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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Research Article

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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, China, 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 hours 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 0.98 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 31.5 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 49.4%, with 1.2% 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.

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 km^2 by 2100 (Gao and O'Neill, 2020; UN, 2018). Nevertheless, this accelerating urbanization and anthropogenic activities have brought great challenges for urban development, such as accelerated demands for affordable housing and well-connected transport system (Guo and Wilson, 2011; Zhang et al., 2003). Consequently, traffic congestion at present turns to be a serious problem in cities, especially for 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 (Lasley, 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); 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 attentions on traffic congestion and its associated economic losses.

Climate condition would have impacts on local traffic systems, and bad weather (like rainfall) could cause more serious traffic congestion (Papakonstantinou et al., 2020). Due to more slippery roads and worse visibility, rainfall can reduce car speed and traffic capacity, and thus it could exacerbate traffic congestion to some degree (Ivey et al., 1975). Compared with sunny days, light rainfall can reduce 2 ~ 13% of freeway speed and 4 ~ 10% of freeway capacity, but they could increase to 17% and 30% under heavy rainfall (FHWA, 2012; Smith et al., 2004). Therefore, heavy rainfalls would cause more serious traffic congestion. Global climate change would bring more intensive extreme weathers in future (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 influence 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; Sarzynski et al., 2016; 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). What's more, the extreme rainfall event on July 21st in 2012 caused transportation paralyzed in Beijing, leading to a total economic loss of 10 billion yuan. Thus, it is of high importance to explore how rainfalls influence traffic congestion and its associated economic losses in the BTH region at present and in future. However, limited studies focused on above issues, 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 influence 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 influence 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 km^2 (Fig. 1a). 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 population of the BTH region was 112.47 million in 2017, and its total amounts of private car were 20.48 million. However, there existed great differences among cities in the BTH region (Fig. 1b), considering their economic level, 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 ~ 1.5mm of hourly rainfall or 0 ~ 10mm of daily rainfall) and heavy rainfall (hourly rainfall > 1.5mm or daily rainfall > 10mm)**. 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.

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.bjtrc.org.cn/List/index/cid/7.html
Socioeconomic data	Employed population of secondary and tertiary industries in the urban area	Statistical data	Traffic congestion cost	China City Statistical Yearbook 2018;
	Urban resident gasoline consumption; Cars per one hundred people			Beijing Statistical Yearbook 2018; Tianjin Statistical Yearbook 2018; Hebei Statistical Yearbook 2018;
	The trade price of carbon			http://www.tanpaifang.com/
Meteorological data	Hourly rainfall	Hourly	Influence of rainfall on traffic congestion	China Meteorological Data Service Center: http://data.cma.cn/
	Future rainfall under RCP 4.5	Daily; 6.25km	Impact of climate change on traffic congestion	National Climate Center, China Meteorological Administration

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 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.

Traffic volume

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

$$V_t = P \times CC \times TP \times TT \times b_t \qquad (1)$$

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.bjtrc.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).

The direct economic cost and its losses due to rainfall

The direct economic cost referred to the expenditure of consumed more gasoline, compared with the free flow. We collected the total gasoline consumption in each city (*TGc*); then, we estimated gasoline consumption on holidays and on workdays (*Gc*), based on their days, travel proportion of private cars and daily frequency on road on holidays and workdays. The total gasoline consumption on workdays or holidays consisted recurrent gasoline consumption and extra gasoline consumption due to rainfall. For hourly recurrent gasoline consumption, it can be estimated by daily recurrent gasoline consumption (*DGc*), hourly proportion of cars on road (b_t), gasoline consumption on workdays or holidays (*Gc*); for hourly extra gasoline consumption due to rainfall, it can be estimated with the increased TCI due to rainfall (*ITCIt*), *DGc*, and b_t. Therefore, with the price of gasoline and total hours of rainfall, we can estimate the direct economic cost of recurrent traffic congestion and also its direct economic losses due to rainfalls (More detailed information see SI).

The social cost and its losses due to rainfall

The social cost referred to the economic costs of extra travel time due to traffic congestion, and it can be calculated with population, travel time, traffic congestion and local salaries for different cities. Therefore, we can estimate the social cost caused by recurrent traffic congestion based on extra travel time, travel volume and hourly salaries for different cities. Besides, the social losses due to rainfall can be estimated by the increase of traffic congestion index, travel volume and their salaries (Detailed information in SI).

The environmental cost and its losses due to rainfall

The environmental cost referred to the economic costs of extra carbon emissions from gasoline consumption due to traffic congestion, and it could be estimated by the carbon price and carbon emission intensity of gasoline. Thus, the environmental losses due to rainfall could be estimated with the increased traffic congestion and carbon emissions (Detailed information in SI).

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

The total economic cost included the direct economic, social and environmental costs; therefore, the total economic cost of recurrent traffic congestion was the sum of direct economic, social and environmental costs caused by recurrent traffic congestion. Besides, the total economic losses due to rainfall included the extra direct economic, social and environmental costs caused by rainfall (Detailed information in SI).

Future traffic congestion and their economic costs

Based on future climate scenario of RCP 4.5, we obtained the rainfall frequency and rainfall intensity in the BTH region for the period of 2080 ~ 2098. Therefore, future traffic congestion can be estimated by the relationship between traffic congestion and rainfall intensities, as well as their future economic costs.

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 hours 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.

3.2 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 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 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.

3.3 The economic cost of recurrent traffic congestion

The annual economic cost of recurrent traffic congestion totaled to 30.23 billion yuan in the BTH region; besides, the daily economic cost on workdays was about 93 million yuan and it was about 41% higher than holidays (Fig. 5a). More detailed, both the social cost and direct cost were 15.1 billion yuan (49.4%), due to recurrent traffic congestion. In spite of being 1.2%, the annual environmental cost of recurrent traffic congestion still amounted to 0.3 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 2/3 of that on workdays, with about 40 and 61 million yuan, respectively. The recurrent traffic congestion in Tianjin also resulted in large economic costs, with its daily costs of 12.5 million yuan on holidays and 16.7 million yuan on workdays. Moreover, great differences of total economic costs existed among different time windows. The only 2 hours 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.

3.4 The economic losses of traffic congestion due to rainfalls

Traffic congestion due to rainfalls led to a total economic loss of 979 million yuan in the BTH region; therefore, the total economic costs of traffic congestion could amount to 31.5 billion yuan, accounting for 0.4% of its GDP in 2019. Rainfalls on workdays totally led to the economic losses of 890.9 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 10–21 million yuan more than each light rainfall event (Fig. 6a and 6b). If it rained for whole one day, daily economic losses in Beijing could amount to 18 ~ 33 million yuan on workdays and 1 ~ 9 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 6d). 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 13 ~ 22 million yuan, following by 8 ~ 17 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 979 million yuan in 2019. Based on future climate data, we found that the frequency of light rainfall would decrease by 1.5% in the BTH region during the period of 2080 ~ 2100, but its heavy rainfall frequency would increase by 2.4% (see SI). However, there existed great differences of rainfall intensities in future among cities in the BTH region. Less rainfalls would occur in some cities (like Tianjin, Langfang and Qinhuangdao), but more heavy rainfalls will occur in Handan and Zhangjiakou in future, whose traffic congestion were highly vulnerable to rainfalls. Therefore, the economic losses due to rainfalls will increase by at least 20% in future, without taking the increase of private cars into account.

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 (Ec, 2011). 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., 2013). What's more, it was estimated that more extreme rainfalls could occur in the BTH region in future (Shi Ying, 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 Philp, 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., 2020; 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 United States, the United Kingdom and Germany (Lasley, 2019; Nash, 2003). 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. Besides, more cars on road could result in more serious air pollution in cities, (Mraihi et al., 2015), which was also a great problem in the BTH region. Therefore, it is of high importance to balance urban development, traffic congestion and air pollution in the BTH region in future.

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 death all over the world (Peden, 2004). With growing urbanization, more vehicles and climate change could lead to more occasional events (especially traffic accident) in the BTH region, with much higher economic losses. Reasonable urban transportation plan can effectively relieve traffic congestion and reduce traffic accidents (Anik et al., 2020; Wang et al., 2020c); therefore, it is of high significance to avoid serious traffic accidents and economic losses in the BTH region, with the help of better traffic plan in future.

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. For example, we only obtained the traffic volume in Beijing, and we used the same proportion for other cities in the BTH region. However, there existed some differences among cities due to different economic levels and different traffic systems, and thus our assumption could bring in some uncertainties. Besides, only employed population and local gasoline consumption was 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. Despite of some limitations in our study, it is of high importance to explore how rainfall influence traffic congestion in cities and their associated economic losses there. With this important information, 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. Conclusion

Despite of 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 statistics 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 hours 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 total economic costs of traffic congestion were nearly 31.5 billion yuan in 2019, including 30.53 billion yuan of the recurrent costs and the 0.98 billion yuan of extra economic losses due to rainfalls. The only 2 hours 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 less rainfalls in the BTH region, future climate change could lead to 20% more of 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.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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.

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.

Author Contributions

Yi Zhou: Conceptualization, Methodology, Software, Validation, Visualization, Writing-Original draft preparation. Sicheng Mao: Methodology, Software. Haile ZHAO: Investigation, Validation. Guoliang ZHANG: Investigation, Validation. Xin CHEN: Investigation, Validation. Yuling JIN: Investigation, Validation. Lin XU: Resources. Zhihua Pan: Resources, Supervision, Funding acquisition. Pingli AN: Resources, Supervision. Fei Lun: Conceptualization, Supervision, Writing - Review & Editing.

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Figures

Figure 1

The location of the BTH region and their social and economic levels

Figure 2

The research framework in this study

Figure 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. k: the relationship between TCI and Job-housing balance)

Figure 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))

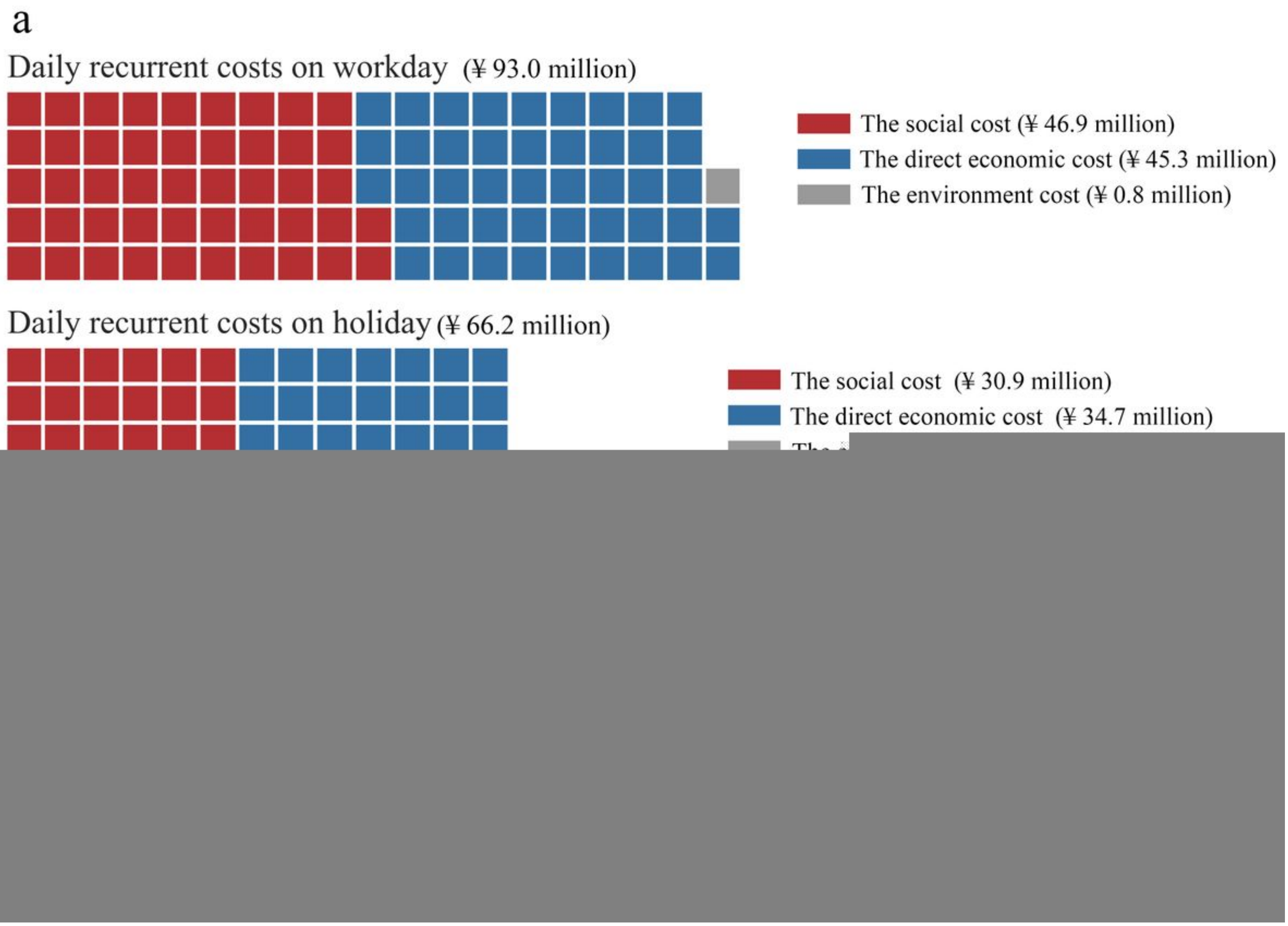

Figure 5

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))

Figure 6

The economic losses of traffic congestion due to different rainfall intensities (Note: different cities on workdays (a) and holidays (b); different time windows on workdays (c) and holidays (d). Plot figures present the ratio of economic losses to the economic cost of recurrent traffic congestion, while heat maps present the traffic congestion costs under different rainfall intensities (million yuan). Besides, S: sunny, L: Light rainfall, H: Heavy rainfall))

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