International Journal of Intelligent Transportation Systems Research
https://doi.org/10.1007/s13177-018-0162-x

# Impact Analysis of Rainfall on Traffic Flow Characteristics in Beijing

Weiwei Zhang [1,2] · Ruimin Li [1,2] · Pan Shang [1,2] · Hao Liu [3]

Received: 7 March 2018 / Revised: 23 August 2018 / Accepted: 27 August 2018


## Abstract

To improve traffic operations and management under inclement weather, this work quantificationally investigated the influence of rainfall on the traffic flow characteristics of urban expressways in Beijing. Four basic traffic flow models (Greenshields model, Greenberg model, Underwood model, and Drake function model) were compared to determine the most suitable model for the detected data, which were collected by microwave detectors in the Beijing 2nd and 4$^{th}$ring expressway under normal or rainfall condition. Results showed that the Greenshields model was the best-fitted model. Under rainfall conditions, varying degrees of reductions were observed in the road capacity, free-flow speed, and speed at capacity. The findings also showed that the reductions of road capacity were 7.26%, 10.87%, and 17.09%, and the reductions of free-flow speed were 3.07%, 5.29%, and 6.64% under light rain, medium rain, and heavy rain, respectively. The reductions of speed at capacity revealed a similar tendency as that of the free-flow speed. Simultaneously, a new model that incorporated rainfall intensity is proposed on the basis of the Greenshields model and can achieve good performance. Overall, the results are beneficial for traffic managers in improving their decisions and predictions under rainfall weather.

**Keywords** Urban road · Traffic flow characteristics · Rainfall weather · Updated Greenshields model

## 1 Introduction

With the rapid economic development, people are more willing to own private cars for work, entertainment, travel, and so on. Undoubtedly, increasing vehicle ownership in cities has imposed a great pressure on urban road systems. Therefore, many big cities in China have begun to observe regular daily congestion in recent year. Adverse weather conditions, such as rainfall and snow, have aggravated the traffic congestion in big cities. Obviously, slippery road and decreased visibility during rainy days make drivers more careful and slow down their vehicles, thereby influencing the road traffic system.

Under adverse weather, the traffic flow condition differs from that under normal condition. Changes in traffic-flow condition indicate that the road needs corresponding traffic-management measures under adverse weather. Thus, investigation of the influences of adverse weather on the traffic-flow characteristics has become an important research direction.

Several studies have analyzed the effects of adverse weather on traffic [1–16]. Some of them are devoted to investigate the effects of inclement weather on traffic-flow characteristics [6, 11, 17–25]. Some studies mainly analyzed the influences of bad weather on free-flow speed [23, 26–29], whereas others examined the effects of adverse weather on capacity [2, 4, 5, 10, 12, 13, 26, 30–34].

Over the past few years, with the development and popular use of data-acquisition technologies and tools, several studies have been concentrated on the effects of inclement weather on traffic-flow characteristics based on numerous detected data, particularly those regarding rain and snow. Rakha and Farzaneh et al. [35] studied the effects of precipitation and snow on three traffic-flow parameters, namely, free-flow speed, capacity, and speed at capacity; their efforts proved that inclement weather adversely affected the traffic-flow characteristics, and the reductions of free-flow speed, capacity, and speed at capacity under various precipitation intensities were 6 to 9%, 10 to 11%, and 8 to 14%, respectively. And they proposed new weather-adjustment factors to calculate the proposed values of the three parameters under inclement weather conditions. Billot and El Faouzi et al. [36] established a

✉ Ruimin Li
lrmin@tsinghua.edu.cn

[1] Department of Civil Engineering, Tsinghua University, Beijing 100084, China

[2] Hang Lung Center for Real Estate, Tsinghua University, Beijing 100084, China

[3] Beijing Transportation Information Center, Beijing 100161, China

Published online: 15 September 2018

multilevel evaluation system for the effect of rainfall on traffic flow at three levels, namely, microscopic, mesoscopic, and macroscopic levels. At macroscopic level, a macroscopic fundamental diagram was used in their study, which found that the capacity declined from 21 to 18.5%, and the free-flow speed decreased from 12.6 to 8% under different rainfall intensities; however, the jam density was not influenced during rain, and this finding was consistent with previous reports. Asamer and Reinthaler [26] presented the product limit method and weighted harmonic mean method for estimating the capacity and free-flow speed of urban roads under inclement weather conditions such as rain and snow; their study indicated that the capacity and free-flow speed significantly declined when urban roads suffered from rain and snow. Akin and Sisiopiku et al. [18] analyzed the effects of several factors including weather conditions, surface conditions, and large vehicle presence on speed–flow–density relationships among urban freeways; their outcome revealed that the capacity decreased by 7 to 8%, and the vehicular speed declined by 8 to 12% during rainy weather. Alhassan and Ben-Edigbe et al. [30] studied the capacity and speed of highway under dry and wet conditions and proposed a linear regression equation to predict the traffic parameters under both conditions; they concluded that under wet condition, the speed decreased by 3.52%, and the flow rate changed 8.62%. Alhassan [2] predicted the capacities of a single-lane carriageway under dry condition and three rainy conditions and found out that the road capacity decreased under rainfall weather. Roh and Sharma et al. [13] investigated the effects of snow and temperature on the traffic volumes of two types of vehicles; they subsequently analyzed the interactions between them on a highway.

A consensus has been reached indicating that inclement weather provides negative implications on traffic-flow characteristics, particularly on the three key traffic flow parameters (free-flow speed, capacity, and speed at capacity). Lam and Tam et al. [22] analyzed the influences of rainfall in Hong Kong and found that the reduction of free-flow speed was 4.21 to 10.19%, the speed at capacity was 14.78 to 31.71%, and the capacity was 8.83 to 21.92%. Angel et al. [3] examined the driver response to rainfall and found that the speed declined with the rain precipitation intensity, and the capacity decreased under rainfall conditions, particularly during traffic peak periods.

At present, Beijing also experiences rainfall during summer every year and the traffic condition becomes worse in rainy days compared with that of normal condition. As previous studies have indicated that traffic flow behavior and traffic-flow condition are different under rainfall condition, we need to further understand the traffic-flow characteristics under rainfall condition to improve traffic management. Considering the limitations of data and other aspects, few special studies are reported in the literature to investigate the influences of rainfall on traffic-flow characteristics such as volume, speed, and occupancy. Therefore, through the integration of massive traffic-flow data and related rainfall data detected, we conducted a comparative analysis of various models and quantificationally investigated the influence of rainfall on traffic flow characteristics by utilizing the collected traffic-flow data and rainfall data to enhance the support of traffic management.

The structure of this paper is organized as follows. The second section mainly discusses the data collection and extraction for the subsequent analysis. The third section compares the traffic-flow modes and investigates the most satisfying model. The fourth section presents the speed–flow relationship by dividing the rainfall precipitation into different intensities, followed by the presentation of a new model for traffic flow under rainfall conditions in the fifth section. The final section illustrates the conclusions and recommends suggestions for future research.

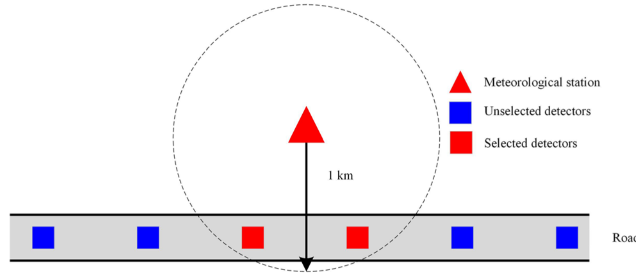


**Fig. 1** Schematic of the evaluation criterion

## 2 Data Collection and Extraction

The traffic data used in this study were collected by microwave detectors located on the 2nd and 4th ring expressways in Beijing. These data provided the exact and explicit traffic-flow parameters, including the traffic-flow volume, speed, and occupancy of the selected lanes of the target roads, and these parameters were updated every 2 min.

**Table 1** Size of each dataset in the analysis

| Dataset number | Examples | Dataset number | Examples |
|---|---|---|---|
| 1 | 316,848 | 7 | 254,166 |
| 2 | 261,762 | 8 | 262,242 |
| 3 | 263,382 | 9 | 257,718 |
| 4 | 262,866 | 10 | 262,608 |
| 5 | 261,192 | 11 | 263,286 |
| 6 | 394,443 | 12 | 264,294 |

**Table 2** Four models applied in the study

| Models | Function |
|---|---|
| Greenshields [39] | $q = k_j\left(u - \frac{u^2}{u_f}\right)$ |
| Greenberg [38] | $q = k_j u \exp\left(-\frac{u}{u_m}\right)$ |
| Underwood [40] | $q = k_m u \ln\left(\frac{u_f}{u}\right)$ |
| Drake [37] | $u = u_f \exp\left[-\frac{1}{2}\left(\frac{1}{2}\right)^2\right]$ <br> $q = ku$ |

The rainfall data were obtained from the weather detectors deployed by Beijing Meteorological Bureau. A total of 19 meteorological stations within the 4th ring expressway in Beijing provide rainfall data. To match the meteorological station and the corresponding traffic-flow detector, a circle was drawn with the radius of 1 km centering on each of the mentioned 19 meteorological stations. The evaluation criterion implies that the weather condition at the location of the traffic-flow detector is the same as the meteorological station if the traffic-flow detector is located in a circle with the meteorological station as a center. The schematic is illustrated in Fig. 1. We selected 19 meteorological detectors and 54 traffic-flow detectors in advance by following the aforementioned rule.

However, not every traffic-flow detector is useful for the analysis of rainfall on traffic-flow characteristics because of the data quality. In fact, the microwave detectors have been deployed in the expressway for about 10 years; hence, some data may cause certain problems. Each detector is examined carefully to select the appropriate detectors. Afterward, 12 traffic-flow detectors with 10 detectors from the 2nd ring road and 2 detectors from the 4th ring road were found suitable for the traffic-flow model development.

The traffic-flow data and rainfall data were obtained simultaneously from June 1 to July 31 in 2013. The raw traffic-flow detection data were updated every 2 min, and the traffic volume was subsequently multiplied by 30 to convert to hourly unit for simplification. Compared with the traffic data, the precipitation in the collected rainfall data was recorded every 5 min. Each precipitation entails a record time, and the record time minus 5 min is considered the start time of the precipitation. If the time corresponding to traffic volume is within the time interval composed of start time and record time of some precipitation, the precipitation is successfully matched up with the traffic volume. For example, one precipitation is 0.5 (mm/5 min), and the record time is 22:00 on June 1; hence, the start time is 21:55 on June 1. One traffic volume record time is 21:58 on June 1 and is within the time interval [21:55, 22:00]; therefore, the precipitation corresponding to the traffic volume is 0.5 (mm/5 min). We adopt the aforementioned rule to match the traffic-flow detection data (veh/h/lane) and rainfall data (mm/5 min), eventually detecting 12 datasets for the following analysis. The sizes of each dataset are shown in detail in Table 1.

## 3 Model Development

Over the past decades, many traffic-flow models and functions have been introduced to describe the relationship between speed and traffic volume [37–40]. In the current study, we investigated four extraordinary popular models: Greenshields model, Greenberg model, Underwood model, and Drake function model. These models are listed in Table 2.

Through regression analysis, the four models in Table 2 are applied to determine the most suitable model for urban traffic-flow conditions in Beijing. $R^2$ and RootMean Square Error(RMSE) are used as the evaluation indices to determine whether the model fittings are good. The fitting is better when $R^2$ is larger, and the model can be considered precise when $R^2$ exceeds 0.70. On the contrary, the fitting is worse when its RMSE is larger.

We used each of the four models to test the 12 datasets under normal or rainfall conditions, which added up to 144 cases, and examined them in turn. With regard to every detector, different data led to varied fitting results. However, the fitting results indicated that the Greenshields model outperformed the others in 123 cases according to statistics. The fitting degrees of the four models are shown in Table 3. Bold numbers are the best values for each indicator.

**Table 3** Fitting degrees of traffic-flow models utilized in the analysis

| Model | $R^2$ | | | RMSE | | |
|---|---|---|---|---|---|---|
| | Distribution | Mean | Variance | Distribution | Mean | Variance |
| Greenshields | **[0.73,0.97]** | **0.874** | **0.053** | [201.6583.0] | **374.80** | 101.37 |
| Greenberg | [0.04,0.91] | 0.498 | 0.220 | [222.0,933.7] | 506.45 | 130.98 |
| Underwood | [0.56,0.97] | 0.863 | 0.060 | [199.1550.3] | 385.92 | 94.70 |
| Drake | [0.12,0.99] | 0.639 | 0.226 | [271.4723.9] | 442.83 | 99.27 |

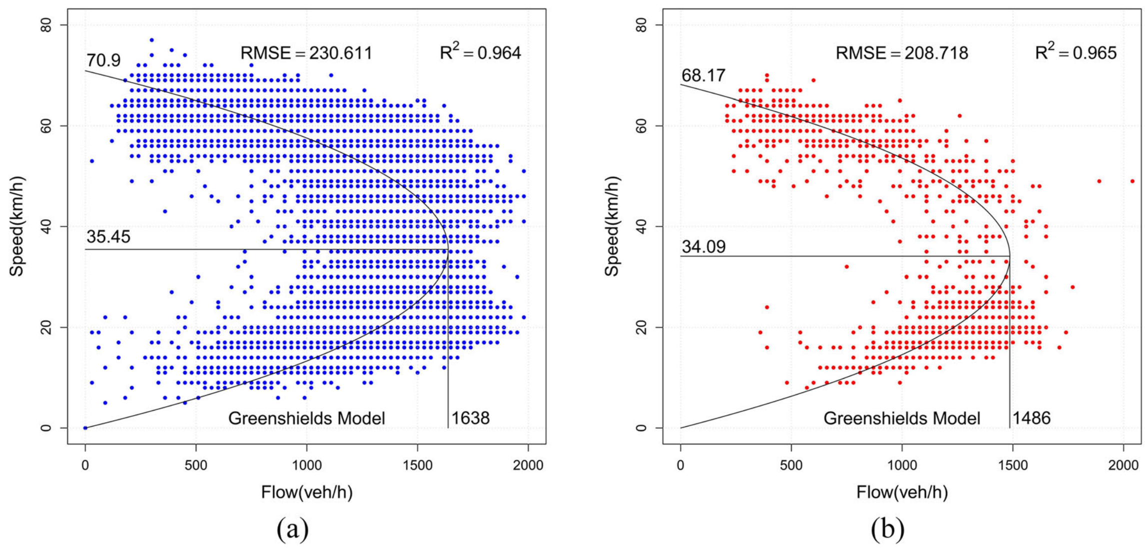


**Fig. 2** Speed–flow relationship of lane 2 of detector 2046 on 2nd ring road: (a) Under dry condition; (b) Under rainfall condition

As presented in Table 3, when the Greenshields model is used to fit with the data, both $R^2$ and RMSE contribute the most compact distribution and the minimum variance. Consequently, the Greenshields model is the optimum model to describe the traffic-flow characteristics for the selected location.

## 4 Speed–Flow Relationships under Different Weather Conditions

Prior to investigation of the effects of rainfall on traffic-flow characteristics, especially the capacity, speed at capacity, and free-flow speed, the weather conditions are divided into two situations, namely, dry condition and rainfall condition, without considering the rain intensity categories.

Notably, the lane number is named from left to right for either direction of each road. Figure 2 show the observed and fitted speed–flow relationship of lane 2 of detector 2046 on the 2nd ring road under dry and rain conditions, regardless of rainfall intensities. In addition, they present $R^2$, RMSE, and three key traffic stream parameters: free-flow speed, speed at capacity, and capacity. The evaluation index $R^2$ exceeded 0.95, which implied a good fitting of the speed–flow relationship.

As shown in Fig. 2, the free-flow speed, speed at capacity, and capacity of the 2nd ring road decreased under rainfall condition. The speed at capacity was 35.45 km/h under dry condition, which then slightly declined to 34.09 km/h under rainfall condition. Moreover, the reductions of capacity under different weather conditions indicate a similar tendency. Without rain, the capacity was 1638 veh/h/lane and then declined to 1486 veh/h/lane under rain condition; this finding indicates a 9.28% decrease.

Table 4 shows the fitting results of the key traffic-flow parameters of detector 2010 by adopting the Greenshields

**Table 4** Fitting results of free-flow speed, speed at capacity, and capacity of detector 2010 on 2nd ring road

| Lane number | Free-flow speed (km/h) | | Speed at capacity (km/h) | | Capacity (veh/h) | |
|---|---|---|---|---|---|---|
| | Dry | Rain | Dry | Rain | Dry | Rain |
| Lane 1 | 75.35 | 71.45 | 37.67 | 35.73 | 1454 | 1123 |
| Lane 2 | 71.54 | 67.07 | 35.77 | 33.54 | 1422 | 1108 |
| Lane 3 | 59.12 | 57.94 | 29.56 | 28.97 | 1149 | 910 |
| Lane 11 | 79.89 | 75.12 | 39.95 | 37.56 | 1459 | 1143 |
| Lane 12 | 75.53 | 69.89 | 37.76 | 34.94 | 1465 | 1233 |
| Lane 13 | 66.37 | 61.09 | 33.19 | 30.56 | 1359 | 1098 |

Note: Lane numbers 1, 2, and 3 are named from left to right for either direction of each road, and lane numbers 11, 12, and 13 stand for those of the opposite direction of the road

**Table 5** Reductions of free-flow speed under rainfall condition compared with dry condition (%)

| Detector | 2011 | 2012 | 2023 | 2030 | 2036 | 2037 | 2046 | 2052 | 2054 | 4050 | 4051 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lane 1 | 13.59 | *−2.36* | 3.70 | 5.98 | *−1.45* | 11.30 | 3.66 | 4.90 | 4.73 | −1.44 | −3.20 |
| Lane 2 | 3.03 | 0.05 | 7.64 | 6.58 | 1.37 | 0.63 | 3.85 | 3.27 | 6.03 | −1.34 | −3.66 |
| Lane 3 | 4.47 | 1.06 | 13.20 | 4.45 | 2.13 | 0.66 | 4.67 | 5.17 | 5.90 | −1.67 | −2.49 |
| Lane 4 | – | – | – | – | – | – | – | – | – | −3.60 | −0.01 |
| Lane 11 | 8.36 | 2.06 | 1.34 | 8.04 | 5.15 | *−1.60* | 3.50 | 2.71 | 4.03 | −2.79 | −3.46 |
| Lane 12 | *−2.67* | 5.40 | 10.84 | 6.26 | 5.26 | 3.42 | 4.95 | 6.06 | *−1.79* | −4.77 | −7.51 |
| Lane 13 | 8.36 | 6.54 | 13.27 | 11.94 | 6.41 | 2.15 | 6.90 | 5.68 | 1.50 | −0.20 | −2.36 |
| Lane 14 | – | – | – | – | – | – | – | – | – | −0.67 | *1.85* |

Notes: The symbol "–" in Tables 5, 6, and 7 means that the location of the detector does not have the corresponding lane number. The detector number beginning with 2 stands for the 2nd ring road, whereas the detector number beginning with 4 stands for the 4th ring road

model, including free-flow speed, speed at capacity, and capacity under both dry and rain conditions.

Tables 5, 6, and 7 indicate that the variations of the three key traffic-flow parameters establish different tendencies within the 2nd and 4th ring roads in Beijing under rainfall conditions. The reductions of free-flow speed within the 2nd ring road ranged from −2.67 to 13.59%, whereas the variations of free-flow speed within the 4thring road ranged from −7.51 to 1.85%. The negative sign in Tables 5, 6, and 7 in italic indicates that the free-flow speed, speed at capacity, and capacity increases during rain. Given the characteristic of the Greenshields model, the speed at capacity exhibits characteristics similar to those of free-flow speed. Remarkably, the capacity changes significantly compared with the two other parameters from −16.85 to 31.22%. This finding can accurately explain why the traffic flow becomes crowded during rainy days.

Notably, Table 7 reveals the capacity of the 4thring road declines under rainfall condition, and the effect of rainfall on the 4thring road is similar to that on the 2ndring road. However, the majority of the reductions of free-flow speed and speed at capacity with the 4thring road in Beijing are negative, indicating that the free-flow speed and speed at capacity on the 4thring road increase under rainfall condition, that is, the opposite tendency compared with the 2ndring road. This event is a kind of perplexing phenomena compared with the 2ndring road. Unfortunately, we cannot obtain additional data on the 4thring road to test this phenomenon because the weather detector is very limited near the 4thring road.

The above analysis indicates that the traffic flow in Beijing is evidently more crowded during rainy days, in which the traffic-flow capacity decreases sharply compared with the condition without rainfall.

## 5 Speed–Flow–Density Relationships under Different Rainfall Conditions

To further study the effects of different rainfall conditions on traffic-flow characteristics, we studied the variations of key traffic-flow parameters under different rainfall intensities with the aid of the relatively abundant data of Beijing.

**Table 6** Reductions of speed at capacity under rainfall condition compared with dry condition (%)

| Detector | 2011 | 2012 | 2023 | 2030 | 2036 | 2037 | 2046 | 2052 | 2054 | 4050 | 4051 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lane 1 | 13.60 | *−2.36* | 3.68 | 5.99 | *−1.46* | 11.29 | 3.66 | 4.89 | 4.72 | −1.43 | −3.20 |
| Lane 2 | 3.00 | 0.08 | 7.65 | 6.57 | 1.36 | 0.64 | 3.84 | 3.27 | 6.02 | −1.34 | −3.66 |
| Lane 3 | 4.47 | 1.05 | 13.21 | 4.44 | 2.13 | 0.65 | 4.67 | 5.18 | 5.90 | −1.67 | −2.50 |
| Lane 4 | – | – | – | – | – | – | – | – | – | −3.61 | −0.03 |
| Lane 11 | 8.37 | 2.09 | 1.32 | 8.05 | 5.15 | −1.61 | 3.50 | 2.71 | 4.02 | −2.77 | −3.45 |
| Lane 12 | *−2.67* | 5.40 | 10.87 | 6.26 | 5.26 | 3.43 | 4.94 | 6.07 | *−1.80* | −4.78 | −7.51 |
| Lane 13 | 8.37 | 6.55 | 13.28 | 11.94 | 6.39 | 2.15 | 6.91 | 5.66 | 1.53 | −0.22 | −2.39 |
| Lane 14 | – | – | – | – | – | – | – | – | – | −0.68 | *1.83* |

**Table 7** Reductions of capacity under rainfall condition compared with dry condition (%)

| Lane | 2011 | 2012 | 2023 | 2030 | 2036 | 2037 | 2046 | 2052 | 2054 | 4050 | 4051 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lane 1 | 25.57 | 47.04 | 9.13 | 4.30 | 16.46 | 37.86 | 14.73 | 13.80 | 16.20 | 8.28 | 19.75 |
| Lane 2 | 11.01 | 31.22 | 2.65 | 1.11 | 10.01 | 14.48 | 9.28 | 13.32 | 14.57 | 8.19 | 19.01 |
| Lane 3 | 14.11 | 22.72 | 2.67 | *−16.85* | 15.63 | 1.93 | 11.55 | 4.24 | 3.51 | 5.64 | 12.22 |
| Lane 4 | – | – | – | – | – | – | – | – | – | 15.92 | 7.55 |
| Lane 11 | 4.80 | 20.60 | 5.18 | 8.67 | 21.55 | 6.17 | 15.13 | 21.42 | 17.64 | 11.08 | 15.30 |
| Lane 12 | *−6.11* | 16.50 | *−1.07* | 10.67 | 19.11 | 2.32 | 15.46 | 14.93 | 21.85 | 9.25 | 16.78 |
| Lane 13 | 4.80 | 20.47 | *−3.18* | 0.00 | 14.11 | 13.44 | 7.93 | 12.37 | 15.50 | *−3.91* | 3.13 |
| Lane 14 | – | – | – | – | – | – | – | – | – | *−4.55* | *−3.72* |

Unlike other cities, Beijing receives much rain during July in the whole year. Thus, the rainfall intensity measured by the precipitation (mm) every 5 min is adopted in this study to determine the different categories of rainfall conditions. In detail, "no rain" denotes the rainfall intensity being 0 mm/5 min; "light rain" denotes the rainfall intensity being within the range between 0 and 0.2 mm/5 min; "light rain" denotes the rainfall intensity being within the range between 0.2 and 0.5 mm/5 min; and "heavy rain" denotes the rainfall intensity within the rage larger than 0.5 mm/5 min as shown in Table 8 with corresponding sample sizes.

If either of the traffic-flow data or the rainfall data were missing during the study period, both the corresponding records would be eliminated from the dataset for the analysis. As shown in Table 8, the sample size of the condition without rain is 96.08% of the whole sample size, whereas the sample sizes of light rain, medium rain, and heavy rain are 2.77, 0.71, and 0.44%, respectively, which all play a small part but obviously reveal that the amount of rainfall time in Beijing is relatively small.

Figure 3 show the speed–flow relationships of lane 2 of detector 2046 under different rainfall intensity categories, namely, light rain, medium rain, and heavy rain. The capacity of the road under light rain condition is 1519 veh/h, indicating a 7.26% reduction compared with that under dry condition. The capacity subsequently declines to 1460 veh/h under medium rain and decrease to 1358 veh/h under heavy rain, implying 10.87 and 17.09% reductions, respectively. Additionally, the free-flow speed and the speed at capacity indicate the similar decline tendency. The free-flow speed is 70.9 km/h under dry condition and then slightly decreases to 68.72 km/h under light rain, 67.15 km/h under medium rain, and 66.19 km/h under heavy rain. The reductions of the free-flow speed under different rainfall conditions are 3.07, 5.29, and 6.64% for light, medium, and heavy rain, correspondingly. The speed at capacity reveals slight reductions as that of the free flow.

Figure 4 exhibit the speed–density relationship of lane 2 of detector 2046 under dry, light rain, medium rain, and heavy rain conditions. The evaluation index $R^2$ indicates whether the fittings are good as we expected. Notably, the speed–density relationship significantly differs between dry and rain conditions, but it shows slight changes under rain conditions.

## 6 Development of a New Model for Rainfall Conditions

As all the three key traffic-flow parameters under different weather conditions have been obtained, we expect to detect the relationship between the free-flow speed and the rainfall intensity. Fox has modeled and validated the relationship by using a nonlinear regression method [41]. In our study, several relationship functions are tested to determine the best fitting model, such as exponential functions, power functions, and polynomial functions.

**Table 8** Different rainfall precipitation categories in the analysis

| Road | Speed limit (km/h) | Rainfall intensity (mm/5 min) | Rainfall category | Sample size | Percentage |
|---|---|---|---|---|---|
| Expressways | 80 | 0 | No rain | 41,994 | 96.08 |
| | | (0, 0.2] | Light rain | 1210 | 2.77 |
| | | (0.2, 0.5] | Medium rain | 312 | 0.71 |
| | | >0.5 | Heavy rain | 191 | 0.44 |

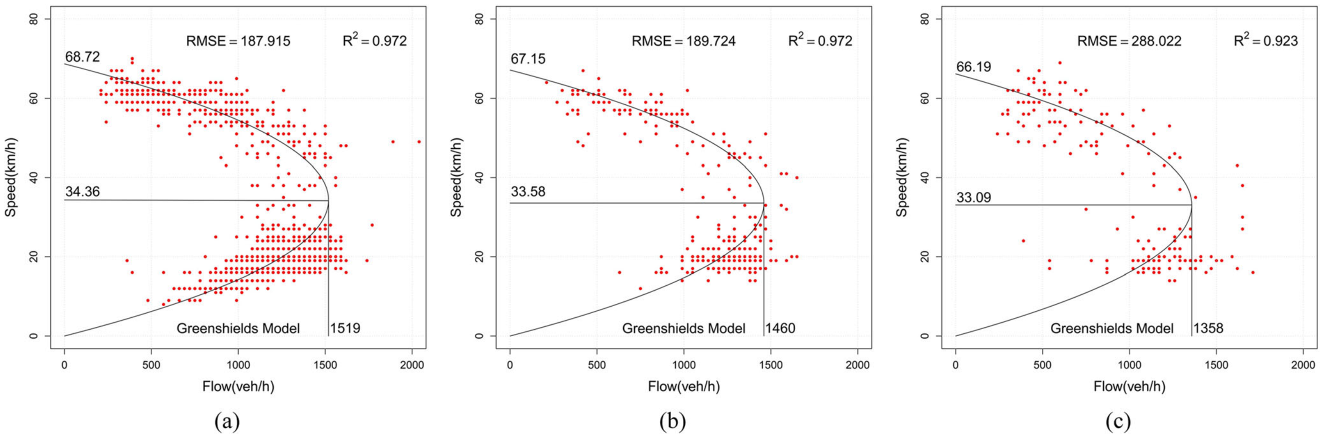


**Fig. 3** Speed–flow relationship of lane 2 of detector 2046 on 2ndring road: (a) Under light rain condition; (b) Under medium rain condition; (c) Under heavy rain condition

As shown in Table 9, the exponential function form is the optimum model with maximum $R^2$ value (bold number) for describing the relationship between free-flow speed and rainfall intensity:

$$u_f(r) = \exp\left(-a \cdot r^b + c\right) \tag{1}$$

where $u_f(r)$ is the free-flow speed which is a polynomial function of the rainfall intensity; the dependent variable $r$ is the rainfall intensity; and $a$, $b$, and $c$ are three parameters for calibration.

Therefore, on the basis of the traditional Greenshields model, the speed–flow relationship under rainfall condition is explicitly demonstrated as Eq. (2), which we called as the updated Greenshields model.

$$q = k_j\left(u - u^2 \cdot \exp\left(a \cdot r^b - c\right)\right) \tag{2}$$

where $k_j$ is the jam density of the traffic flow, $u$ is the space mean speed of the traffic flow, and $q$ is the traffic flow.

Figure 5(a) exhibits the observed speed–flow relationship scatterplot of lane 2 of detector 2046 under different rainfall intensities and illustrates the fitting surface of the updated Greenshields model for the speed–flow relationship for different rainfall intensities simultaneously ($k_j = 87.525$, parameter$a = 0.08644$, parameter$b = 0.4421$, and parameter$c = 4.261$). The $R^2$ in Fig. 5(a) is 0.895, which indicates a good fitting by the updated Greenshields model. We can observe in Fig. 5(a) that the free-flow speed and the capacity decrease as the rainfall intensity increases, and this finding is coincident with the aforementioned conclusions.

To verify the performance of the updated Greenshields model, we selected detector 2052 to test the effectiveness and reliability. The observed speed–flow relationship scatterplot of lane 13 of detector 2052 and the fitting surface of the updated Greenshields model for the speed–flow relationship of lane 13 of detector 2052 under different rainfall intensities are shown in Fig. 5(b). The calibration results are $k_j = 77.174$, $a = 0.1092$, $b = 0.3424$, and $c = 4.36$. From Fig. 5(b), we can determine that the free-flow speed is 78.26 km/h, and the maximum flow is 1509.9 veh/h/lane under dry condition; these rates decrease nonlinearly with the rainfall intensity. The $R^2$ in the figure below suggests that the updated Greenshields model has achieved a good fitting.

The capacity, free-flow speed, and speed at capacity comparisons of detector 2046 and 2052 under different rainfall intensities are illustrated in Fig. 6, in which the red square symbols represent the three parameters of lane 2 of detector

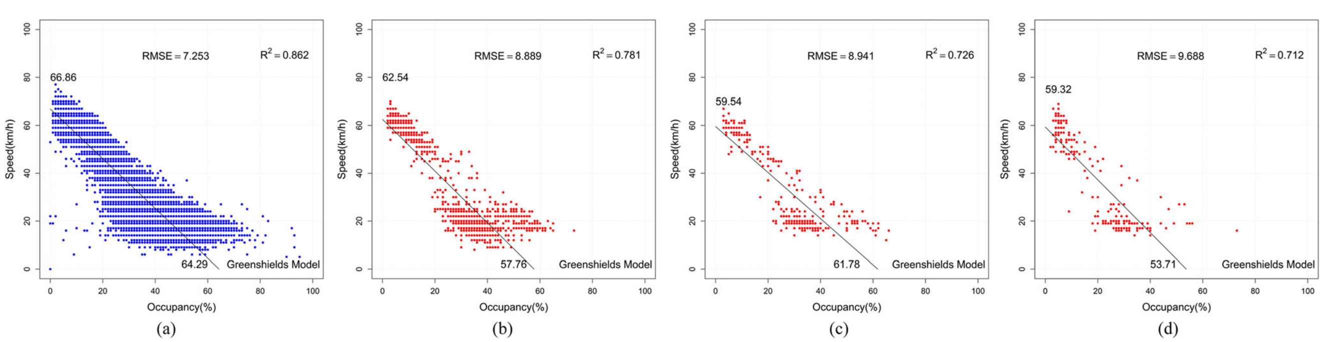


**Fig. 4** Speed–density relationship of lane 2 of detector 2046 on 2ndring road under dry condition: (a) Under dry condition; (b) Under light rain condition; (c) Under medium rain condition; (d) Under heavy rain condition

**Table 9** Different rainfall precipitation categories in the analysis

| Function | Exponential function | Power functions | Polynomial functions |
|---|---|---|---|
| $R^2$ value | **0.971** | 0.948 | 0.956 |

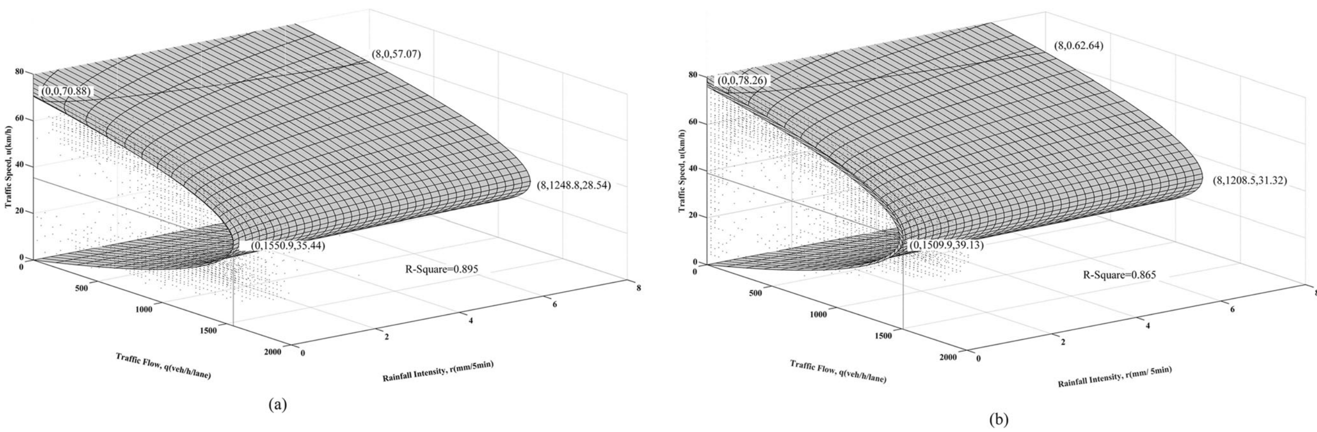


**Fig. 5** Observed speed–flow–rainfall intensity values and fitting surface by using the updated Greenshields model: (a) Lane 2 of detector 2046; (b) Lane 13 of detector 2052

2046, and the blue triangles represent the three parameters of lane 13 of detector 2052. As shown in Fig. 6, the capacity of each lane declines when the rainfall intensity increases, and the tendency indicates similar features. As such, the capacity of lane 13 of detector 2052 cannot exceed that of lane 2 of detector 2046, mainly because compared with the inner lane, the outside lane is more likely to be subjected to traffic interferences. The discrepancy percentages of capacity are 2.64, 4.68, 4.20, 3.70, and 3.23% at different rainfall intensities, whereas the difference percentages of free-flow speed are 10.41, 8.11, 8.65, 9.26, and 9.78%.

## 7 Conclusions and Further Study

Traffic congestion, characterized by slow speed and long travel time, is an oversaturated queuing state when the vehicular demand is larger than the road capacity during a particular time period. The inclement weather (i.e., rain, snow, and fog) usually makes the traffic congestion problems worse due to the drop of road capacity, the speed limit of vehicles, and the breakdown of driving conditions. To improve the level of traffic operations and management under inclement weather, especially for rainfall condition, this study quantificationally investigated the influence of rainfall on the traffic flow characteristics of urban expressways, and use Beijing as a case study. First, we test the adaptabilities of the four basic traffic flow models into Beijing expressway, including Greenshields model, Greenberg model, Underwood model, and Drake function model based on the flow-density-speed sample

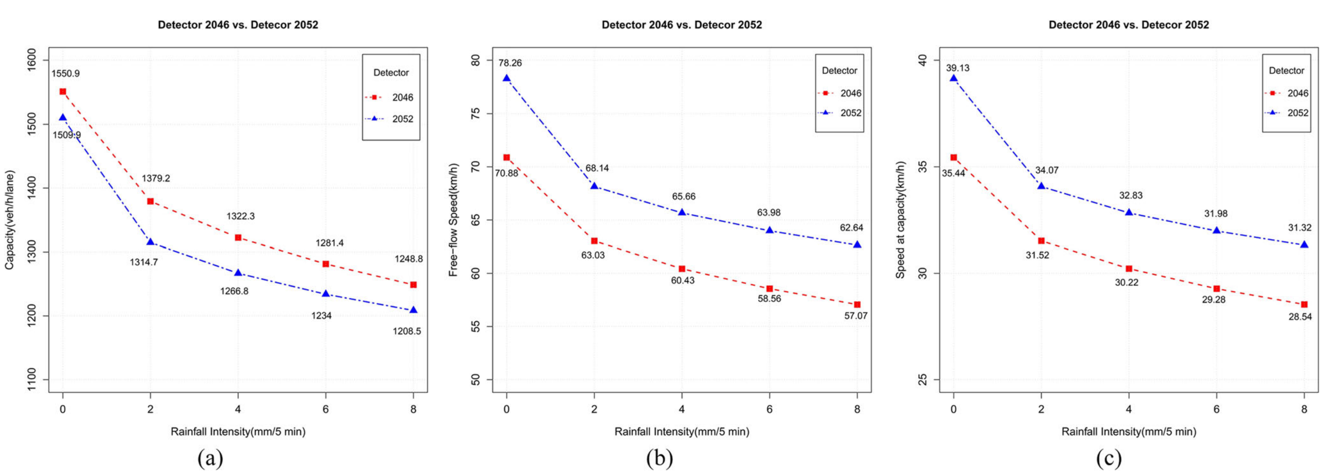


**Fig. 6** Capacity comparison of detector 2046 and detector 2052 under different rainfall intensities: (a) Capacity comparison; (b) Free-flow speed comparison; (c) Speed at capacity comparison

data collected by microwave detectors in the Beijing 2nd and 4th ring expressway. The results show that the Greenshields model is the best fitted model with largest $R^2$ value and least RMSE value. Then, we use the sample data to calibrate the parameters in the Greenshields model under both dry and rainfall conditions. The road capacity, free-flow speed, and speed at capacity have different degree of reductions under rainfall condition compared with the corresponding values under dry condition. Finally, we proposed a modified Greenshields model which incorporates the rainfall intensity to model the effect of different rainfall intensities on the key parameters of traffic flow characterizes. The proposed modified Greenshields model can offer the reference values of road capacity, free-flow speed, and speed at capacity under different degree of rainfall intensity, which can improve the observability and controllability of traffic flow under rainfall conditions.

There are several further research directions: (1) the other types of inclement weather, such as now and fog, can be further studied based on available sample data from other cities; (2) the network-level effect of inclement weather can be modeled in the further which is beneficial for city managers, based on network modelling theories, such as Macroscopic Fundamental Diagram; and (c) the quantitative effect of inclement weather on traffic flow can be used as an additional input into the traffic simulation model, to predict the network-wide dynamic traffic state under inclement weather.

**Acknowledgments** The authors are grateful to the National Natural Science Foundation of China (71361130015), Beijing Natural Science Foundation (8162024), and the Collaborative Innovation Center for Capital World City's Smooth Traffic Construction for sponsoring and supporting this study.



## References

1. Agarwal, M., Maze, T.H. and Souleyrette, R.: The weather and its impact on urban freeway traffic operations. Proc., the 85nd annual meeting of the Transportation Research Board, Washington DC, pp. 15 (2006)
2. Alhassan, H.M.: Reliability of single lane road capacity subjected to rainfall disturbances. Int. J. Emerg. Technol. Adv. Eng. **3**(2), 587–594 (2013)
3. Angel, M., Sando, T., Chimba, D., Kwigizile, V.: Effects of rain on traffic operations on Florida freeways. Transp. Res. Rec. J. Transp. Res. Board. **2440**(2440), 51–59 (2014). https://doi.org/10.3141/2440-07
4. Datla, S., Sharma, S.: Impact of cold and snow on temporal and spatial variations of highway traffic volumes. J. Transp. Geogr. **16**(5), 358–372 (2008). https://doi.org/10.1016/j.jtrangeo.2007.12.003
5. Hall, F.L., Barrow, D.: Effects of weather on the relationship between flow and occupancy on freeways. Transp. Res. Rec. J. Transp. Res. Board. **1194**, 55–63 (1988)
6. Ibrahim, A.T., Hall, F.L.: Effect of adverse weather conditions on speed-flow-occupancy relationships. Transp. Res. Rec. **1457**, 184–191 (1994)
7. Knapp, K., Smithson, L.: Winter storm event volume impact analysis using multiple-source archived monitoring data. Transp. Res. Rec. J. Transp. Res. Board. **2**(1), 10–16 (2000). https://doi.org/10.3141/1700-03
8. Lam, W.H.K., Shao, H., Sumalee, A.: Modeling impacts of adverse weather conditions on a road network with uncertainties in demand and supply. Transp. Res. B Methodol. **42**(10), 890–910 (2008). https://doi.org/10.1016/j.trb.2008.02.004
9. Maze, T., Agarwai, M., Burchett, G.: Whether weather matters to traffic demand, traffic safety, and traffic operations and flow. Transp. Res. Rec. J. Transp. Res. Board. **1948**, 170–176 (2006). https://doi.org/10.3141/1948-19
10. Mohammed, A.H., Ben-Edigbe, J.: Highway capacity prediction in adverse weather. J. Appl. Sci. **11**(12), 2193–2199 (2011). https://doi.org/10.3923/jas.2011.2193.2199.
11. Oh, J.S., Shim, Y.U., Cho, Y.H.: Effect of weather conditions to traffic flow on freeway. KSCE J. Civ. Eng. **6**(4), 413–420 (2002). https://doi.org/10.1007/BF02841995
12. Okamoto, N., Ishida, H., Furuya, H. and Furukawa, K.: Including weather condition factors in the analysis of the highway capacity. 83rd annual meeting of the Transportation Research Board, Washington DC (2004)
13. Roh, H., Sharma, S., Sahu, P.K.: Modeling snow and cold effects for classified highway traffic volumes. KSCE J. Civ. Eng. **20**(4), 1514–1525 (2016). https://doi.org/10.1007/s12205-015-0236-0
14. Shang, P., Li, R., Liu, Z. and Li, X.: Inclement weather impacts on urban traffic conditions. Proc., CICTP2015, ASCE, pp. 2213–2227 (2015)
15. Snelder, M., Calvert, S.C.: Quantifying the impact of adverse weather conditions on road network performance. Eur. J. Transp. Infrastruct. Res. **16**(1), 128–149 (2016)
16. Xu, F., He, Z., Sha, Z., Zhuang, L. and Sun, W.: Survey the Impact of Different Rainfall Intensities on Urban Road Traffic Operations Using Macroscopic Fundamental Diagram. Proc., 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013), IEEE, Hague, Netherlands, pp. 664–669 (2013)
17. Agarwal, M., Maze, T.H. and Souleyrette, R: Impacts of weather on urban freeway traffic flow characteristics and facility capacity. Proceedings of the 2005 mid-continent transportation research symposium, Ames (2005)
18. Akin, D., Sisiopiku, V.P., Skabardonis, A.: Impacts of weather on traffic flow characteristics of urban freeways in Istanbul. Procedia. Soc. Behav. Sci. **16**, 89–99 (2011). https://doi.org/10.1016/j.sbspro.2011.04.432
19. Hooper, E., Chapman, L., Quinn, A.: The impact of precipitation on speed–flow relationships along a UK motorway corridor. Theor. Appl. Climatol. **117**(1–2), 303–316 (2014). https://doi.org/10.1007/s00704-013-0999-5
20. Saberi, M., Bertini, R.L.. Empirical analysis of the effects of rain on measured freeway traffic parameters. Proc., 89th Annual Meeting of the Transportation Research Board, Washington, DC, pp. 1–15 (2010)
21. Kwon, T., Fu, L., Jiang, C.: Effect of winter weather and road surface conditions on macroscopic traffic parameters. Transp. Res. Rec. J. Transp. Res. Board. **2329**(2329), 54–62 (2013). https://doi.org/10.3141/2329-07
22. Lam, W.H.K., Tam, M.L., Cao, X., Li, X.: Modeling the effects of rainfall intensity on traffic speed, flow, and density relationships for

urban roads. J. Transp. Eng. **139**(7), 758–770 (2013). https://doi.org/10.1061/(ASCE)TE.1943-5436.0000544
23. Smith, B.L., Byrne, K.G., Copperman, R.B., Hennessy, S.M. and Goodall, N.J.: An investigation into the impact of rainfall on freeway traffic flow. Proc., 83rd annual meeting of the Transportation Research Board, Washington DC (2004)
24. Xing, E. and Wang, R.: Traffic flow characteristics of urban expressway in the period of ice and snow of cold areas. Proc., Traffic and Transportation Studies 2010, ASCE, 2, 444–450 (2010)
25. Yang, S., Ye, J., Zhang, X., Liu, H.: Study of the impact of rainfall on freeway traffic flow in Southeast China. Int. J. Crit. Infrastruct. **8**(2/3), 230 (2012). https://doi.org/10.1504/IJCIS.2012.049043
26. Asamer, J. and Reinthaler, M.: Estimation of road capacity and free flow speed for urban roads under adverse weather conditions. 13th International IEEE Annual Conference on Intelligent Transportation Systems Madeira Island, Funchal (2010).
27. Camacho, F., García, A., Belda, E.: Analysis of impact of adverse weather on freeway free-flow speed in Spain. Transp. Res. Rec. J. Transp. Res. Board. **2169**(2169), 150–159 (2010). https://doi.org/10.3141/2169-16
28. Hablas, M.E.: A study of inclement weather impacts on freeway free-flow speed. Master thesis, Virginia Polytechnic Institute and State University, Blackburg, Virginia (2007)
29. Kyte, M., Khatib, Z., Shannon, P., Kitchener, F.: Effect of environmental factors on free-flow speed. Transp. Res. Circ. **56**(2), 181–185 (2000)
30. Alhassan, H.M., Ben-Edigbe, J.: Effect of rainfall intensity variability on highway capacity. Eur. J. Sci. Res. **49**(1), 123–129 (2011)
31. Alhassan, H.M., Ben-Edigbe, J.: Extent of highway capacity loss due to rainfall. World Acad. Sci. Eng. Technol. **72**, 1889–1896 (2012)
32. Christian, J.T.: Weather and road capacity. Selected Proceedings From the Annual Transport Conference at Aalborg University, Denmark, pp. 32 (2014)
33. Keay, K., Simmonds, I.: The association of rainfall and other weather variables with road traffic volume in Melbourne, Australia. Accid. Anal. Prev. **37**(1), 109–124 (2005). https://doi.org/10.1016/j.aap.2004.07.005
34. Yang, Z., Lin, Y., Gao, X.: Urban expressway capacity under adverse weather conditions. J. Transp. Inf. Saf. **28**(1), 75–78 (2010)
35. Rakha, H., Farzaneh, M., Arafeh, M., Sterzin, E.: Inclement weather impacts on freeway traffic stream behavior. Transp. Res. Rec. J. Transp. Res. Board. **2071**(1), 8–18 (2008). https://doi.org/10.3141/2071-02
36. Billot, R., El Faouzi, N., De Vuyst, F.: Multilevel assessment of the impact of rain on Drivers' behavior. Transp. Res. Rec. J. Transp. Res. Board. **2107**(1), 134–142 (2009). https://doi.org/10.3141/2107-14
37. Drake, J., Schofer, J., May, A.: A statistical analysis of speed density hypotheses. Highw. Res. Rec. **154**, 53–87 (1967)
38. Greenberg, H.: An analysis of traffic flow. Oper. Res. **7**(1), 79–85 (1959). https://doi.org/10.1287/opre.7.1.79
39. Greenshields, B.D., Bibbins, J.R., Channing, W.S., Miller, H.H.: A study in highway capacity. Highw. Res. Board Proc. **14**, 448–477 (1935)
40. Underwood, R.T.: Speed, volume and density relationships: quality and theory of traffic flow. Yale Bureau of Highway Traffic, 141–188 (1961)
41. Fox, J.: Applied Regression Analysis and Generalized Linear Models. Sage Publications, Thousand Oaks (2015)

**Weiwei Zhang** is a project manager at Beijing Infrastructure Investment co., Ltd. He was a postgraduate at Department of Civil Engineering of Tsinghua University, majoring in transportation engineering during 2014 and 2017.

**Ruimin Li** is an associate professor of the Institute of Transportation Engineering in the Department of Civil Engineering at Tsinghua University, China. He received his B.S. and Ph.D from Tsinghua University in 2000 and 2005, respectively. He was born in 1979 in Shandong province, China. He joined the Institute of Transportation Engineering, Tsinghua University in 2005. His current research interests include intelligent transportation system, traffic control, traffic management, and traffic simulation.

**Pan Shang** is a Ph.D. candidate of the Institute of Transportation Engineering in the Department of Civil Engineering at Tsinghua University, China. He received his B.S. from Beijing Jiaotong University in 2013, and M.S. from Tsinghua University in 2016. His current research interests include urban transit network state estimation and optimization.

**Hao Liu** received the M.S. degree in transportation planning from the research institute of highway ministry of transport, Beijing, China, in 2002, and the Ph.D. degree from the Delft University of Technology. Netherlands, in 2008. He is currently a researcher with the Beijing Transportation Information Center. His research interests include transportation planning and intelligent transportation system.