Urban Traffic Operation Pattern and Spatiotemporal Mode Based on Big Data (Taking Beijing Urban Area as an Example)

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Abstract. An analysis of urban traffic operation pattern and spatiotemporal mode is an important basis to solve the problems of traffic congestion, emergency and extreme weather. Traditional studies on the urban traffic operation pattern and spatiotemporal mode usually are restricted by issues as poor time effectiveness, large space scale and coarse time granularity of traffic flow data, thus this essay choose to use the urban traffic speed data based on floating vehicle trajectory to dissect the urban traffic operation pattern and spatiotemporal mode in Beijing in a multi-dimensional and fine granularity. Differences of features in weekdays and weekends are also compared. This paper reports that "two-peak" mode is obvious in the urban traffic condition. Besides, the morning peak of weekends is postponed to 11-12 am, and the night peak appears shorter in 5 pm compared to weekdays. Finally, four modes of traffic and its driving mechanism are concluded.

Keywords: Traffic flow · Impact factors · Traffic speed data · "Two-peak" mode · Tide mode

1 Introduction

With urbanization and economic development fastened in recent years, traffic congestion has become an urgent issue to solve for urban economy and social development in China. Beijing, as the capital of the country with the largest population and fastest economy development, is now suffering from traffic congestion a lot, and traffic speed in Beijing now is also one of the slowest in the world. In 2008, the amount of social time delay and extra fuel consumption due to traffic congestion occupies between 0.5 % and 2.5 % of GDP of Beijing [1]. Main reasons of traffic congestion in Beijing include discordance of road network and urban planning layout, unreasonable road design, unreasonable arrangement of bus stops as well as entrances and exits of ring roads, and large amount of vehicles. The amount of vehicles has doubled from 2000 to 2007.

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In order to deal with the stressful condition of traffic congestion in cosmopolitans, both domestic and foreign scholars have studied the issues from various perspectives.

Firstly, studies have been made from the perspective of urban traffic operation: Chen Xin has studied the method of evaluation and optimization of urban traffic network, and conducted field study in Gongyi, Henan [2]. The optimized solution was later applied in the city. Mao Tao used the main street road network in Xi'an as an example to analyze the static and dynamic efficiency of urban traffic network [3]. Ibrahim and Hall provided regression analysis on how the highways in Mississauga, Canada are affected by different weather elements, and they discovered that the average speed of rainy days may have a 5–10 km/h reduction, and the effect of snowy days can be larger, with a 38–50 km/h reduction [4]. Knapp and Smithson analyzed that average reductions range from 16 % to 47 % for different storm events in Iowa State during winter storms [5]. Keay and Simmonds reported that the traffic reductions resulted from rain-fall and other weather variables during wet days were 1.35 % in winter and 2.11 % in spring [6]. Smith investigated the impact of rainfall at varying levels of intensity on freeway capacity and operating speeds [7].

Secondly, researches have been made from the internet perspective of traffic flow structured by vehicle positioning based on urban GPS vehicle data. Bin Jiang analyzed the road network structure of Gavle, an eastern city in Sweden, based on taxi driving data from GPS, and received traffic flow allocation in different roads and hotspot information of urban traffic [8]. Guo Jing used the driving data collected from the 4th Ring Road expressway and main street floating vehicles in five weekdays in Beijing to accomplish the assessment of urban traffic condition, and he also provided related suggestions to deal with traffic congestions [9]. Gou Xirong used the data of taxi GPS and road network in Kunming to finish the work of data matching and dynamic visualization of data traffic, and he also analyzed the spatiotemporal allocation pattern of traffic condition in Kunming. In the essay, the mostly used map-matching algorithm and GPS data processing method are introduced in detail [10]. Jayakrishnan and Mahmassani used the method of on-line generation and real-time evaluation to convince that real-time simulation of a traffic network can predict future conditions and thus help design and implement more effective traffic operations [11, 12].

Existing studies are usually restricted by issues as poor time effectiveness, large space scale and coarse time granularity of traffic flow data, thus in this essay we choose to use the urban traffic speed data based on floating vehicle trajectory (three weekends and three weekdays) to dissect the urban traffic operation pattern and spatiotemporal mode in Beijing in a multi-dimensional and fine granularity using analysis of time series and spatiotemporal statistics. The feature differences between weekdays and holidays are also compared to provide strong theory support for solving congestion issues, adjusting urban road traffic security contingency plan and setting comprehensive traffic manage and control measures.

2 Areas Studied and Data Source

2.1 Brief Introduction of the Areas Studied

Currently, the areas inside the 3rd Ring Road of Beijing are capable of political, economic, scientific, educational, medical, financial functions. The overlap of urban functions on the one hand creates a dual economic structure between the urban area and the areas around; on the other hand, the condition of agglomeration economy has reached its extreme in the areas. Institutions, national sectors and functional organizations are intensely located in the urban areas, while residential areas are outside the 4th Ring Road, which causes a large cost of commute and directly influence the urban traffic condition. As supervised, the morning peak of weekdays witness 1.6 times as many cars driving into the 2nd Ring Road area as that driving outside, whereas twice as many driving outside during the evening peak. Every day, 5.5 million vehicles are on the road of Beijing [13], and floating population inside the 6th Ring Road is as high as 30.33 million (pedestrians are not included). According to statistics, an average commute time for people in Beijing is 97 min in 2014 [14], which lead to heavy burden on urban load and road traffic. Based on this, the government has conducted a series of measures including massive underground construction, real-time management and control, vehicle restrictions based on license plate number, congestion prompt and limited driving time for special vehicles.

2.2 Data Source and Management

Based on the trajectory data of floating vehicles, the driving speed of all floating vehicles can be received and an average speed is used in this essay. The data cover more than 470 main roads in Beijing and are collected every 5 min, so that real-time road network condition can be reflected. The advantage of data is the high spatiotemporal resolution ratio and accuracy, and the data are collected from 1 Jan, 2015 to 6, Jan 2015, which consist of three vacation days and three workdays. In order to guarantee the credibility and accuracy, all data used in analysis of traffic operation mode, spatiotemporal pattern and comparison between days are mean of corresponding periods of time.

2.3 Research Method

Auto-correlative indexes of space measurement include Moran Index, Geary Coefficient and G-statistics, which can all be used to study data of the whole areas and one specific unit of area. The standardized statistics of the general index can be used to judge if the aggregation of attribute value of the areas studied is notable from a mathematical perspective.

The formula of Moran I is shown as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i-\bar{x})\left(x_j-\bar{x}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\sum_{i=1}^{n}(x_i-\bar{x})^2} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i-\bar{x})\left(x_j-\bar{x}\right)}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}} \tag{1}$$

In which, x_i represents the attribute value of unit i, I refers to the calculated Moran Index, i and j represent two different space units, and n is the amount of units in the whole area studied.

$$S^2 = \frac{1}{n}\sum_{i=1}^{n} (x_i - \overline{x})^2 \tag{2}$$

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

The mathematical expectation of I:

$$E(I) = -\frac{1}{n-1} \tag{4}$$

With an increasing sample size n, E(I) will approach 0.

The result of calculation is usually between -1 and 1. When the result is positive, there is positive aggregation between the attribute values of the objective areas studied, which means the distance of space location is short and probable interactions may exist between the areas with similar attribute values. When the result is negative, it indicates that there is negative aggregation between the attribute values of the objective areas studied. When the result is zero, there is no aggregation between the attribute values. When the result is close to the mathematical expectation of I, then there is no interaction between the units of areas, and the distribution is random.

For the result of calculation I, the standardized statistic Z can be used to identify the significant level of the aggregations between the spatial area units. The formula of calculation is shown below:

$$Z = \frac{I - E(I)}{\sqrt{Var(I)}} \tag{5}$$

The two general statistics can reflect the overall situation of the attribute values of spatial area units in the areas studied, however, the level and the position of the attribute values under the abnormal aggregation cannot be gained; therefore, the local statistics are applied to analyze the data. The research shown below emphasize on applying local Moran index.

The local Moran index is defined as:

$$I_i = \frac{n(x_i - \overline{x})\sum_{j=1}^{n} W_{ij}(x_j - \overline{x})}{\sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{6}$$

The standardized statistics are:

$$Z(I_i) = \frac{I_i - E(I_i)}{\sqrt{Var(I_i)}} \tag{7}$$

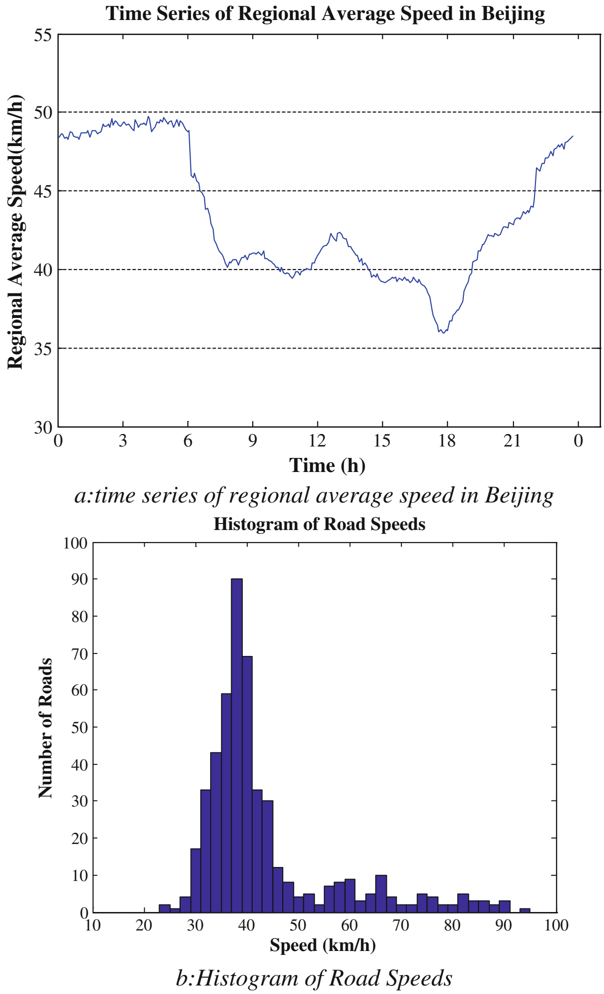


Fig. 1. Temporal evolution feature in weekdays

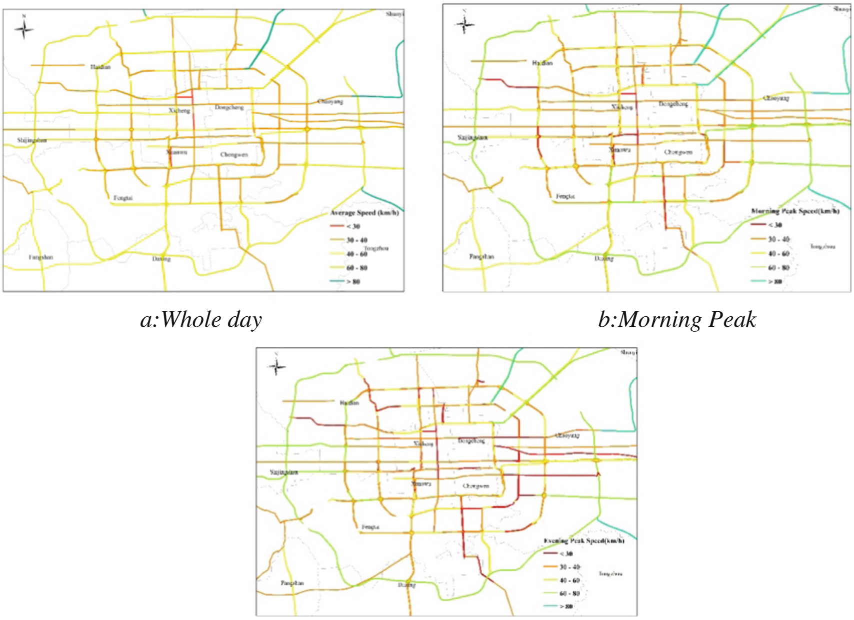
3 Analysis of Spatiotemporal Mode in Weekdays

3.1 The Spatiotemporal Evolution Pattern of Traffic Capacity

According to Fig. 1, the temporal evolution feature throughout a day shows an apparent "two-peak" mode in Beijing urban areas, in other words, there is a marked feature of morning peak and evening peak. From 12 am to 6 am, the average speed in the road network is nearly 50 km/h; after 6 am, the average speed drops drastically until the morning peak is formed at 7:30, when the average speed maintains at 40 km/h. It is until 11 am that the average speed begins to rise slowly. After 1 pm, the average speed declines again and lasts to the evening peak after 5 pm. It reaches the lowest—35 km/h

—at 6. After that, it rises and exceeds 40 km/h at 8 pm. The normal distribution curve for average speed in the road network is shown in the following figure, and the axis is at the point less that 40 km/h, while few roads have an average speed over 60 km/h.

The spatial distribution features of driving speed in the study area, shown in Fig. 2, reflects that ring roads and mainly roads into the city have a rather slow driving speed, for instance, the 2nd ring road, the northern and eastern part of the 3rd ring road, the Beijing-Tibet Highway, Xueyuan Road and Chang'an Avenue. We then analyze the spatial distribution features of morning and evening peaks, which is shown in the figure as well. During morning peak, areas with slow speed appear around Xuanwumen, Xinjiekou, Xizhimen, Jianguomen, Guangqumen, Guang'anmen, Fuxingmen and Deshengmen. During the evening peak, such areas still exist and expand to roads of more directions as well as side roads, which to some extent proves the basic analysis mentioned above that the average speed of evening peak is obviously slower than that of morning peak.

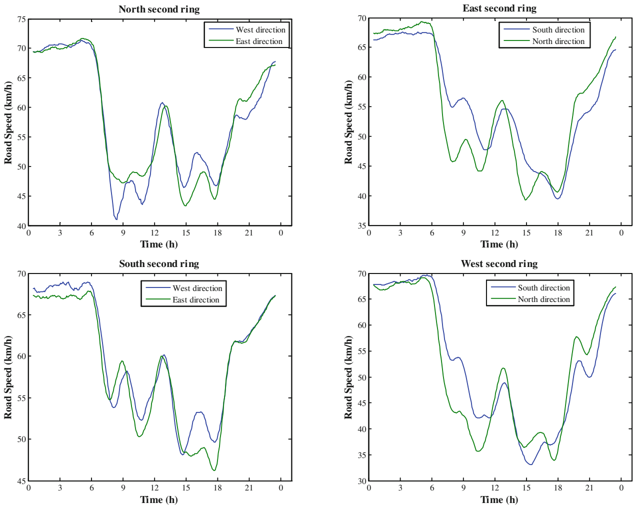


a:Whole day b:Morning Peak

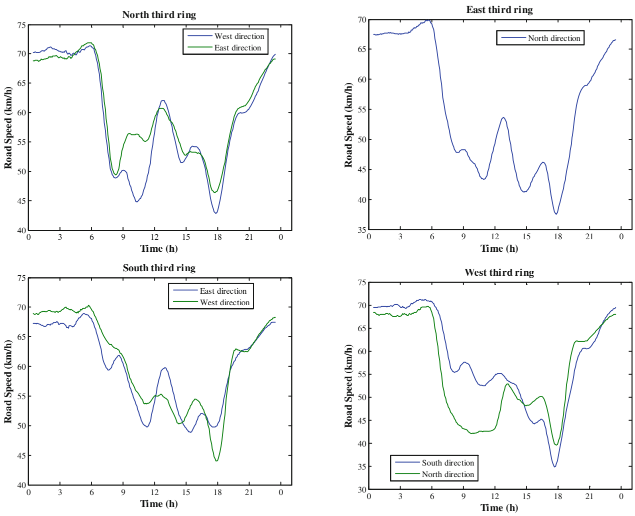
c:Evening Peak

Fig. 2. Spatial distribution features of driving speed

In Fig. 3, a further analysis of distinctions of driving speed on difference directions of road is made, using the ring roads as an example. Both directions on different parts of the 2nd ring road have significant "two-peak" patterns, yet the change rules of different parts are various. Take the northern part as an example, the speed on the side to the west is much slower than that to the east during the morning peak, while the situation is the opposite during the evening peak, thus a "tide" phenomenon can seen



Note: the 2nd Ring Road



Note: the 3rd Ring Road

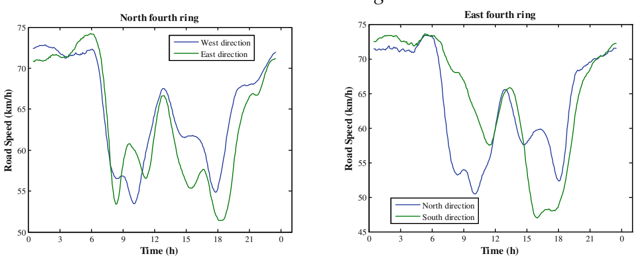
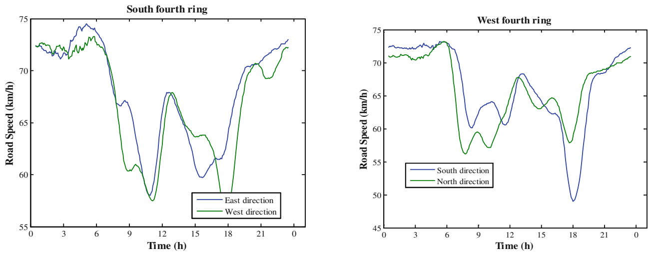
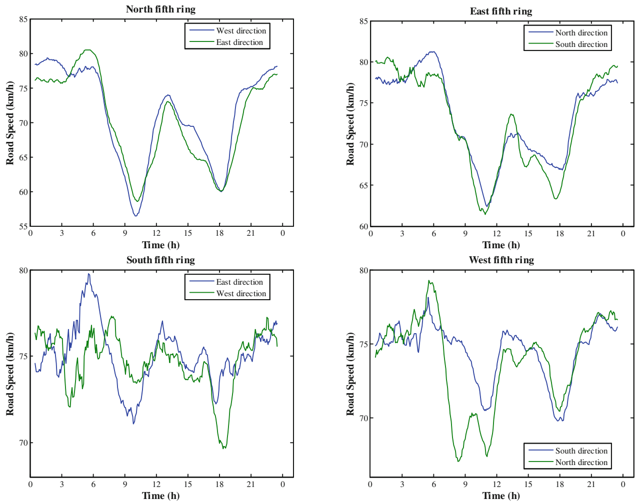


Fig. 3. Average speed of 24 h on a two-way ring road



Note: the 4th Ring Road



Note: the 5th Ring Road

Fig. 3. (continued)

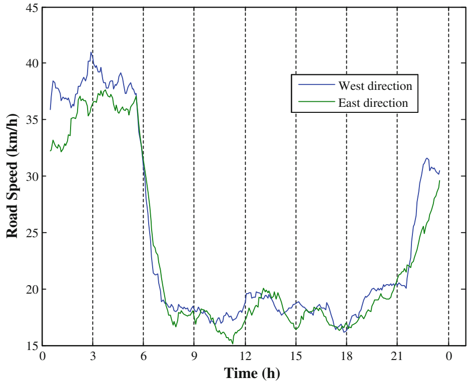
here, as well as on the western part of the 2nd ring road. Differently, the eastern part always sees a slower speed on the side to north than that to south, while the two directions on the southern part are largely similar. All parts of the 3rd ring road has the “two-peak” features, and the western part has the tide pattern while the other parts have similar variation trend on both directions. All parts of the 4th ring road has the “two-peak” features, and the eastern and western parts have the tide pattern while the other parts have similar variation trend on both directions. All parts of the 5th ring road has the “two-peak” features, but the average speed is much faster than the other ring roads mentioned. In all, all ring roads have the “two-peak” mode while it is easy for the tide mode to appear on the eastern and western part due to fact that most labor markets are located in the northern part of the city.

3.2 Analysis on Evolution Mode in Hotspot Areas

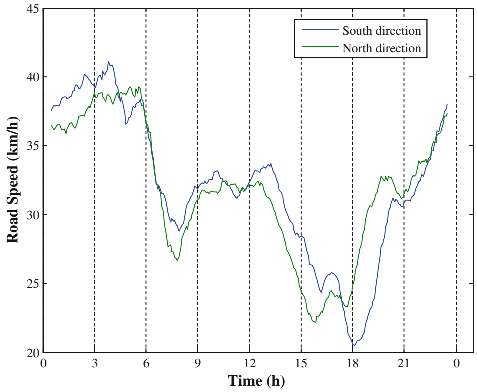
Based on different stages, patterns and distinctions of congestions on the same road, we can further generalize the evolution pattern of Beijing and classify as follows: (1) all-day congestion appears on both directions; As shown in Fig. 4a, Yaziqiao Road, which is located in the southwestern part of 2nd Ring Road (continuous congestions from 8 am to 22 pm on both directions), has a similar condition for both sides of the road—the congestion starts at 6 am and reaches the peak at 7 with a speed below 20 km/h. The peak lasts till 9 pm when the speed finally rises. The Yaziqiao Road is located to the west of Baizhifang Bridge near the west 2nd Ring Road, and as a junction for Beijing-Kowloon Railway, West Station Street, South Honglian Strret and Lianhuahe Road, it experiences large traffic flows every day. (2) both directions of road have same feature of "two-peak". As shown in the Fig. 4b, the Xuanwumen Inner Street, which connects West Chang'an Avenue and East Xuanwumen Street, has a similar speed change on both sides of the street and two peaks as well. The morning peak starts at 8 am and alleviates after 9, and the evening peak is between 4 and 6 pm (the side to the north is earlier, at around 4 pm, and the southern one is around 6 pm). The evening peak alleviates at 8 pm. (3) the tide mode is shown in the Fig. 4c using the example of Jianguo Road—east to the Guomao Bridge and ends up at old Beijing-Yushu Highway. The "tide" feature refers to the congestion on only one direction of the road with specific stage, time period and rules. It describes a kind of spatiotemporal imbalance that mainly takes place during the two peaks on main roads connecting residential and working areas. CBD usually has large influence on peripheral satellite areas, and the commute mode of working in the city center during daytime and live in the suburb at night leads to the regular and periodic "tide" mode in traffic. Also, the occasional tide traffic caused by large activities and festivals also exists due to residents' visits to specific places. (4) the one-direction congestion is shown in the Fig. 4d with the example of Shuanglong Road—which lies between east 3rd Ring Road and 4th Ring Road. The congestion on the side to the west starts from 8 am and ends at 8 pm, while the east side barely suffers from congestion. The reason is that Shuanglong Road is a vital part for Beijing-Harbin Highway, which brings much pressure on the specific side of the road.

3.3 Regional Differentiation Characteristics and Effect Mechanism

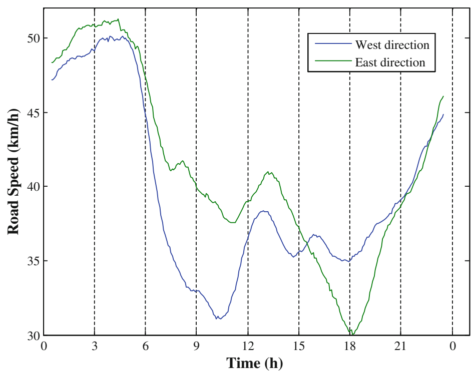
Through the recognition of local Moran I index, similar characteristics can be seen shared by the areas with morning and evening congestions in Beijing, which mainly locate inside the 3rd Ring Road, especially the north-south streets are in continuous congestion in the morning peak. Moreover, the congested streets located outside the 4th Ring Road mainly are roads into the city as Daxing City Road, Tongzhou City Road, as Fig. 5 shows below. The traffic operation pattern and congestion mode in Beijing are the results of several prospects: firstly, early as 2005, Beijing's overall urban planning determined the strategic goal of restricting the increase of downtown population and enhance regulation of land used as well as the core economic function including finance, commerce and trade. Such plan results in the enhancement of economic



a. Yaziqiao

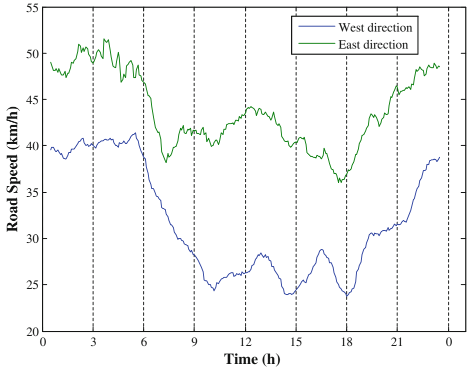


b. Xuanwumen



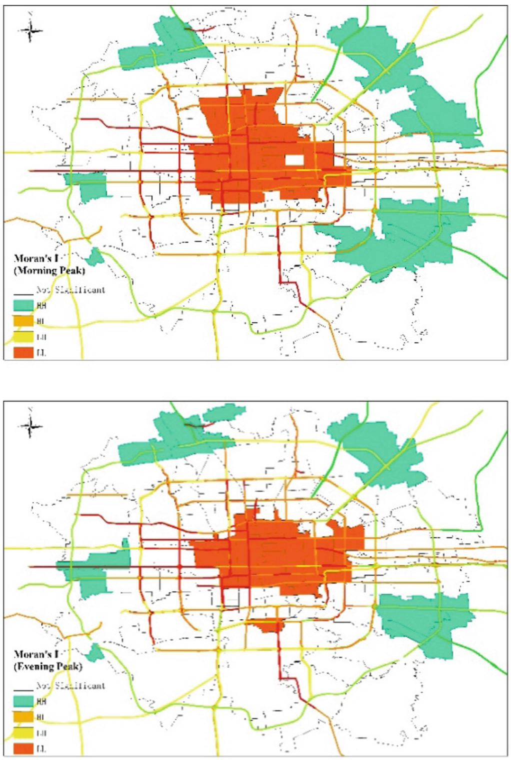
c. Jianguo

Fig. 4. Average driving speed on two-way road of hotspot areas in weekdays



d. Shuanglong

Fig. 4. (continued)

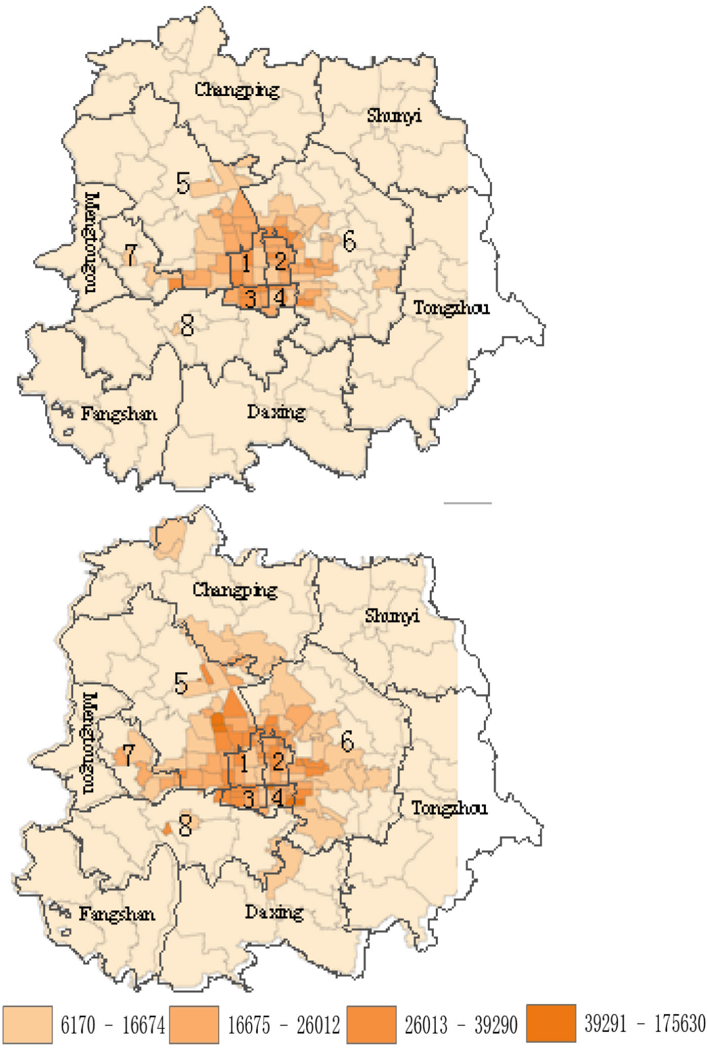


a:Morning Peak

b:Evening Peak

Fig. 5. Congestion pattern from local Moran I

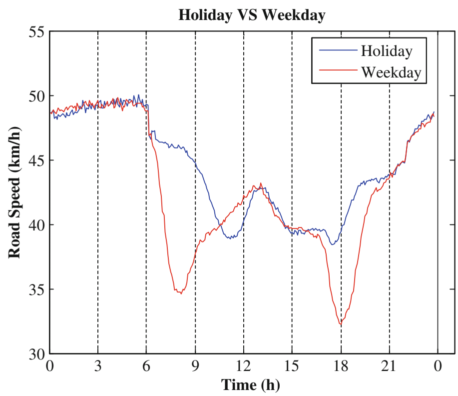
function, the growth in industry and the increase in the density of building land. In addition, as to the plentiful residential areas built outside the city, the total population



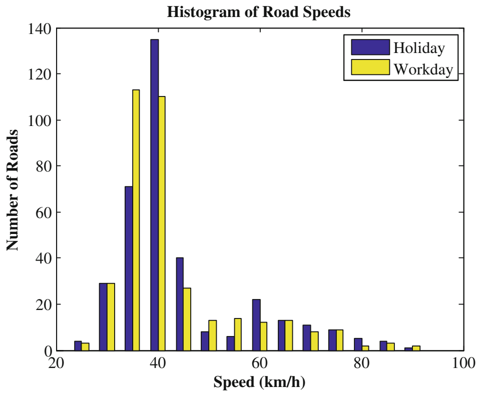
1.Xicheng;2.Dongcheng; 3.Xuanwu;4.Chongwen;
5.Haidian; 6.Chaoyang; 7.Shijingshan; 8.Fengtai;

Fig. 6. Total population distribution (Left 2000, Right 2010)

of Wangjing, Tiantongyuan and Huilongguan is equivalent to a medium-sized city. However, due to the lack of forecast and evaluation to the traffic effect, corresponding industrial planning and commercial activities, the cities turn out to become ‘sleeping cities’. Therefore, an outward movement of living functions facilitates the separation of workplace and residence and tidal traffic phenomena, which causes traffic problem to deteriorate.



a:Road average speed



b:Evening Peak

Fig. 7. Temporal evolution feature in weekends

As Fig. 6 shows (take the changing trend of the resident population density as an example), there are only four streets with a risen density level in the capital function core area, namely Beixinqiao in Dongcheng Distinct, Desheng in Xicheng Distinct, Longtan in Chongwen Distinct and Guangwai in Xuanwu Distinct, which all locate on the edge of the second ring road. In addition, the level of population density in the Stadium Road and Qianmen Streets decreased, in which the Qianmen Streets leveled down for two degrees. Since the government introduced the general plan for restoration improvement in the Qianmen District, the work has been accomplished gradually by having large buildings built and large number of residents directed to move out of the district. The city function expansion area, which includes 9 streets of Haidian District, 12 streets of Chaoyang District and several streets in Shijingshan and Fengtai District, now becomes the main area with a rising population density level. In other areas, districts as Changping and Huilongguan has their population density leveled up, and the rest remain stable. Thus it can be seen that most residents are moving outward and have formed new aggregation areas. Plus, there is no necessary traffic corridor established between the city center and outward residential areas, and only the east 3rd Ring

Road, east 4th Ring Road, west 3rd Ring Road and west 4th Ring Road are working as arterial traffic, which worsens the traffic congestion issues.

In addition, Beijing is now in the period of fast development of private transportation, with a ratio of private transportation usage higher than some of the cosmopolitan cities in developed countries, thus the conflict between the demand of private transportation and the supply of road traffic has become more serious. Till 2010, the vehicle inventory in Beijing has reached 4.809 million, which occupies 5.2 % of domestic inventory. Related policies have been introduced by the government of Beijing, from the vehicle restrictions based on license plate number to the car registration lottery, mainly to limit the inventory of private transportation in Beijing as well as the ratio of trip by private transportation. However, the policies forced citizens to buy more than one car to break the limitation, thus actually add the inventory. Moreover, there is a lack of foresight during the formulation of policies. For instance, the government considers the automobile industry as the breakthrough of modern manufacturing business, while gaining large amount of economic development, the easing policy of vehicle usage also has caused the sharp increase of number of cars.

4 Discussions

The Fig. 7 illustrate the contrast features of time-order evolution between driving speed during vacations and that of weekdays, and the “two-peak” mode can apparently be seen from the traffic operation during vacations in Beijing. Different from the weekday morning peak, which starts at 7:30 and ends at 11, morning peak during vacation is postponed to 11-12 am, and the night peak appears shorter in 5 pm. In Fig. 7, the contrast features of the normal distribution curves for average speed in both vacations and weekdays are shown. The axis of the data for vacation days locates at the point of 40 km/h, which is much higher than that of the workdays, and the frequency to the left of axis declines while that to the right rises.

Affected by family visits, shopping, self-driving tour and the cancellation of traffic controls during vacations, main transportation junctions, tourist attractions, business districts, main national roads, travel routes and four highways connected Beijing and Tibet, Chengde, Hong Kong, Macau and Kaifeng all suffer from large traffic pressure, while roads in nearby places may also witness traffic congestions. Also, some temporal traffic control measures may also influence social traffic during vacations. As shown in the figures, comparing the spatial distributions between the traffic speed of vacation days and that of weekdays, tourist attractions as Xiangshan Mountain, the Summer Palace, the Palace Museum and the Beihai Park, other areas for large activities, and business districts will become hotspot areas with large traffic.

5 Conclusions

(1) The temporal evolution feature of the areas studied throughout a day shows an apparent “two-peak” mode in Beijing urban areas, in other words, there is a marked feature of morning peak and evening peak. The spatial distribution feature of the

driving speed in the areas studied shows a slow speed on the ring roads and entrance route into Beijing. In general, morning peaks and evening peaks can be seen on every sector of the ring roads, while a "tide" phenomenon appears in the vehicle flows on the eastern part and the western part of the ring roads.

(2) According to different traffic speed in various time periods and directions, four modes of traffic are concluded: with same modes on both directions, congestion is an all-day feature; with similar modes on both directions, peaks occur in mornings and nights; tide mode; and one-direction congestion. The four modes have provided reliable evidence for setting comprehensive traffic control and management measures to solve various types of congestion issues based on specific regional conditions.

(3) Emphasize the importance of real-time report and alert of traffic condition, especially value the utility of apps on mobile phones. When serious congestion and extreme weather take place, relevant government departments must decisively take actions as temporary traffic control and restriction on visitor number in tourist attractions. Meanwhile, the congestion during vacations is different from the usual congestions which happen because demands cannot be met efficiently, and the vacation congestions usually appear as instant peaks. Such situation requires a larger effort of traffic dispersion by traffic management departments, which include technical supervision, on-site dispersion and alert beforehand.

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