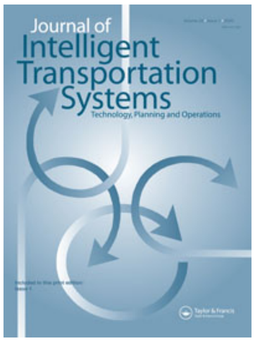

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Expressway bottleneck pattern identification using traffic big data—The case of ring roads in Beijing, China

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ABSTRACT
How to efficiently identify traffic bottlenecks in the expressway network and implement targeted measures is an important issue to mitigate traffic congestion. In recent years, with the proliferation of smartphones, smartphone-based navigation applications are receiving the worldwide popularity, which are being treated as an extremely rich source of traffic data. In this paper, we are devoted to proposing a novel approach to investigate traffic state and identify recurrent bottlenecks quickly and accurately from macroscopic network perspective, through fusing the data sources of fixed detectors and mobile navigation apps. First of all, this paper plots flow-speed fundamental diagram to derive critical speed, which is treated as the criterion to determine traffic state. Once the criterion has been established, typical bottlenecks in the entire expressway network can be efficiently identified through only utilizing smartphone-based probe speed data. Secondly, three pioneering indicators are put forward to quantify oversaturated traffic state and classify bottleneck patterns on urban expressway network. Applying this methodology, we take Beijing expressway network as a case to identify different patterns of bottlenecks, which are validated to comply with the reality. Moreover, the relationship between critical speed and the associated road segment features is explored and shows the possibility of predicting the critical speed even without flow data. As an end, some recommendations are proposed for improving different types of traffic bottlenecks.

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Critical speed; data fusion; expressway bottleneck; fundamental diagram; oversaturated state

Introduction

Congestion is always a headache especially for big cities. Many cities have constructed urban expressway systems to provide a more convenient and faster way to travel within the city. Generally, expressways connect different functional areas in the form of circular and radiation. This probably causes a large amount of tidal traffic flow flooding in and out of the downtown area through expressway system. With the increase of traffic demand, expressways are frequently caught in congestion. As we all know, traffic congestion is always caused by bottlenecks, including recurrent and non-recurrent bottlenecks. Non-recurrent bottlenecks are always induced by incidents, which is out of our research. For recurrent bottlenecks on expressways, completely different from those on urban arterial roads contributed by traffic signal, they are always fixed and resulted from the physical conditions, such as merge, diverge and weaving sections. They will obstruct the traffic flow and spread the congestion to a larger area. Although it is hard to completely eliminate the congestion, we can find out the main bottlenecks and take appropriate strategies to relieve them, such as dynamically managed lanes and ramp metering. Therefore, it is quietly important to identify the main recurrent bottlenecks of expressways.

Generally, traffic state measurement and bottleneck identification rely on traffic data originating from fixed sensors or floating car. Despite fixed sensors are used to collect traffic flow and speed information, these devices might be less accurate in speed detection, and frequently malfunction, thus causing high maintenance expenditure. In contrast, with the proliferation of smartphones, smartphone-based navigation applications are receiving the worldwide popularity, which are being treated as an extremely rich source of speed data, both spatially and temporally (Li, Chen, & Ni, 2016; Liu, Taylor, Porter, & Wei, 2018). In this

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paper, we are devoted to proposing a novel approach to investigate traffic state and identify traffic bottlenecks on the expressways, which combines the data sources of fixed detectors with mobile navigation apps. Doing this can take advantage of the spatial and temporal availability of the emerging mobile navigation application data, and hence generalize the applicability of our proposed approach. More specifically, we first integrate the flow data from fixed microwave detectors and speed data from mobile navigation application to obtain the critical speed. In the light of this criterion, a large amount of speed data collected by mobile navigation apps is then utilized to determine traffic state and diagnose bottlenecks. This method enables us to quickly identify bottlenecks once the criterion has been established, even without the data from fixed sensors. Furthermore, we will explore the critical speed pattern in future work, thus it can be determined without flow data from fixed sensors. In this revolutionary way, the identification of bottlenecks will be thoroughly simplified. We made some preliminary discussion in the paper about the relationship between critical speed value and the road section characteristics and showed the possibility of this prospect. Based on the above envision, the following problems are to be addressed:

- how to identify bottlenecks on expressway network
- how to recognize different bottleneck patterns
- how to improve traffic condition with regards to different bottleneck patterns

This work takes Beijing as the case study. As the capital and one of the biggest cities in China, Beijing is also famous for its congestion. Though Beijing has constructed an expressway network of six ring roads, connecting roads extending in all directions among them, the traffic is always congested within urban area. Because of high traffic demands and inappropriate design of roads, there are many recurrent bottlenecks located on these expressways. These bottlenecks contribute significantly to network congestion on the city level. It should be noted that the expressway system in many metropolis, like Houston, has the similar form with Beijing. This fact ensures our case study can offer reference to other cities.

The rest of this paper is organized as follows. Literature review section makes a review of previous studies. Methodology section elaborates the methods adopted in this study. In Data introduction and preliminary analysis section, we introduce the data on Beijing expressway and make a preliminary analysis. Bottleneck pattern identification section applies our proposed methodology to identify bottlenecks and investigate their patterns. Finally, Conclusion section concludes the paper.

Literature review

Scholars have studied bottlenecks for many years and have come up with many conclusions in transportation literature. This section will make a review about the present studies of bottlenecks from the aspects of identifying bottlenecks and analyzing their relevant features.

Earlier research adopted methods in identifying bottlenecks are based on traffic parameters, such as the queue length, speed, flow changes, etc. Daganzo (1997) defined an active bottleneck to be the location that separated the downstream free-flow traffic from the upstream congestion. Chao, Skabardonis, and Varaiya (2004) set some rules according to the distance between detectors and difference between speeds to identify bottlenecks on freeways. In 2005, Bertini & Myton used the cumulative count and occupancy from the inductive loop detector to identify the active bottleneck. Ban, Chu, and Benouar (2007) proposed a percentile-speed-based method to identify bottlenecks for corridors. Zhang, Song, Yu, Guo, and Lu (2018) identified the bottleneck on expressways based on the speed difference and the speed-at-capacity. Another approach to identify bottlenecks considered the reliability of traveling on the road using probe vehicle data. Zhao, Mccormack, Dailey, and Scharnhorst (2013) identified the truck bottlenecks by the reliability of the speed distribution of the truck probe GPS data. Wang, Lu, Chen, and Wang (2015) also defined the reliability with the floating car data and set a threshold to identify the congested links in a road network. Some researchers used travel time reliability measures to identify and rank recurrent bottlenecks at the network level (Gong & Fan, 2017). In recent years, the automatic bottleneck identification has been developed (Bai, Wu, Sun, & Wang, 2011). Elhenawy and Rakha (2015) applied a two-component mixture model for automatic congestion identification. Chen and Rakha (2017) further proposed a method for various data sources.

Finding out the bottleneck is the first step, and studying the bottleneck's feature is important as well (Zhang et al., 2018). Cassidy and Bertini (1999) studied queue formation and discharge flow at the bottleneck. Zhang and Levinson (2004) investigated some properties of flows at freeway bottlenecks. Sun, Ma, and Chen (2018) further provided a detailed description of traffic flow phase transition at urban expressway diverge bottlenecks. Some work studied the potential signals of bottleneck activation before upstream queue formation, the impact of lane reduction and severity of congestion after locating the bottlenecks (Ahmed, Rouphail, Tanvir, & Pan, 2017; Bertini, 2005; Bertini & Leal, 2005). Other studies involved the relationship between the static and dynamic bottleneck, and the suggestions for control measures (Cassidy, Anani, & Haigwood, 2002; Daganzo, Cassidy, & Bertini, 1999; Li, Liu, Xu, & Wang, 2018).

To conclude, most of previous studies study the bottlenecks located on some particular roads from a microscopic perspective and hardly recognize recurrent bottlenecks on the whole road network efficiently. Furthermore, in most of the studies, the threshold value of speed or occupancy to identify congestion is often set by subjective experience, and thus fails to consider the features of different road segments. Lastly, the conflict between traffic demand and supply is not reflected either.

In this paper, we concentrate on identifying typical recurrent bottlenecks on urban expressway network. They are defined as the original locations dropping into the oversaturated state and emerging congestion. It should be emphasized that despite these places always suffer oversaturation frequently, traffic oversaturated state is not definitely caused by bottlenecks. The spread of traffic congestion could contribute to oversaturation as well. This is the difference between oversaturated traffic state and bottleneck. A novel method is developed to finding out and analyzing typical recurrent bottlenecks from macroscopic network perspective. Specifically speaking, the main contributions of this research are summarized as three aspects. First of all, we integrated the flow data from fixed microwave detectors and speed data from mobile navigation application to plot the speed-flow fundamental diagram and linearly fit the curve to get the critical speed. Secondly, we used the critical speed to determine the traffic state and proposed three indexes related to oversaturation state to quantify traffic performance. Thirdly, different kinds of bottlenecks were identified according to the quantitative indexes and distinguished their characteristics to put forward individual improvement measures.

Methodology

The methodology in this study involves some basic knowledge about traffic flow theory, such as fundamental diagram, critical speed and oversaturated state. This section will briefly introduce the methodology.

To identify bottlenecks on the expressway by mining huge amount of traffic data, it is important to distinguish the traffic states. In traffic flow theory, the fundamental diagram provides the relationship among traffic flow, density and speed. In this paper, the speed-flow diagram (Figure 1(a)) is used to determine the speed at which the optimum flow occurs, namely the critical speed, which is related to traffic demand and road segment feature. The speed-flow curve can be generally divided by the critical speed into two parts, the oversaturated part and the unsaturated part.

Here introduces a method to obtain the critical speed. In Figure 1(a), suppose the fundamental diagram is a triangular form, then the relationships between flow and speed for oversaturated and unsaturated parts are both linear. For unsaturated state, the flow (q_1)–speed (v) relationship can be expressed as

$$q_1 = k_1 \rho_{jam} \cdot (v - v_{free})/v_{free} \tag{1}$$

where k_1 denotes the slope of the fitting line for unsaturated part. ρ_{jam} represents the jam density. v_{free} is the free-flow speed. For oversaturated state, the flow (q_2)–speed (v) relationship can be formulated as

$$q_2 = k_2 \rho_{jam} \cdot v/v_{free} \tag{2}$$

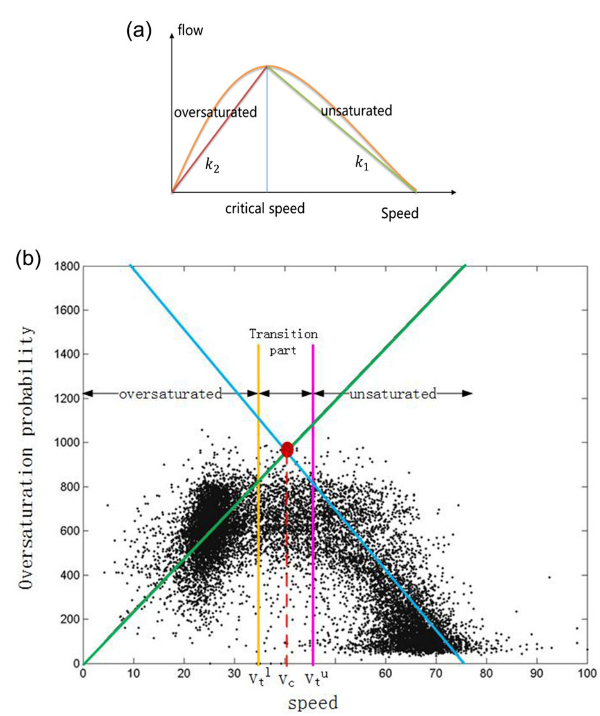

Figure 1. (a) Speed-flow fundamental diagram. (b) Partition of traffic states.

where k_2 denotes the slope of the fitting line for oversaturated part. To obtain the critical speed, the parameters, k_1 and k_2, should be figured out based on the fundamental diagram, which is illustrated by a scattered plot as Figure 1(b). The following describes how to fit the fundamental diagram and obtain the critical speed.

Step 1: Set an initial transition range $[a,\ b]$ according to experience, which is supposed to cover the critical speed. Thus, the speed range is divided into three parts, $[0,\ a]$, $[a,\ b]$, $[b,\ v_{free}]$.

Step 2: Linear fitting of the points in range $[0,\ a]$ and $[b,\ v_{free}]$, respectively. So the slopes k_1 and $k_2$can be figured out in accordance with Equations (1) and (2).

Step 3: Calculate the intersection point of the two fitting lines by Equation (3):

$$v_c = k_1 v_{free}/(k_1 - k_2) \tag{3}$$

Step 4: Reset the transition range:
if $v_c \in [a,\ b]$,
then $a = a + 90\% \cdot (v_c - a),\ b = b - 10\% \cdot (b - v_c)$;
else if $v_c < a$,
then $a = v_c$;
else $b = v_c$.

Step 5: Repeat Step 2 to Step 4 until the intersection point v_c converges, i.e., the following equation should be satisfied. The latest intersection point v_c^* is determined to be the critical speed.

$$v_c^i - v_c^{i-1} < \varepsilon \tag{4}$$

After determining the critical speed of each detector section, the traffic states can be distinguished by it. As Figure 1(b) shows, each flow-speed fundamental diagram can be partitioned into three parts representing three traffic states: oversaturated state, transition state and unsaturated state. The transition state in the middle part is unstable and critical. Here, we define the three traffic state with two parameters v_t^l and v_t^u, where v_t^l denotes as the 90th percentile of all the speed values lower than v_c^*, and v_t^u as the 10th percentile of all the speed values greater than v_c^*. If the speed is within this interval $[v_t^l,\ v_t^u]$, the traffic belongs to transition state. If the speed is lower than v_t^l, the traffic is stuck in oversaturated state. Otherwise, the traffic state can be regarded as unsaturated. The intention of such definition is to determine oversaturated state more convincingly and effectively.

We further develop three indexes to quantify the oversaturation conditions for urban expressway system. To do that, we first partition the road into many segments, called spatial units. Similarly, we partition the timeline into many short intervals, called temporal units. Then the average speed of each temporal and spatial unit is calculated, which determines the traffic state of the unit as shown in Figure 2. Finally, three indexes are proposed to quantify the oversaturation state.

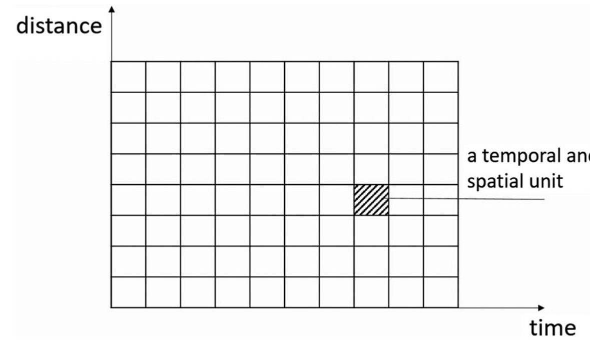

Figure 2. Temporal and spatial unit.

1. **Oversaturation equivalent.** It represents the total number of oversaturated temporal and spatial units. For a road and a period of time, suppose there are L spatial units and T temporal units in each day, and the period of time is M days. Then The average daily oversaturation equivalent is

$$\overline{N_{oe}} = \frac{\sum_{k=1}^{M} \sum_{i=1}^{L} \sum_{j=1}^{T} I_{i,j,k}}{M} \tag{5}$$

where $I_{i,j,k}$ is a 0-1 binary variable, which determined by Equation (6) below:

$$I_{i,j,k} = \begin{cases} 1, & \overline{v_{ij,k}} < v_{ti}^l \\ 0, & \overline{v_{ij,k}} \geq v_{ti}^l \end{cases} \tag{6}$$

where $\overline{v_{ij,k}}$ is the average speed in the i^{th} spatial unit during the j^{th} temporal unit of the k^{th} day. v_{ti}^l is the lower boundary of the transition area of the i^{th} spatial unit.

2. **Oversaturation equivalent density.** It is the spatial proportion of oversaturated state during a certain temporal unit. The oversaturation equivalent density of the road in the j^{th} temporal unit of the k^{th} day is

$$\rho_{j,k} = \frac{\sum_{i=1}^{L} I_{i,j,k}}{\mathrm{L}} \times 100\% \tag{7}$$

It indicates how much length of the road is in the bad traffic condition during a certain temporal unit.

3. **Oversaturation probability.** It implies the frequency of a spatial unit being oversaturated

during a period of time, i.e., M days. It is calculated by Equation (8).

$$p_{ij} = \frac{\sum_{k=1}^{M} I_{i,j,k}}{M} \times 100\% \quad (8)$$

where p_{ij} represents the oversaturation probability of the i^{th} spatial unit during the j^{th} temporal unit of one day. It reflects how frequent the traffic state of the spatial unit is oversaturated during the temporal unit. The higher the probability is, the more often the road segment falls into oversaturated state. We use the oversaturation probability to reflect the conflict between traffic demand and supply in our research. The oversaturation probability is calculated based on the traffic fundamental diagram, rather than depends on some subjective experiences. It is capable of revealing the inherent characteristics of the interaction between traffic supply and demand on road segments.

It can be verified that our definition of oversaturation equivalent is closely related to the metric of the amount of congestion. However, we believe that they are defined from different perspectives. Congestion is more related to the travelers' feeling, whereas the oversaturation is from the fundamental diagram in traffic flow theory and reflects the unstable traffic condition where the traffic flow will easily collapse. Therefore, to keep traffic flow stable and avoid road capacity collapse, traffic operators need to control that the traffic speed does not fall below the critical speed and assures the traffic sate not to be oversaturated. Considering our paper is designed to assist traffic operators to identify the bottlenecks and then improve the traffic conditions, we thus choose the oversaturation indexes, which can better reflect the traffic operating conditions for the purpose of traffic controlling. Moreover, since we concentrate on identifying typical recurrent bottlenecks, the prime metrics is the oversaturation probability. It indicates the frequency of a road segment dropping into the oversaturated state and evaluates the recurrence of oversaturation

Applying this methodology, the following two sections will take Beijing ring road system as a case to diagnose the bottlenecks and analyze bottleneck patterns.

Data introduction and preliminary analysis

We examine traffic data covering the second to fifth ring road in Beijing from October to December, 2014 in this research. These data with the size of 120 G are composed of two parts, the section traffic flow collected by more than 180 microwave detectors on ring roads and the sample data obtained by navigation system.

Data preparation

One part of the data, the traffic flow of each section in both directions, is collected every 2 minutes, which represents the number of vehicles passed during the time interval. Owing to high accuracy of the flow information from microwave detectors, we utilize it to obtain the aggregated flow. The other part of data includes the speed, location and time of each vehicle uploaded by the car navigation system or mobile navigation application. It is recorded according to the trajectory of each vehicle with the time interval 5 seconds to 10 seconds. Owning to the project cooperation with Gaode-Map company (hereinafter referred to as Gaode), we obtain an accurate and reliable dataset that has been matched to the map by Gaode, who has developed its own effective probabilistic-graph-based algorithm called trajectory probability deduction matching to solve the map-matching problem. Sufficient validation tests have also been conducted by Gaode, and it is showed that the matching accuracy on expressways is more than 99%. Additionally, the penetration rate of this data source is about 5% to 10%. Due to the lack of necessary traffic flow data, it is hardly to estimate the sample rate for each temporal-spatial unit. In this context, we assume that the sample rate does not significantly vary in the spatial dimension. In fact, some studies have indicated that sampling GPS data with only 1% penetration rate but collected during a long survey period can still ensure accurate speed estimation (Argote-Cabañero, Christofa, & Skabardonis, 2015; Bolbol, Cheng, Tsapakis & Chow, 2012). Obviously, these data are reliable in precision, sampling rate and map-matching method. Considering many studies have proven that the reasonable traffic state estimation can be obtained by calculating the average speed (Cheu, Xie & Lee, 2002; Jiang, Gang & Cai, 2006), we use the average speed of all vehicles located in the range of 100 meters around the detector to represent the traffic condition and determine the vehicle's driving state near the detector on the road.

In our case study, the speed data from navigation application and flow data from microwave detectors are fused to obtain the speed-flow fundamental diagram as shown in Figure 3. By the method described in Methodology section, the critical speed of each section can be obtained and the traffic state can be determined. On expressways, the ramps are deployed more densely than on freeways, which inevitably affect the traffic condition, possibly makes the traffic condition fall into a chaotic state, and thus brings difficulties for the critical speed calibration. Furthermore, the average distance between two fixed detectors is not so long in our study, ranging from 600 m to 1000 m. In light of these facts, although we cannot precisely obtain the fundamental diagram of road segments between detectors, we make a simple and reasonable assumption that a road segment's critical speed is similar to that of its nearest detector section. In this way, each road segment owns its criterion to distinguish traffic states.

To illustrate the traffic state more distinctly, we set temporal unit as 10 minutes and spatial unit as 100 meters. Namely, the ring road is divided into hundreds of segments of 100 meters, then the second to fourth ring road in Beijing have 327,484 and 656 spatial units, respectively. The traffic flow from detectors is aggregated in every 10 minutes for each spatial unit. Besides, the average speed of the vehicles in each road segment within every 10 minutes can be calculated using GPS data. The results representing the driving state for each temporal and spatial unit are intended to compute oversaturation metrics.

Critical speed

The critical speed is supposed to be fixed since it is related to traffic demand and road segment characteristics. In this study, we proof this assumption by comparing the monthly critical speeds obtained for three consecutive months as shown in Figure 4. Obviously, three critical speeds associated with the same road section for each month are numerically stable. The average standard deviation of three critical speeds on all the road sections is 1.2. Accordingly, we believe the critical speed associated with some road section is unchanged and it can be used to evaluate the traffic state as well.

In addition, we make a further analysis on the relationship between critical speed and the associated road segment features, which only refer to location here. Essentially, the road section locations can be classified into four types, i.e., upstream of on-ramp, downstream of on-ramp, upstream of off-ramp and downstream of off-ramp. The corresponding average critical speeds are 43.1 km/h, 41.6 km/h, 43.4 km/h and 45.7 km/h, respectively, indicating a substantial relationship between the value of critical speed and road section feature. In such context, advanced methods such as supervised learning can be potentially applied to predicting the critical speed of a road section even without the flow data. In this sense, the bottleneck identification method proposed in this paper indeed has the potential of being widely utilized if the speed data from the navigation app is generally available, which exactly happens nowadays.

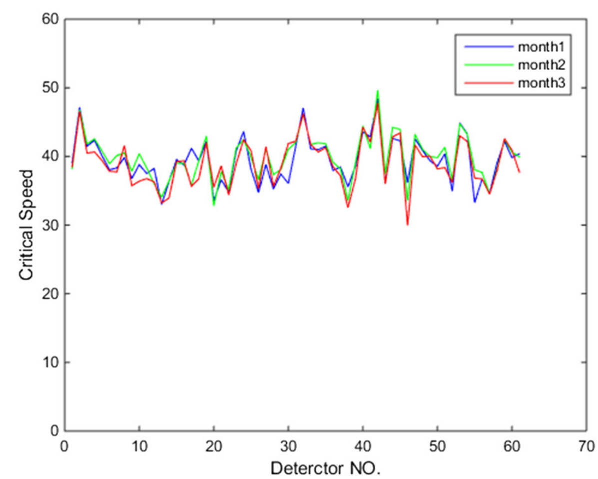

Figure 4. Critical speeds of different sections in three months.

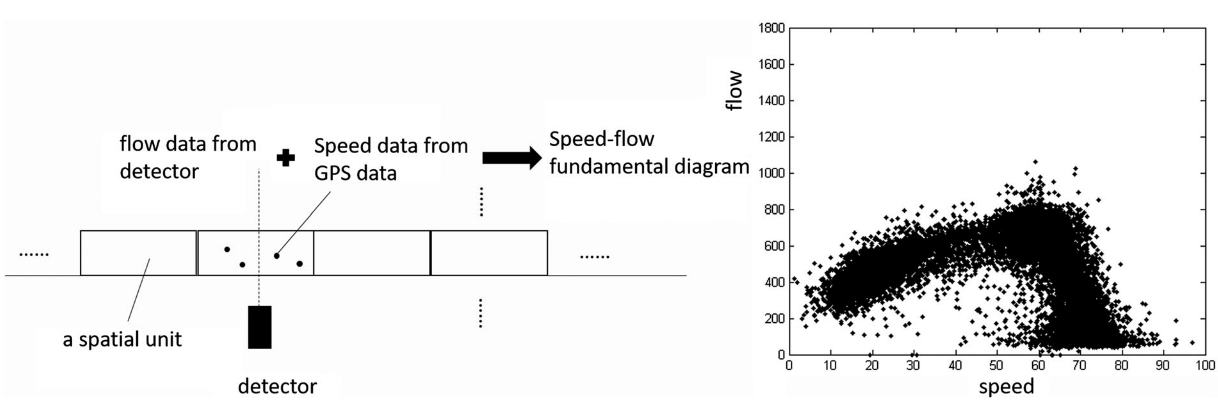

Figure 3. Data fusion to form the speed-flow fundamental diagram.

Overall traffic condition of Beijing ring road

According to the method of flow statistics as described above, the maximum traffic flow of each road segment within 10 minutes is basically about 800–1200 on Beijing ring roads. Figure 5 shows the average flow of weekdays in December, 2014 on the second ring road in Beijing. We can find that the flow keeps at a high level on during the daytime and the other peak appears at about 21 o'clock. It indicates two obvious phenomena: commuting trip and night entertainment. Too many people flood into the area within the second ring road to go to work since the central business districts are mostly located there. This clearly reflects the mono-centric feature of Beijing.

This paper applies the temporal and spatial distribution of speed to illustrate the overall traffic condition of Beijing ring road. Figure 6(a) is the map of Beijing and Figure 6(b) is the distribution of speed on the second to fifth ring road in Beijing. It is a three-dimensional diagram with different colors reflecting the magnitude of speed. As shown below, the horizontal axis is geographic location and the vertical axis is time across the whole day. We can find out that speed is apparently lower in the morning and evening peak. Moreover, there exists great discrepancy on speed distribution and magnitude between the second to fifth ring roads. The last but not the least, the red areas are congested and most likely to be the places where the traffic bottlenecks are located.

We calculate the three oversaturation indexes mentioned in Section 3 based on processed data. Tables 1 and 2 respectively show the oversaturation equivalent and oversaturation equivalent density of Beijing ring roads (from the second ring to the fourth ring) during weekdays, weekends, the Spring Festival, the New Year's Day and National Day. We can see that the third ring road has the highest oversaturation equivalent, while the second ring road has the highest oversaturation equivalent density among the three ring roads. Except this difference, the values of these two indexes display the consistent tendency. In particular, the oversaturation equivalent and oversaturation equivalent density of New Year's Day and National Day are both lower than half of those of weekdays. It reveals that many citizens choose to travel outside of Beijing in these holidays. While in the Spring Festival, these two indexes of Beijing ring road drop to the trough since hundreds of people return home for family reunion. Finally, the third and fourth ring roads experience more obvious decline and more native-born Beijing citizens live within the second ring road, which indicates that Beijing is an immigrant city.

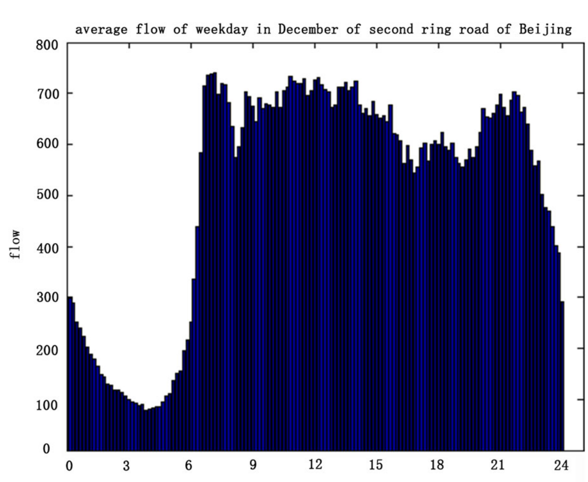

Figure 5. Average flow of weekdays on the second ring road in Beijing.

Based on the preliminary analysis above, it is found that Beijing is a mono-centric and immigrant city, which is especially congested during morning and evening peak in weekdays. For the record, these features are not unique to Beijing, but common to many metropolises. Therefore, it is necessary to find which places are always oversaturated and why these bottlenecks obstruct traffic, so that we can take correct measures to improve the traffic condition.

Bottleneck pattern identification

In this section, based on the preliminary and quantitative analysis of Beijing ring roads, some rules will be found in light of the oversaturation probability, and contribute to diagnose different patterns of bottlenecks.

Diagnosis of bottlenecks

Considering the traffic demand reaches the top in the peak hour in the morning and evening and it is more possible to fall into oversaturated state that time, the oversaturation probability refers to the peak hour probability in this study. Additionally, the peak hour probability can better reflect the conflict between traffic demand and supply, as well as the frequency of the oversaturation happens.

We adopt bar graph to show the variation of oversaturation probability with the location of different detector sections. In Figure 7, the horizontal axis is the number of detectors in a ring road, while the vertical axis is the oversaturation probability of a detector section. Since the detectors are deployed clockwise or anticlockwise on a ring road, the number of detectors can reflect their location information. From the bar

(a)

(b)

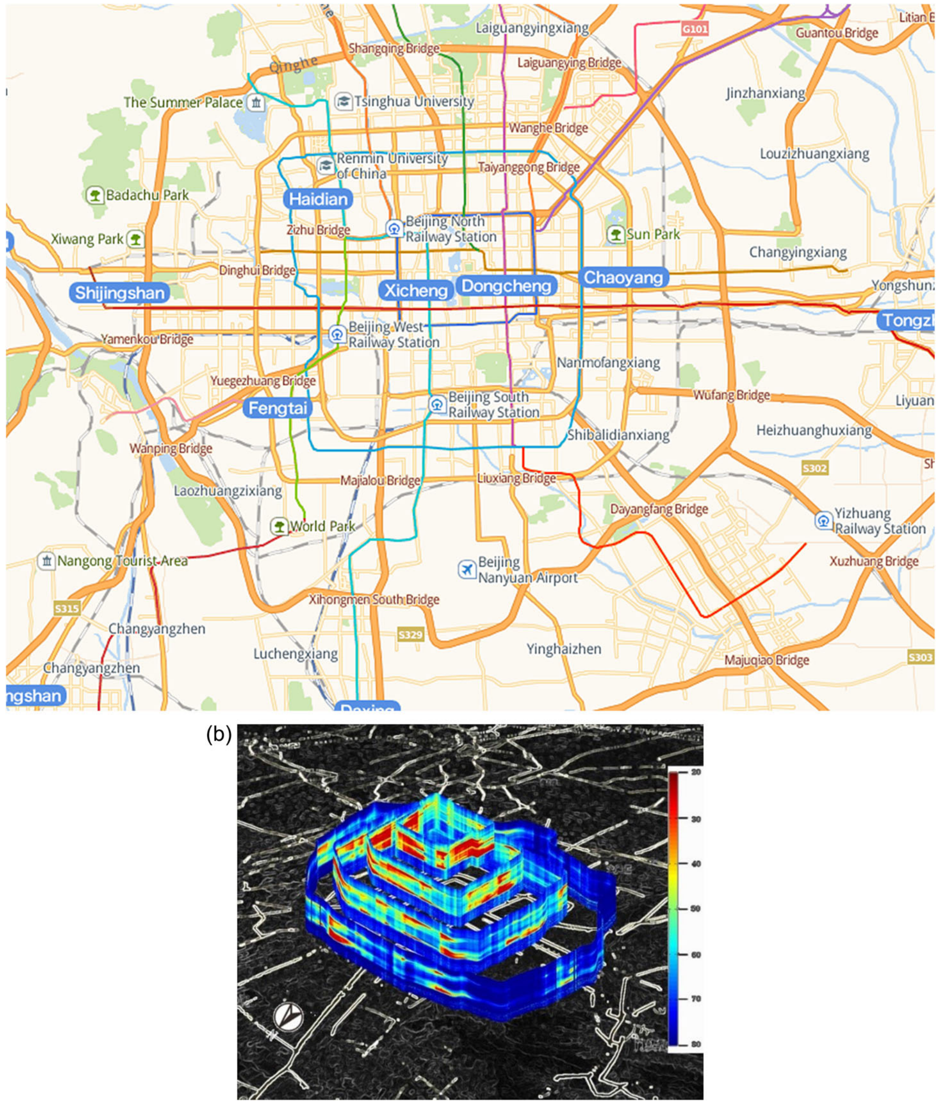

Figure 6. (a) Map of Beijing. (b) Temporal and spatial distribution of speed on Beijing ring road.

Table 1. Oversaturation equivalent of Beijing ring road.

Day	2nd Ring	3rd Ring	4th Ring
weekday	21432	23205	16548
weekend	17952	22933	15320
New Year's Day	10048	11106	5366
Spring Festival	5797	1531	673
National Day	6515	6247	2701

graphs of all the two driving directions on the second to fourth ring road in Beijing, it is obvious that there are some peak values, step-wise increase in the upstream and sudden decrease in the downstream. The different features of the distribution of oversaturation probability result in different patterns of bottlenecks. As mentioned in the beginning of our methodology, the position which is at bad traffic state most frequently is more likely to be the bottleneck. So in this paper, the diagnosed bottlenecks refer in particular to those recurrent main bottlenecks. These

Table 2. Oversaturation equivalent density of Beijing ring road.

Day	2nd Ring	3rd Ring	4th Ring
weekday	45.5%	33.3%	17.5%
weekend	38.1%	32.9%	16.2%
New Year's Day	21.3%	15.9%	5.7%
Spring Festival	12.3%	2.2%	0.7%
National Day	13.8%	9.0%	2.9%

bottlenecks may be caused by imperfect road design or large demand. The following will introduce the steps to confirm bottlenecks and how to classify them into different patterns.

Firstly, preliminarily determines the location of bottlenecks. Perform statistical analysis of all the oversaturation probabilities of a ring road, and set a limit to find the peaks. Due to the disparity of three ring roads, the limit is not same. For instance, the limit on the second ring road is 50% (see the red line in

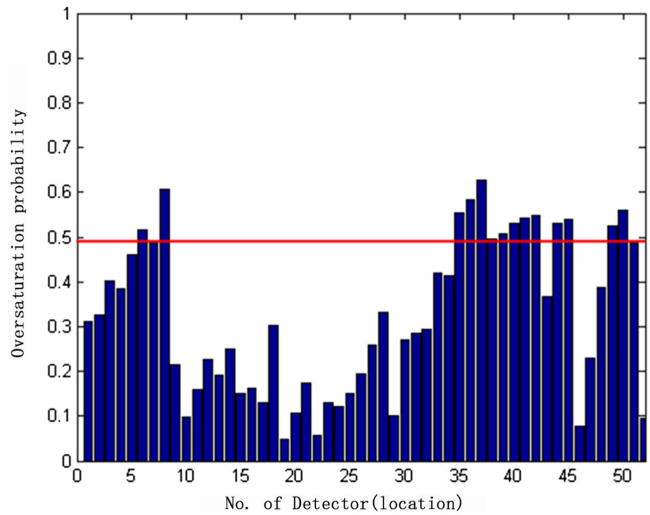

Figure 7. Bar graph of oversaturation probability.

Figure 7), and those locations with higher oversaturation probability than 50% are defined as peak locations, which are assumed to be bottlenecks for the time being.

Furthermore, to verify the location of the peak is just the bottleneck that blocks the traffic flow, the temporal and spatial distribution of speed could solve this problem. Figure 8 is the speed distribution of a road segment on the east second ring road named Jianguomen on 12th, October, 2014. The axes and color have the same meaning as Figure 6(b). Apparently, Jianguomen is the initial bottleneck during the day. The congestion happens at that location and spreads to the upstream as time goes. Many other days have the same characteristics on this road segment. Accordingly, in the probability distribution graph, the oversaturation probability of Jianguomen is the highest on the segment. In this way, it has proved that bottleneck identification by oversaturation probability is in accordance with the speed distribution. So the distribution graph of probability is reliable and their different features can be employed to classify bottleneck patterns.

Bottleneck patterns

Four different bottleneck patterns are introduced according to their features:

1. 1st pattern of bottleneck
2. The first pattern of bottleneck is a kind of typical bottleneck, such as Jianguomen, Fenzhongsi and Yuting Bridge. In the upstream of it, the oversaturation probabilities of the several adjacent sections increase step-wisely, while the probability of the first section in the downstream decrease suddenly to a low level (just as the area circled in Figure 9(a)). This indicates that the bottleneck influences the upstream a lot; however, once having left the bottleneck, the traffic turns into unobstructed immediately.
3. Apparently, this pattern of bottleneck is located at crucial transportation junctions that link the main roads of different directions and play an important role in dispersing traffic flow. For example, Fenzhongsi Bridge links the third ring road and the fourth ring road in the south-western corner. Thus the traffic flow in the upstream of these bottlenecks is so large that the road falls into oversaturated state. On the contrary, the traffic volume in the downstream decreases a lot, with higher speed and lower oversaturation probability.
4. 2nd pattern of bottleneck
5. Compared with the first pattern of bottleneck, the second pattern is an isolated one. The oversaturation probability of it is very high but the neighboring sections' probabilities are much lower, as shown in Figure 9(b). The range of influence by the bottleneck is narrow, as only a section in the area is often oversaturated. This pattern of bottleneck usually locates at the upstream of on-ramps and off-ramps. If the traffic demand of the ramp is very large, vehicles will queue on the weaving section. Along with large flow on the main road, a bottleneck at the upstream of the ramp is formed. But no other ramps nearby have equivalent demand, so the bottleneck is standalone. Similar bottlenecks are Guang'anmen, Dongzhimen Bridge and Sihui Bridge.
6. 3rd pattern of bottleneck
7. The third pattern of bottleneck is similar to the first pattern in the upstream, while the oversaturation

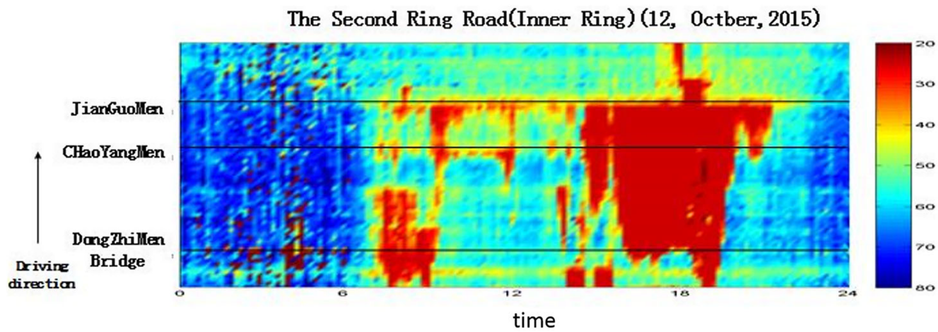

Figure 8. Speed distribution of Jianguomen segment.

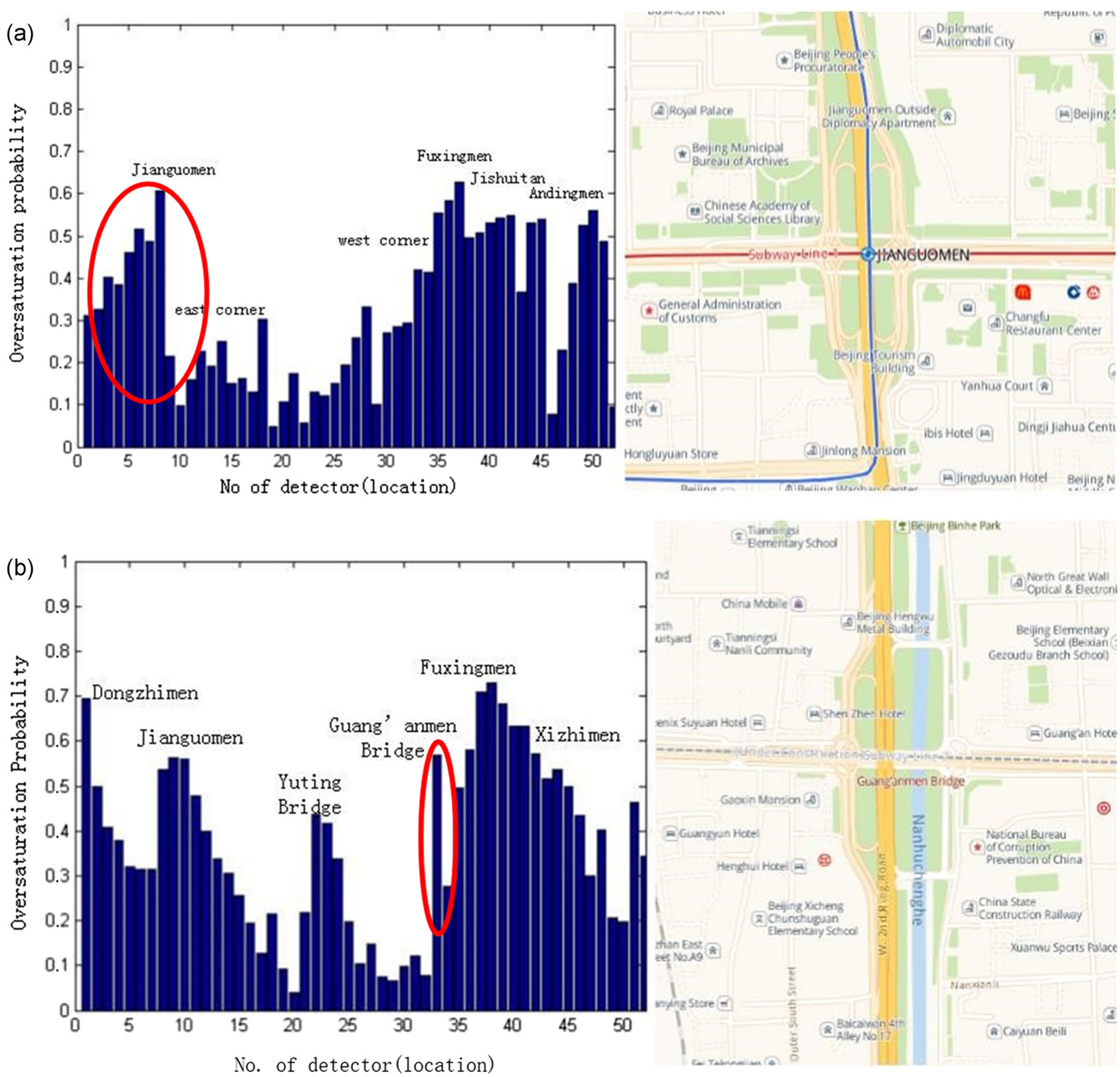

Figure 9. (a) Bottleneck at Jianguomen. (b) Bottleneck at Guang'anmen.

probability downstream also decreases step-wisely. Andingmen, Sanyuan Bridge and Lianhua Bridge can be classified into this pattern. However, relative to the first pattern, the range of influence in the upstream of this pattern is shorter but longer in the downstream. This is because there are still some factors interfering traffic flow passing through fluently. The most common situation is that there exist several successive ramps on the road segment. Take the Andingmen as an example (Figure 10(a)). There are

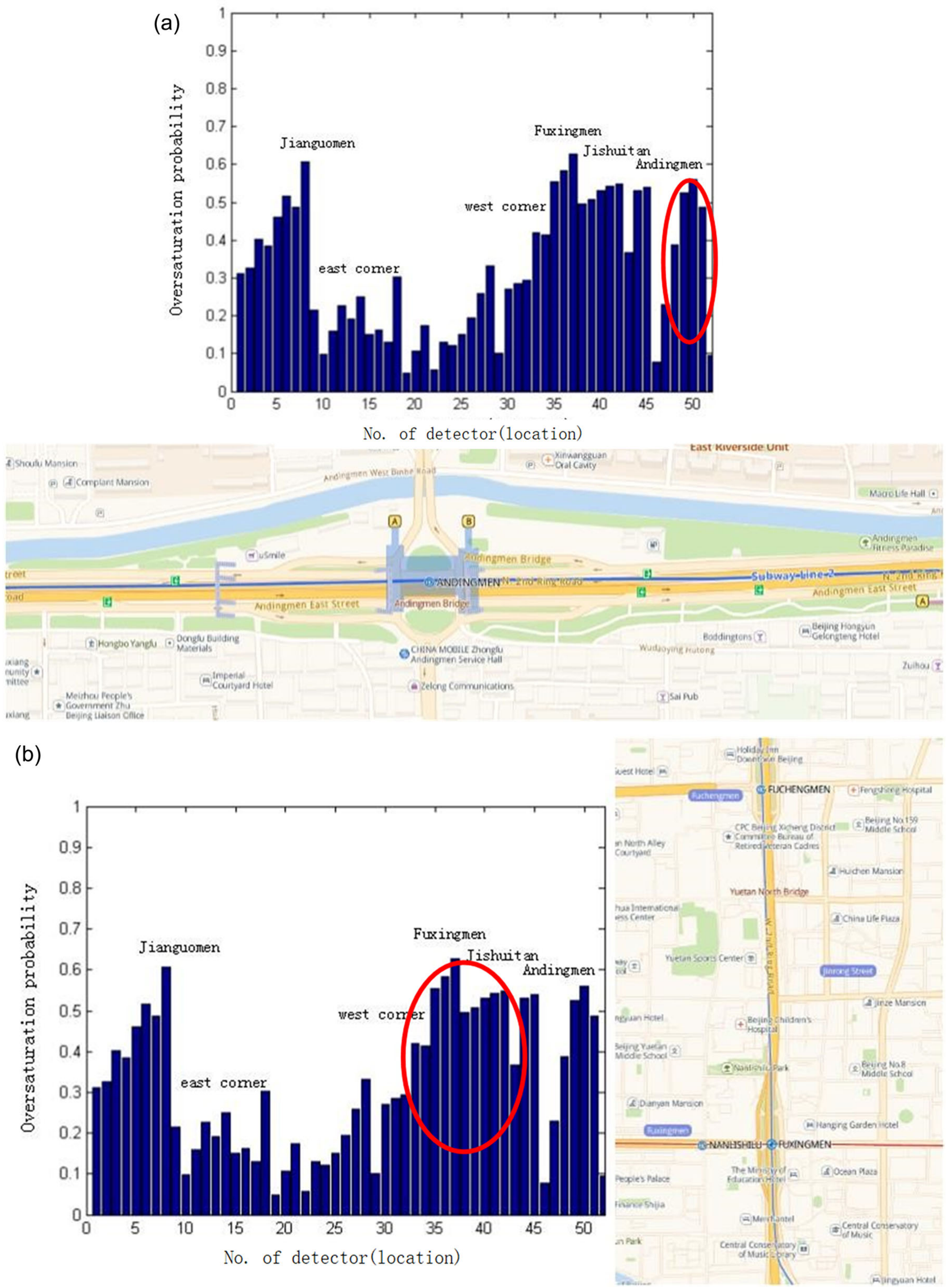

Figure 10. (a) Bottleneck at Andingmen. (b) Bottleneck at Fuxingmen.

two on-ramps and two off-ramps in 1000 meters, and one on-ramp is just located at the downstream of the off-ramp. In consequence, the reduction of traffic flow by the off-ramp doesn't counteract the increase by the on-ramp, which makes the downstream still being in oversaturated state. The particular characteristic of this pattern is the step-wise distribution on both sides of the peak in the oversaturation probability graph.

8. 4th pattern of bottleneck
9. The final pattern of bottleneck is a particular case of the third pattern to some extent. In a wide range of road segments, the oversaturation probabilities keep at a high level, forming a supersized bottleneck. The traffic condition in that area is very complex. Many attractive places appear on the road and the road segment is shared by many routes, let alone the continuous on-ramps and off-ramps along the road. As a result of the large demand and queuing in the weaving segment, the congestion spreads to the upstream and affects a wider range of road, leading the road into oversaturated state. A typical example of this kind of bottleneck is Fuxingmen in the west of the second ring road (Figure 10(b)), which is the necessary passage connecting the north and south city, and the demand there is very large credited to the surrounding commercial and office areas. In addition to other factors, this area becomes a supersize bottleneck.

Discussion

The four patterns of bottlenecks above are most common and recurrent on expressways. They have negative effects on the traffic, including reducing the travel efficiency and lowering the promptness of expressway. After diagnosing and classifying the bottlenecks, some corresponding measures should be taken to alleviate the bottlenecks.

For the first pattern of bottlenecks, since they are usually located at key transportation junctions and the traffic flow in the upstream is large, it can be useful to induce traffic flow to side roads or other city roads. Besides, it is also necessary to develop and improve public transportation, so that some car users will switch to bus or subway.

The second pattern of bottlenecks is caused mainly by the weaving segment in the upstream of a ramp. Consequently, the length of the weaving lane should be designed scientifically. On the other hand, the advisable signal control on the ramp can make vehicles leave the ramp as soon as possible. Both of the two measures can reduce the queue on the main road.

As to the third pattern of bottlenecks, the main problem is the continuous ramps which have high demand and affect each other. To address the problem, coordinated signal control between the ramps may contribute a lot. Set the cycles of the signals based on the traffic state and demand on the ramps, so the interference can be abated.

The fourth pattern of bottlenecks is hard to address by a single instrument because of the complex causes. Therefore, it is important to reduce the unstable influence on traffic state by strengthening police force to exclude accidents and unruly driving behavior. In addition, it may also be effective by adopting some economic leverage such as congestion pricing to reduce conflict between traffic demand and supply. By means of these policies and measures, this kind of supersized bottlenecks can be relived in some degree.

Conclusion

This paper studies how to use big traffic data to identify and analyze bottlenecks on expressways. Based on traffic flow theory, the critical speed is obtained by fundamental diagram to judge the traffic state. Consequently, the locations which are always in oversaturated state are identified as bottlenecks.

The Beijing ring roads are taken as a case in this paper. Through the preliminary analysis of the navigation speed data and section flow data of detectors, it is found that Beijing is a mono-centric and immigrant city. After data processing and analyzing, four different patterns of bottlenecks are diagnosed. They are common and recurrent main bottlenecks on urban expressway. These recurrent bottlenecks are usually caused by the imperfect ramp design, unthoughtful ramp deployment and overlarge traffic demand. To relieve the traffic condition over there, the design of ramps and lanes should be improved; the role of signal control should be played; the development of public transportation should keep carrying forward; and the economic leverage policies can be used befittingly.

Our proposed method can be applied to locate those bottlenecks both quickly and accurately which are main concerns for traffic management department. Furthermore, the critical speeds determination could be significantly simplified as we have shown some promising results. Once the criterion is established, with the huge amount of speed data provided by mobile navigation apps, the identification of bottlenecks will be more convenient. Lastly, the diagnosis of bottlenecks now is macroscopic, while in the future, the microscopic analysis of a typical bottleneck could be worked out as well, including queue length, speed change pattern and so on.

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