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A Traffic Congestion Assessment Method for Urban Road Networks Based on Speed Performance Index

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Abstract

This study aimed to analyze traffic congestion in urban road networks. The speed performance index was adopted to evaluate the existing road network conditions of congestion, then road segment and network congestion indexes were introduced to respectively measure the congestion levels of urban road segment and network. This study also carried out a traffic congestion analysis for Beijing expressway network, based on the speed performance data collected from January 1 to November 1, 2012, by Beijing Traffic Management Bureau (BTMB). Based on these analyses the proposed congestion indexes can well assess the traffic congestion conditions of urban road networks, more importantly, such an assessment study provides traffic control and management agencies an accurate and clear understanding of operation status of traffic networks.

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Keywords: traffic congestion; speed performance; urban road network; traffic control and management

1. Introduction

Traffic congestion has become a serious problem in many cities, especially in large cities. In order to alleviate traffic congestions, and improve the levels of service and efficiencies of urban transportation system, advanced traffic control and management methods have become effective and common approaches. Evaluating traffic congestion levels of road networks is important for traffic management and control, since it could allow the corresponding agencies an accurately and clearly grasping of network traffic operation status including the

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information of location and time for congested roads. Therefore, it is necessary to evaluate traffic congestion situations for urban road traffic networks using applicable evaluation measures.

In present, there is no unified and fixed evaluation measure for evaluating traffic operation conditions. In fact, there are various evaluation measures in different regions. For example, Texas Transportation Institute adopted the Roadway Congestion Index (RCI) in 1994 [1]; Washington State Transportation Department published the congestion report in 2006, in which the congestion evaluation index was defined as the average peak travel time [2]. In 1985, Highway Capacity Manual (HCM) [3] first suggested to use level of service as an evaluation index of road performance. The level of service was defined into six grades in the United States, and three grades in Japan. In China, Ministry of Public Security [4] chose the average travel speed of a city road as the evaluation indicator to describe congestion conditions of road traffic.

A considerable number of studies have explored the urban traffic state in different ways using the single valuation indicator e.g. travel speed and travel time that can be directly obtained through the loop detector, GPS, video, etc. Jia et al. [5] estimated urban traffic state using vehicle average travel speed, considering resident travel characteristics and road network capacities. Zhu [6] studied the urban road traffic congestion evaluation index system and the motor vehicle velocity distributions using the Gaussian mixture model (GMM), for analyzing congestion characteristics. Cesar [7] pointed out the benefit of travel time for measuring transportation network performance, and further discussed the methods of collecting travel time and speed data. Robert et al. [8] compared travel time and travel distance, discussed the influence of various indicators on congestion quantification, and finally presented a congestion classification method based on travel time from the perspective of travelers.

However, considering the complexity and dynamic nature of traffic, it is difficult to comprehensively assess traffic congestion conditions of urban road networks by single evaluation indicator. As a result, several studies began to evaluate the traffic state using multiple indicators. Bertini et al. [9, 10] used transit vehicle travel time and travel speed data in Portland, Oregon, to assess traffic conditions on arterials and freeways. Coifman et al. [11] mined the transit Automatic Vehicle Location (AVL) data to measure travel time and average speed on freeways and thereby quantify the corresponding traffic conditions. Duan et al. [12] integrated the traffic volume and occupancy to form a new value for network-wide traffic states observation and analysis, and then formed a pseudo-color image vividly represented the macroscopic traffic state. Turochy et al. [13] measured variability in traffic conditions by a variability index, which is computed by measuring the size (spatial volume) of the confidence regions defined by multivariate statistical quality control (MSQC) using large sets of archived traffic data (mean speed, and occupancy). Wang et al. [14, 15] presented a comprehensive traffic state estimator derived from traffic flow variables (flows, mean speeds, and densities). Nevertheless, there are some disadvantages, such as the complex computing, difficulty from collection of data and low practical application, for evaluating network traffic congestion using comprehensive indicators.

According to previous studies, both the vehicle speed, as a single evaluation index and combination with other factors to form a comprehensive indicator are important approaches to evaluate the traffic state. In this paper, the speed performance index, formed by the average travel speed and the maximum permissible road speed, was selected as the traffic state classification indicator and the traffic state was defined into four categories. Based on the speed performance, this paper proposed road segment and network congestion indexes to assess urban road network traffic congestion. The proposed indexes are simple and can be easily used for urban traffic management and control.

The remainder of this paper is organized as follows. The second section describes the traffic state classification standard and introduces the road segment and network congestion index. The third section carries out an empirical analysis of Beijing expressways in terms of the description of road network characteristics, road segment congestion assessment and road network congestion assessment. The last section summarizes several important conclusions and recommendations.

2. Method

2.1. Speed performance index

Vehicle speed is an important indicator for measuring the road traffic state. A large amount of vehicle speed data is detected by the loop detector from urban road traffic systems. And based on those data, Beijing Traffic

Management Bureau (BTMB) has presented the speed performance index (expressed in Equation (1)) as the evaluation indicator of urban road traffic state. The index value (ranging from 0 to 100) reflects the ratio between vehicle speed and the maximum permissible speed. BTMB chooses the two values (25, 50) as the classification criterion of urban road traffic state. This study uses this speed performance index to measure the road traffic state, but adopts three threshold values (25, 50, 75) as the classification criterion of urban road traffic state, as shown in Table 1. Base on this evaluation measure, we define the road segment congestion index and the road network congestion index to analyze traffic congestion of urban road networks.

$$R_v = \frac{v}{V_{\max}} \times 100 \tag{1}$$

where,

R_v denotes the speed performance index;

v denotes the average travel speed, km/h;

V_{max} denotes the maximum permissible road speed, km/h.

Table 1. The evaluation criterion of Speed Performance Index on expressway.

Speed Performance Index	Traffic State Level	Description of Traffic State
[0,25]	Heavy Congestion	The average speed is low, road traffic state poor.
(25,50]	Mild Congestion	The average speed is lower, road traffic state bit weak.
(50,75]	Smooth	The average speed is higher, road traffic state better.
(75,100]	Very Smooth	The average speed is high, road traffic state good.

2.2. Road segment congestion index

In order to measure the degree of road segment congestion, this paper chooses the average road segment state and the duration of non-congestion state in the observation period to define the road segment congestion index, expressed in Equation (2) & (3). The non-congestion state includes two traffic states: smooth and very smooth, namely the speed performance index is larger than 50 (km/h). The value of the road segment congestion index R_i is between 0 and 1, and the smaller the value of R_i, the more congestion of road segment.

$$R_i = \frac{\overline{R_v}}{100} \times R_{NC} \tag{2}$$

$$R_{NC} = \frac{t_{NC}}{T_t} \tag{3}$$

where,

R_i denotes the road segment congestion index;

$\overline{R_v}$ denotes the average of speed performance index;

R_{NC} denotes the proportion of non-congestion state;

t_{NC} denotes the duration of non-congestion state, minute;

T_t denotes the length of the observation period, minute.

2.3. Road network congestion index

The road network is formed by many road segments, so this paper gives the road network congestion index based on the road segment congestion index, expressed in Equation (4). Similarly, the value of the road network congestion index R is between 0 and 1, and the smaller the value of R, the more congestion of road network.

$$R = \frac{\sum_i R_i L_i}{\sum_i L_i} \tag{4}$$

where,

R denotes the road network congestion index;

L_i denotes the length of road segment, km;

3. Case study – Beijing expressway congestion analysis

Beijing urban expressway network, consisting of five loops (the Second Ring Road, the Third Ring Road, the Fourth Ring Road, the Fifth Ring Road and Sixth Ring Road) and 15 urban rapid connecting lines, carries huge traffic volumes and represents the overall level of traffic conditions [16, 17]. The expressway traffic state data provide 40280257 records which cover 244 freeway sections (Figure 1) from January 1 to November 1, 2012. Although the volume of data is large, there is no traffic state data on certain sections at a certain time. In addition, the meteorological department usually chooses April, July, October and January respectively as a representative month of the spring, summer, autumn and winter. Given high quality data, annual statistical data and the everyday traffic flow distribution, this study chooses the freeway traffic state data at the third week of every month, including January, April, July and October. The selected data have 3853206 records, 9.57% of the original data.

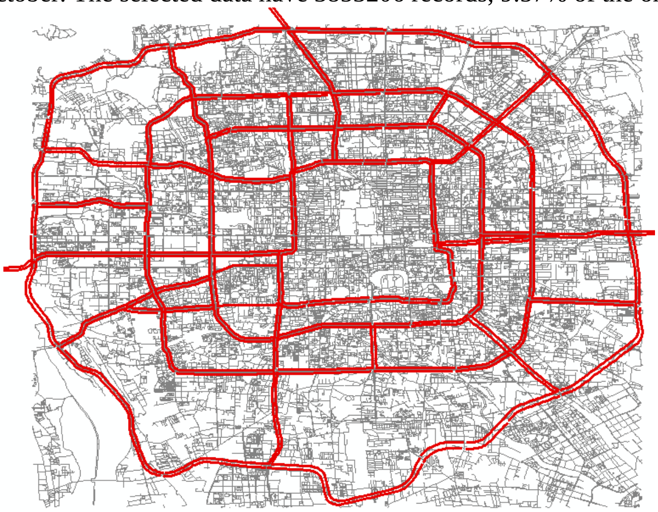


Fig. 1. Beijing urban expressway network.

3.1. Characteristics of Beijing expressway network

Based on the large number of data, this paper analyzes the characteristics of Beijing expressway network. As shown in Figure 2, the cylindrical part of the figure represents the frequency corresponding to the different speed performances, and line segments represent the cumulative probability density of speed performance. The result shows that the proportion of speed performance which over 90 is more than 50%, and 78.8% of the data which the speed performance index is larger than 75. Before the value of 75, the cumulative probability density function of speed performance increases slowly, whereas it increases rapidly after the value of 75.

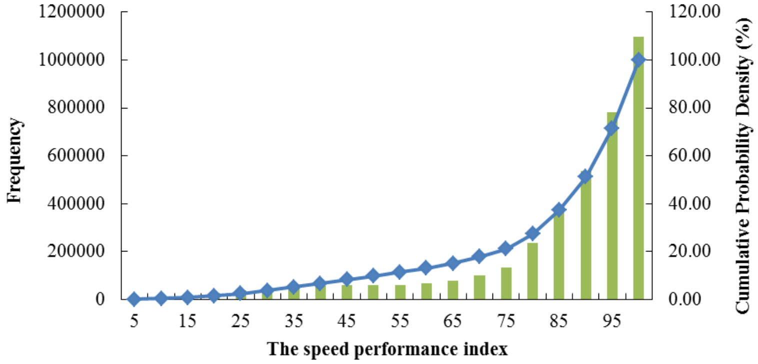


Fig. 2. Frequency distribution of the speed performance on Beijing expressway network.

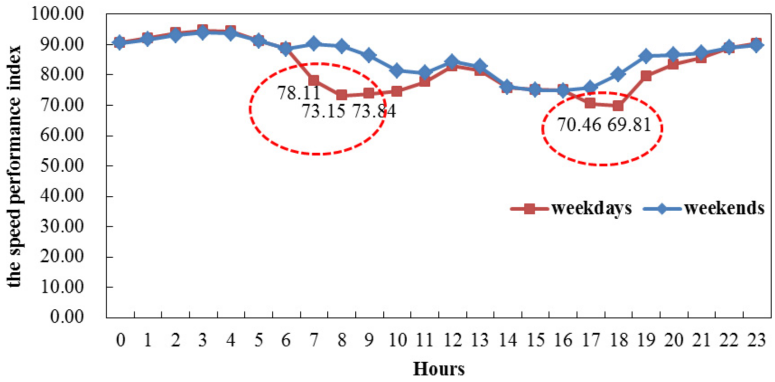
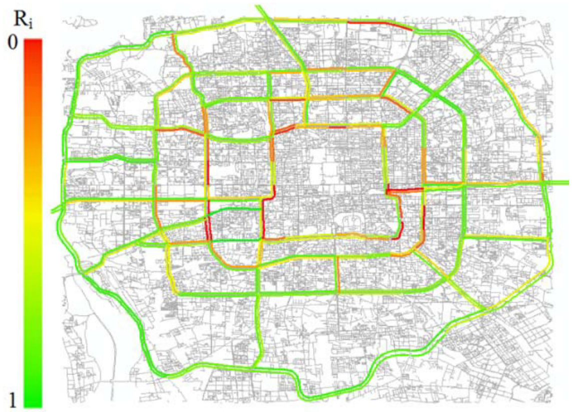


Fig. 3. Hourly speed performance on Beijing expressway network

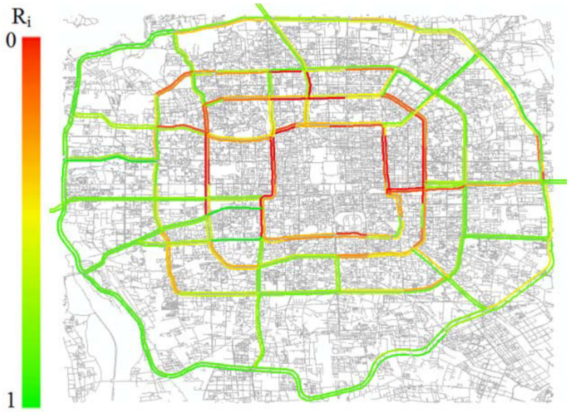
Figure 3 illustrates the hourly speed performance indiced on weekdays and weekends. As it is known to all, the morning peak hour is often from 7:00 to 9:00, and the evening peak hour is from 17:00 to 19:00. Shown in the curve of weekdays, there are obvious morning and evening peak hours. The lowest points during morning and evening peaks are respectively at 8:00 and 18:00. The evening peak is from 17:00 to 19:00, which is in accord with the previous knowledge. During the morning peak, the speed performance begins to decline quickly at 7:00, and then declines to the lowest point at 8:00, but the low speed performance lasts to about 10:00. On weekends, the speed performance is better than weekdays, and the peak hours appear around 12:00, and the speed performance of the morning is better than the afternoon.

3.2. Segment congestion assessment

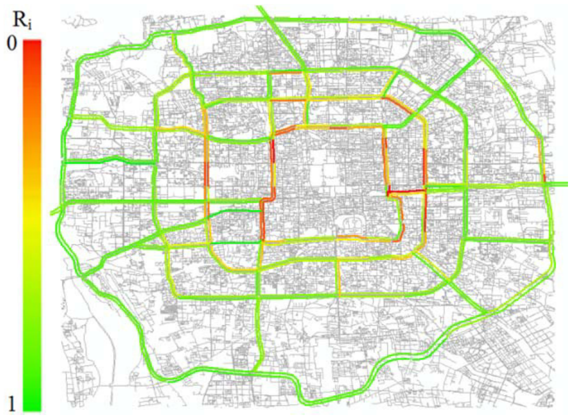
The ArcGIS Map software was used to show the Beijing expressway traffic states, and adopted the road segment congestion index to assess the road segment congestion. Figure 4 includes four graphs, which describe the road segment congestion during four observation periods: the morning peak period, the evening peak period, the flat peak period and the weekend time respectively. Based on previous analysis of Beijing expressway network characteristics, the morning peak is from 7:00 to 10:00, the evening peak is from 17:00 to 19:00, the flat peak is from 10:00 to 17:00, and the weekend time is from 7:00 to 19:00. Figure 4 presents the congested road segments on the Beijing expressway network, i.e., the road segments with the red color. Congested road segments distribute more dispersedly during the morning peak, whereas they are relatively concentrated during the evening peak, mainly on the northeast and northwest regions. And the expressway network traffic state during the morning peak is much better than the evening peak, because there are less heavy congested road segments in morning peak than evening peak. In the plat period, traffic congestions are mainly concentrated on the Second and Third Ring Road, and most of road segments are in mild congestion condition. On weekends, there are only several mild congested road segments focused on the Second and Third Ring Road.



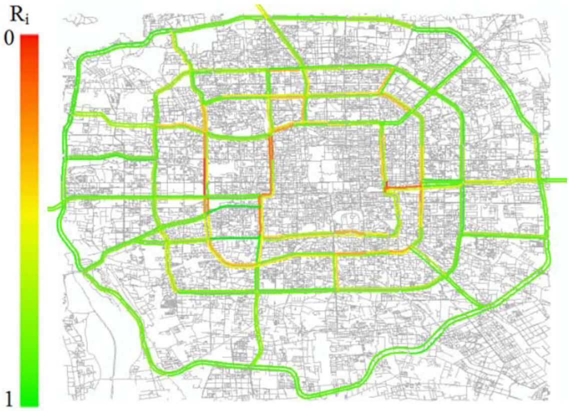
(a) weekdays AM peak;



(b) weekdays PM peak;



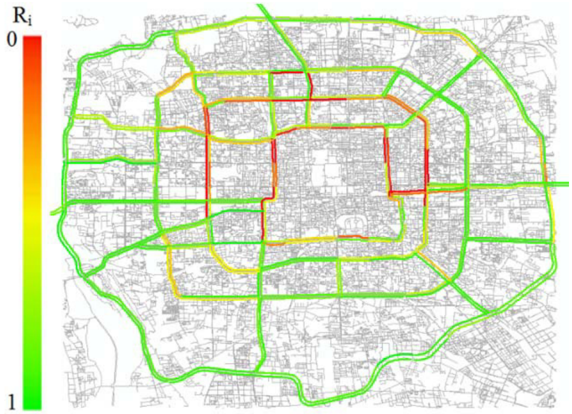
(c) weekdays plat peak;



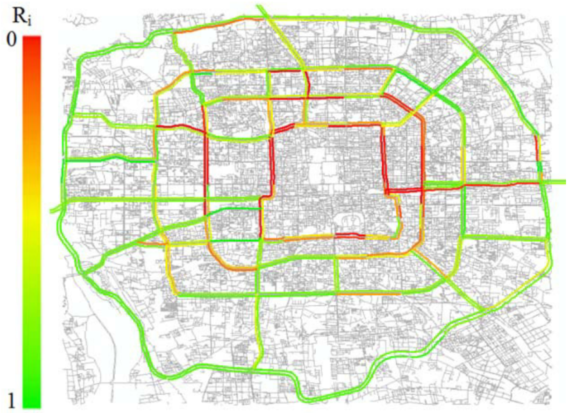
(d) weekends.

Fig. 4. Road segment congestion assessments on weekdays and weekends.

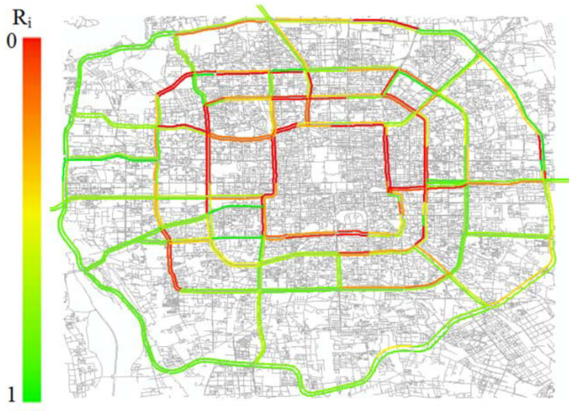
In addition, this paper assessed the road segment congestion under different seasons, as shown in Figure 5. For the seasonal analysis, the evening peak was selected as an observation period, because the road segment condition in the evening peak is the worst as shown in Figure 4. Figure 5 shows that some road segments on the Beijing expressway network have the characteristic of seasonal congestion. In the evening peak, the road segment condition is the best in spring such that a few congested road segments distribute on the Second and Third Ring Road, followed by summer. And in autumn and winter, congested road segments are increased on the Second and Third Ring Road, and appear on the Fourth and Fifth Ring Road. The seasonal analysis was also conducted for the morning peak, which found that the road segment condition is the best in spring, followed by winter.



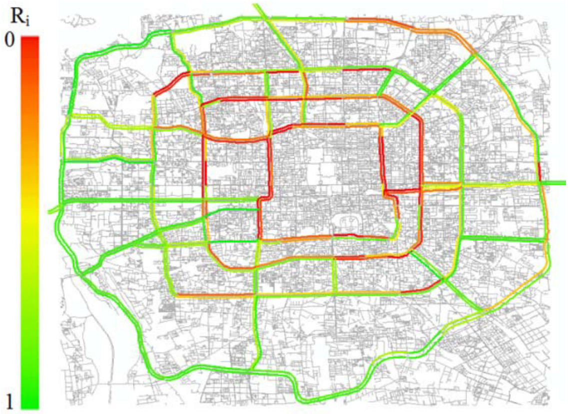
(a) spring;



(b) summer;



(c) autumn;



(d) winter.

Fig. 5. Road segment congestion assessments under different seasons (PM).

3.3. Network congestion assessment

Figure 6 depicts the Beijing expressway network congestion curves for 24 hours on weekdays and weekends, through the road network congestion index. The curves are similar to the trends in Figure 3. The two small figures in Figure 6 reflect the changing trend of network congestion conditions during the morning and evening peak respectively, through calculating the road network reliability index per 15 minutes. In the morning, the road network congestion continues to become worse, until the worst congestion (R=0.681) at the 7th 15 minutes period after 7:00, and heavy congestion keeps stable after a slight improvement. However, the changing trend of PM road network congestion is different, which likes a quadratic curve. It has the worst congestion (R=0.628) at about the fifth 15 minutes period after 17:00.

Moreover, the study also analysed the influence of seasons on the road network congestion. As shown in Figure 7, the road network congestion has obvious seasonal patterns. In spring, the road network traffic state is the best both on weekdays and weekends, followed by winter. And autumn has the worst road network traffic state both on weekdays and weekends. Autumn has the smallest gap (0.02) and summer has the largest gap (0.06) between weekdays and weekends, followed by winter with the gap of 0.05. In Figure 7, this study also found that the road network congestion on weekdays is severer than weekends.

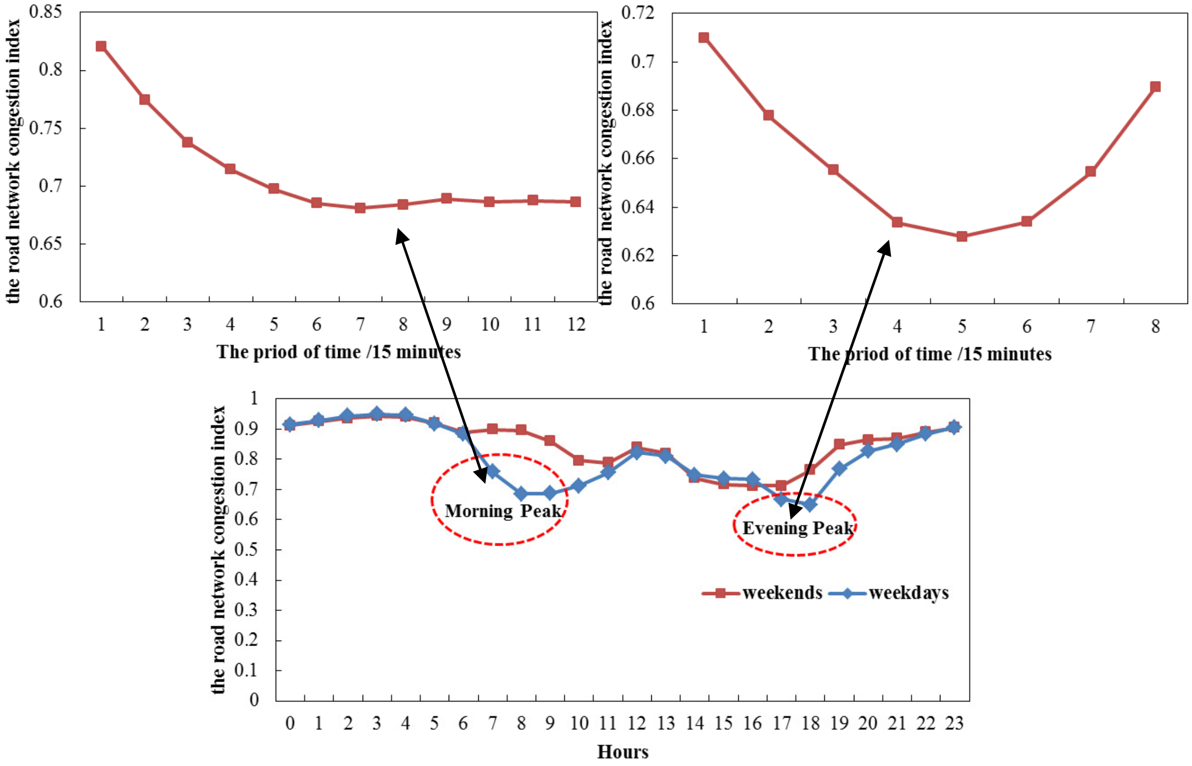


Fig. 6. Beijing expressway network congestion curves for 24 hours one day on weekdays and weekends.

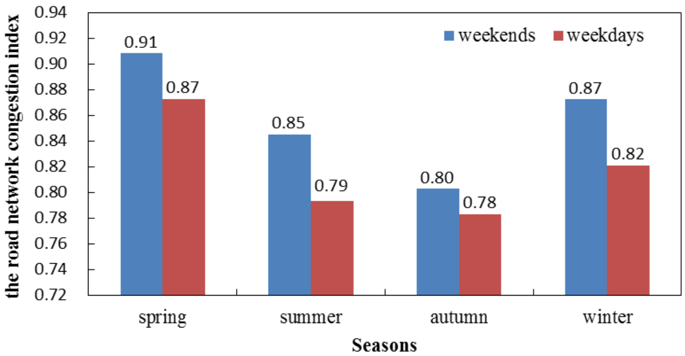


Fig. 7. Beijing expressway network congestion during different seasons.

4. Conclusion

This study selected the speed performance index as the road network state evaluation indicator, and divided the traffic state into four categories: heavy congestion, mild congestion, smooth and very smooth. Based on the traffic state classification standards, the study proposed the road network congestion index and the road network congestion index to measure the congestion degree of road segment and road network respectively. Taking Beijing expressway congestion analysis as a case study, this study carried out Beijing expressway network characteristics analysis, road segment congestion assessment and road network congestion assessment.

According to the Beijing expressway network state analysis, we can have an accurately and clearly grasping of network traffic operation status in Beijing, which provides important information for future traffic management. Overall, 78.8% of the Beijing expressway network is very smooth all the year round. The morning peak has the congestion delay phenomenon in the way that road network congestion continues to about 10:00. According to road segment congestion assessment and road network congestion assessment, the Beijing expressway network during the morning peak is much better than the evening peak, and season is also an important influence factor to urban road network congestion. The Beijing expressway network congestion has seasonal pattern that the road congestion concentrates mainly on the Second and Third Ring Road throughout the year, but spreads to the Fourth and Fifth Ring Road in autumn and winter, which can be found from the road segment congestion assessment. The road network congestion is the worst in autumn, followed by summer and it is severer on weekdays than weekend

Acknowledgements

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