their distinct economic levels and traf - detailed different traffic volumes on the road for cities in the cities. It will be of high significance to explore further more our assumption could bring in some uncertainties for other cities and among time windows. Besides, due to limited data, we explored traffic congestion presented two summits at morning peak and evening peak in the BTH region, but there existed great differences among cities and days (Muneera and Karuppanagounder 2022; Rahman et al. 2022). Thanks to the development of big data, our study combined statistic - al data with open and free big data (hourly TCI), and thus we can highlight differences among different time windows, as well as between workdays and holidays. Besides, due to the same calculation method, differences among cities can also be explored due to these free but detailed hourly TCI data. Besides, these free big data can also have further and abroad applications in future studies on urban resistance after serious weather events. Besides, with important information in our research, government could conduct better traffic planning and urban planning to avoid unnecessary economic losses of traffic congestion, especially considering future climate change and urban development. Besides, our study can also provide some information for drivers to avoid serious traffic congestion in advance.

### 4.3 Limitations and future implications

Our study presented how rainfalls influence traffic congestion and their associated economic losses. However, due to limited data and information, there were still some shortcomings in our studies. The travel proportion of private cars and daily frequency on road were different, but it is hard to acquire these important information and data except Beijing. Due to the similar climate condition, we believe that the travel proportion of private cars and daily frequency on road will present the similar value for different cities in the BTH region; with their total car volumes, we can estimate their traffic volumes on road for other cities. However, there existed some differences among cities due to different economic levels and traffic systems, and thus, our assumption could bring in some uncertainties for other cities. It will be of high significance to explore further more detailed different traffic volumes on the road for cities in the BTH region, with their distinct economic levels and traffic systems. Besides, only employed population and local gasoline consumption were considered in this study, which could also lead to some uncertainties in some large cities (like Beijing). Thereby, we should explore this information and discuss these differences and uncertainties in future. For example, we aim to estimate more accurate traffic volume based on other big data (like cell phone signaling data) in future. Besides, we only estimated the traffic congestion cost of traditional motor vehicles. With the promotion of new energy vehicles, new energy vehicles will play an important role in future urban traffic system; thus, we need comprehensively estimate traffic congestion costs of new energy vehicles in future studies. In particular, it is worth to notice that the promotion of new energy vehicles will offset the cost of traffic congestion. Despite some limitations in our study, it is of high importance to explore how rainfall influences traffic congestion in cities and their associated economic losses there. Previous studies estimated traffic congestion mainly based on the statistical data, and they were hard to compare their differences among cities and days (Muneera and Karuppanagounder 2022; Rahman et al. 2022). Thanks to the development of big data, our study combined statistical data with open and free big data (hourly TCI), and thus we can highlight differences among different time windows, as well as between workdays and holidays. Besides, due to the same calculation method, differences among cities can also be explored due to these free but detailed hourly TCI data. Besides, these free big data can also have further and abroad applications in future studies on urban resistance after serious weather events. Besides, with important information in our research, government could conduct better traffic planning and urban planning to avoid unnecessary economic losses of traffic congestion, especially considering future climate change and urban development. Besides, our study can also provide some information for drivers to avoid serious traffic congestion in advance.

### 5 Conclusions

Despite some limited data, we explored traffic congestion in the BTH region and their differences among cities and time windows, based on the big data of TCI from website. Besides, combined with statistical data and meteorological data, we also analyzed how rainfall influenced traffic congestion and its associated economic losses in the BTH region at present and in future. Traffic congestion presented two summits at morning peak and evening peak in the BTH region, but there existed great differences among cities and among time windows. Besides, the first summit on holidays occurred about 2 h later (around 10 am) than workdays (around 8 am). Beijing faced the most serious traffic congestion in the BTH region, and its traffic congestion presented significant differences between holidays and workdays. Rainfall had significant influences on traffic congestion for most time windows (except midnight), and heavy rainfalls resulted in more serious traffic congestion, especially at evening peak. Traffic congestion was more vulnerable to rainfalls in small and medium-sized cities. The

| City | Light rainfall /% | Heavy rainfall /% |
|------|------------------|------------------|
| BJ   | − 1.00           | 0.00             |
| TJ   | − 7.00           | − 4.00           |
| SJZ  | 0.00             | 5.00             |
| BD   | − 2.00           | 0.00             |
| CZ   | − 4.00           | 0.00             |
| HD   | 9.00             | 13.00            |
| LF   | − 5.00           | − 4.00           |
| QHD  | − 4.00           | − 4.00           |
| TS   | − 7.00           | − 1.00           |
| ZJK  | 6.00             | 19.00            |
| JJJ  | − 1.50           | 2.40             |
total economic costs of traffic congestion were nearly 31.03 billion yuan in 2019, including 30.08 billion yuan of the recurrent costs and the 0.95 billion yuan of extra economic losses due to rainfalls. The only 2 h of morning peak contributed to 33% of the total economic costs on workdays, while traffic congestion at work time on holidays contributed to the largest share of its total economic cost on holidays. Heavy rainfalls on workdays had larger impacts on economic losses of traffic congestion than light rainfalls, especially at evening peak. Although there would be fewer rainfalls in the BTH region, future climate change could lead to more economic losses of traffic congestion in Handan and Zhangjiakou. Besides, more strategies should be applied to avoid serious traffic congestion in future, like better road drainage systems, culvert capacity, more green areas, and warning ahead. Besides, the climate-resilient transportation system is also an effective way to avoid serious economic losses in future.

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available due to legal restrictions but are available from the corresponding author on reasonable request.

Code availability The codes for this research work are available from the corresponding author upon reasonable request.

Declarations

Ethics approval This work complied with all the necessary ethical approval processes and consents from all the co-authors before the beginning of the research work.

Consent to participate Consents from all the co-authors were obtained for participating in this study at the beginning of the research work.

Consent for publication Consents from all the co-authors were obtained for publishing this work in the Theoretical and Applied Climatology journal before correspondence.

Competing interests The authors declare no competing interests.

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