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Study of macroscopic fundamental diagram on Shanghai urban expressway network in China

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Abstract: The macroscopic fundamental diagram (MFD) is studied to obtain the aggregate behavior of traffic in cities. This paper investigates the existence and the characteristics of different types of daily MFD for the Shanghai urban expressway network. The existence of MFD in the Shanghai urban expressway network is proved based on two weeks' data. Moreover, the hysteresis phenomena is present in most days and the network exhibits different hysteresis loops under different traffic situations. The relationship between the hysteresis phenomena and the inhomogeneity of traffic distribution is verified. The MFDs in the years of 2009 and 2012 are compared. The hysteresis loop still exists in 2012, which further verifies the existence of the hysteresis phenomenon. The direct relationship between the length of the hysteresis loop (ΔO) and the congestion is proved based on sufficient data. The width of the hysteresis loop, i. e., the drop in network flow (ΔQ) has no relationship with the congestion, and it varies from day to day under different traffic situations.

Key words: macroscopic fundamental diagram (MFD); hysteresis phenomena; urban expressway network; index of congestion

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With the rapid development of urbanization, congestion in many cities is increasingly severe. Many researchers focused their attention on the network-level traffic flow relations in the last century [1–7]. Daganzo[8] proposed the macroscopic fundamental diagram (MFD) that describes the aggregate behavior of traffic in cities. By aggregating the scattered plots of flow vs. density from individual loop detectors in a homogeneous network, the flow occupancy relations exhibit a figure which is similar to the fundamental diagram. Hence, the model is called the macroscopic fundamental diagram, which can be used to simplify urban network modeling and describe traffic operations at a network-wide level.

The idea is proved by the field experiment in the city of Yokohama, Japan, which reveals that the MFD exists in a large urban area. Geroliminis and Daganzo[9] stated that the MFD exists in the homogeneously congested regions of cities. However, many large-scale areas are not homogeneous. Geroliminis and Sun[10–11] stated that there were hysteresis phenomena on MFD based on empirical data in the Minneapolis area freeway network. The hysteresis phenomena means that higher network flows are observed for the same average network density in the onset and lower in the offset of congestion. They stated that the inhomogeneity of traffic distribution is the important cause of the hysteresis phenomena. Cassidy et al. [12] concluded that when traffic is in a stable regime, the MFD exhibits a well-defined diagram on freeways.

Buisson and Ladier[13] also observed a MFD with a hysteresis loop in the Toulouse freeway network in France and they stated that the heterogeneity can impact the shape of the MFD. Gayah and Daganzo[14] stated that congestion tends to be greater during recovery by use of a two-bin model. They identified four types of pattern: single, clockwise hysteresis loops, counter-clockwise hysteresis loops, and the figure-eight. In the study of Mazloumian et al. [15], the spatial distribution of vehicle density in the network affects the MFD. Saberi and Mahmassani[16–17] discussed the impact of the distribution of congestion on the shape of hysteresis loops. They concluded that generally, the hysteresis loops become larger when the spatial heterogeneity of the network increases.

To sum up, many existing studies mainly focus on MFD on urban arterials or freeways, and the MFD for urban expressways has not been considered. This paper aims to investigate the existence and the characteristics of different types of days' MFD for the Shanghai urban expressway network, such as weekdays, weekends and holidays. The relationship between hysteresis phenomena and the inhomogeneity of traffic distribution are also verified. This paper compares the MFD within three years (2009 to 2012) before illustrating the direct relationship between the length of the hysteresis loop (ΔO) and the congestion with data.

1 Data Description and MFD

1.1 Data description

In this paper, approximately two weeks' data (Sept. 26 to Oct. 1, 2009 and Sept. 23 to Oct. 1, 2012) are chosen

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to analyze the MFD. The data records the traffic situation of the former week before the National Day (Oct. 1), which is one of the biggest holidays in China. The reason why these days are chosen is that this week consists of a typical weekday, unusual weekday (the former day before holiday), weekend, and the holiday. Hence, the MFD over different types of days can be obtained. By comparing the traffic in the same period from different years, the variation of MFD in three years is obtained.

The urban expressway network is located in the central area in Shanghai. The capacity and speed on the urban expressway network in the city-central have an obvious advantage over urban arterials. Hence, it plays an important role in relieving increasing traffic congestion in Shanghai. The raw data consists of the flow, occupancy and speed from the detectors every 20 s. The data comes from the Shanghai urban expressway monitoring center, and there are 2 071 loop detectors in the mainline of the network. The distance between adjacent detectors is 300 to 600 m. Most of the urban expressway network has four lanes per direction, but in some parts there are only two lanes per direction.

The data is aggregated over 5-min intervals. The unweighted mean values are also used in this paper. If i is the index of each loop detector and N is the total number of the loop detectors, the flow and occupancy rate for the i-th loop detector at time t are q_{it} and o_{it}, respectively, and the mean flow Q_t (veh/(5 min · lane)) and the mean occupancy O_t (%) are

$$Q_t = \frac{\sum_{i=1}^{N} q_{it}}{N}, \quad O_t = \frac{\sum_{i=1}^{N} o_{it}}{N}$$

Some missing and inaccurate data which account for 3% in the original data has been deleted.

1.2 Macroscopic fundamental diagram (MFD)

The MFDs for the Shanghai urban expressway network on different days in 2009 are shown in Fig. 1. Clearly, the existence of the macroscopic fundamental diagram in the Shanghai urban expressway network can be demonstrated. However, a well-defined MFD does not appear due to the hysteresis phenomena in most days, and the shape and size of loops varying across different days. On a usual weekday (e. g., 2009-09-28), there are two clear clockwise hysteresis loops during the peak time. A much longer hysteresis loop was observed in the afternoon of the day before the National Day (2009-09-30). That day, most commuters went home early in the afternoon and it was raining slightly. Hence, there was a heavy congestion on the urban expressway network. On Saturday (2009-09-26), the MFD differed significant and there was only one irregular hysteresis loop. Free flow was present during the whole morning, and a slight con-

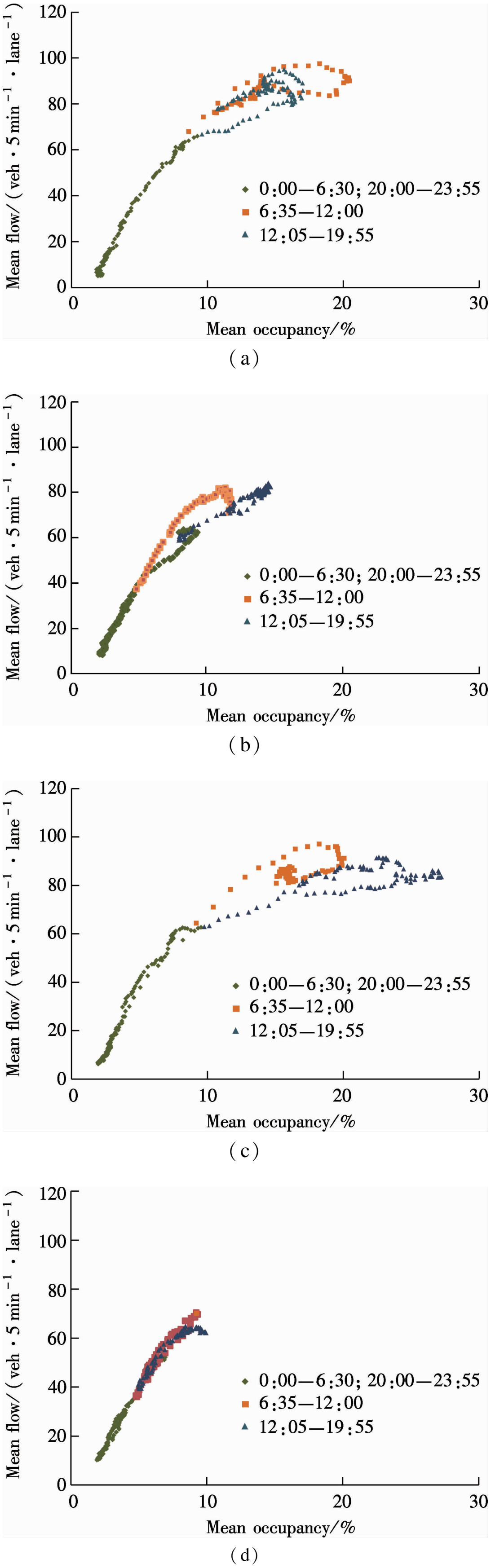

Fig. 1 Macroscopic fundamental diagrams of urban expressways in Shanghai. (a) 2009-09-26 (Saturday); (b) 2009-09-28 (Monday); (c) 2009-09-30 (Wednesday); (d) 2009-10-01 (holiday)

gestion occurred in the afternoon which coincided with the real situation. Many people rose late and started the activities in the afternoon on Saturday. No hysteresis phenomena was observed on National Day (2009-10-01). There was no hysteresis because the traffic was free flowing and the MFD merely exhibited an almost linear relationship. It is worthwhile noting that even on weekends, the traffic in the Shanghai urban expressway network was still heavy and this implies that the network is being fully utilized. It is clear that the MFD describes the aggregate behavior of traffic in cities. The loop appears when the heavy congestion occurs in a network.

2 Hysteresis Loop and Its Characteristics

The hysteresis loops of MFD on September 28, 2009 are shown in Fig. 2. There are two hysteresis loops during morning and evening peaks (7:00 to 9:30, 17:00 to 19:00). The morning hysteresis loop rises from 7:00 to 7:25 where the average flow is the maximum flow rate. Then there is a slow decline in traffic flow, but the occupancy has been increasing up to 8:00. The maximum occupancy is 20.43% at 8:00. After this, the two variables decline until 9:30. Hence, *Q-O* forms a clockwise hysteresis loop during 7:00 to 9:30. The hysteresis loops of MFDs are all clockwise, though their shape differs.

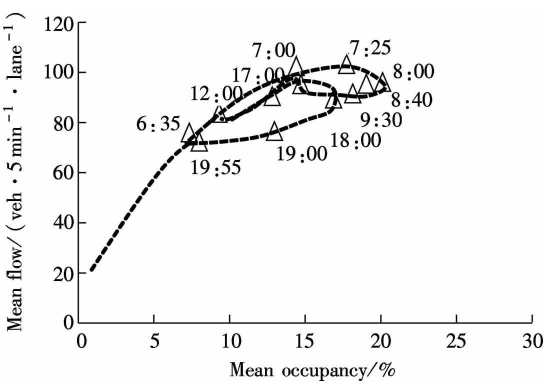

Fig. 2 Schematic illustration of the hysteresis loops

The MFD on weekdays consists of two consecutive hysteresis loops of the morning and evening loading-recovery cycles. There are two flows for two different time intervals with the same average network occupancy which reflects a network flow drop in the hysteresis loop. For example, the average network occupancy is 18% at both 7:25 and 8:40, but the average network flows are different (namely, at 7:25 Q_t is 13 veh/(5 min · lane) higher than that at 8:40). Geroliminis et al. [11] concluded that the cause of the hysteresis phenomena is the inhomogeneity of traffic distribution which can be characterized by occupancy variance. The similar method to verify this statement is to use the standard deviation (Std) of the detectors' occupancy. The standard deviation of the detectors' occupancy expresses the network heterogeneity, and the higher the standard deviation, the larger the inhomogeneity. The standard deviation is defined as

$$\mathrm{Std}(O_t) = \sqrt{\frac{\sum_{i=1}^{N}(O_{it} - \overline{O}_t)^2}{N-1}}$$

Fig. 3 plots *Q-O* and Std(O_t)-*O* in the same graph. Clearly, there is a clockwise loop for *Q-O* and an anticlockwise one for Std(O_t)-*O*. The standard deviation indeed is different between the loading (7:00 to 8:00) and recovery period (8:00 to 9:30), which means that the heterogeneity during the two periods is also different.

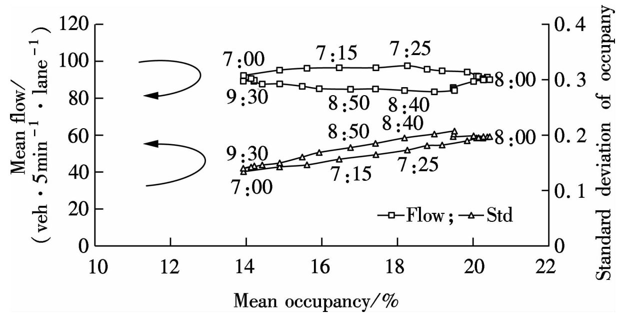

Fig. 3 *Q-O* and the standard deviation of O_t-*O* during the morning peak on September 28, 2009

It is clear that higher standard deviation is associated with lower average network flow during the recovery process. The features of the two periods are analyzed in the following to explain this. In the loading process, the flows of many detectors rapidly increase. Meanwhile, occupancies of detectors also increase. So, the standard deviation of occupancy is relatively low. Also, the average speed is relatively high at that time, so the average flow is relatively high. When the congestion dissipates, many detectors' occupancies which increase rapidly in the onset of congestion have already decreased. However, some high occupancy detectors which are congested are still present. This means that there are more high and low occupancy detectors in the offset of congestion which leads to the high standard deviation.

3 Comparison of the MFD

The days in the same period in 2012 are chosen to compare the difference in MFD. Fig. 4 shows the MFD in 2012. As can be seen, the hysteresis loop still exists after three years under different traffic situations which further verifies the existence of the hysteresis phenomenon. The shape and size of loops in 2012 are a little different from those in 2009.

The difference is that there are many scatters on the flow-occupancy relation figure during 14:00 and 15:50, and there are no rules to follow among the scatters (see Fig. 5(a)).

It is important to note that the mean occupancy relatively does not change (17% to 18.5%). Meanwhile, the

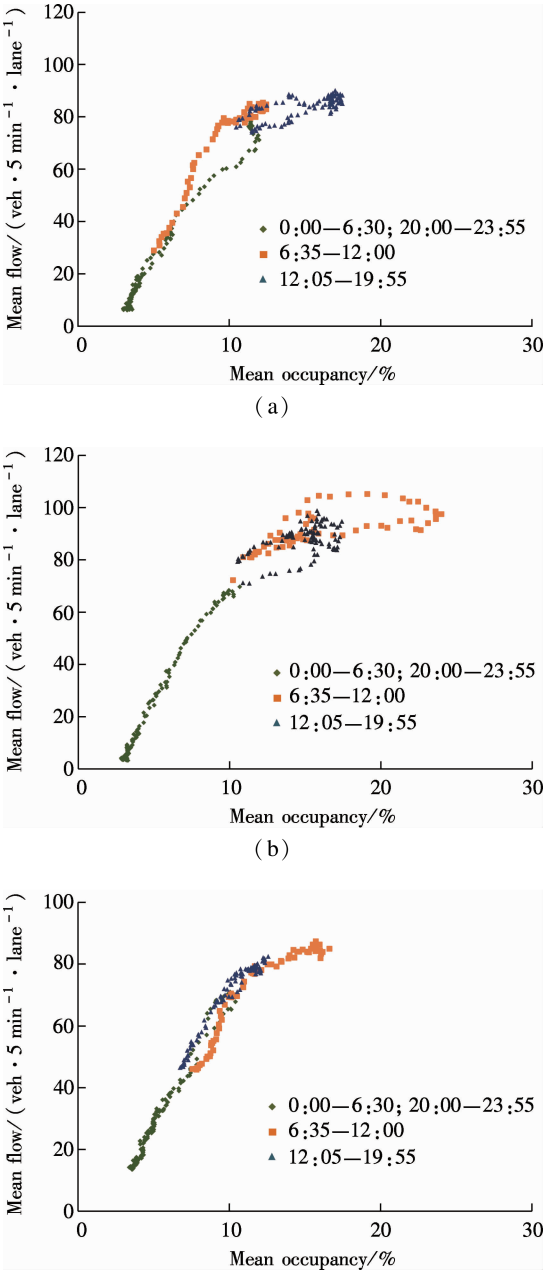

Fig. 4 Macroscopic fundamental diagrams of urban expressways in Shanghai. (a) 2012-09-23 (Sunday); (b) 2012-09-24 (Monday); (c) 2012-10-01 (holiday)

flow fluctuates between 88 and 94 veh/(5 min · lane), and this situation lasts a long time of about 2 h. By comparing the same time in 2009 (see Fig. 5(b)), the mean occupancy is not so high and changeable. It indicates that congestion still exists in the afternoon (average occupancy over 15%). However, there is no sharp loading and recovery process like during a clear peak in the morning (occupancy of 14.9% at 7:00→20.13% at 7:45→14.11% at 9:20). The occupancy remains in the afternoon which implies that the traffic situation does not change. Fig. 6 shows that the standard deviation of the occupancy in 2012 also does not change during the two hours. Hence, the flow also changes a little, which leads to scatters. The high mean occupancy in the afternoon shows that traffic situation is more severe in 2012 than that in 2009. Similar scatters are observed for other days. As a result, when the traffic situation persists for some time, the scatters may occur on the MFD.

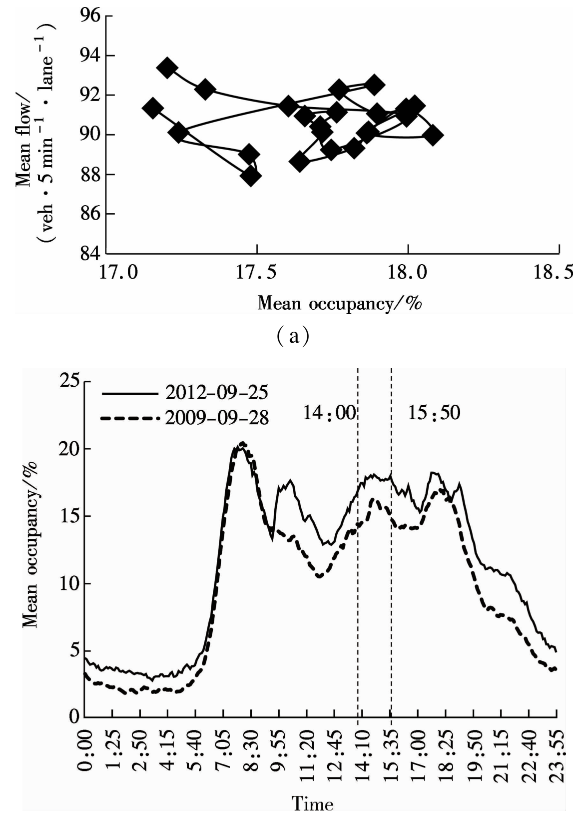

Fig. 5 The analysis of the differences. (a) Mean flow vs. mean occupancy during 14:00 and 15:50 (2012-09-25); (b) The time series of mean occupancy (2009-09-28 and 2012-09-25).

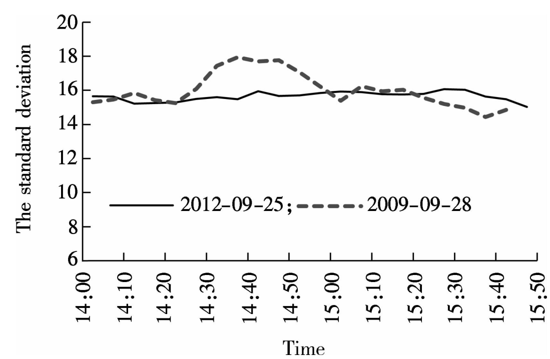

Fig. 6 Time series of the standard deviation of occupancy

4 Discussion on the Shape of Hysteresis Loop

It is clear that MFD varies across days. Saberi and Mahmassani[16] concluded that generally the hysteresis loops become larger when the spatial heterogeneity of the network increases. However, there is no clear correlation between the spatial heterogeneity of the network and the shape of the loops. Hence, in this paper, the length and the width of the loops are used for analysis. The length of hysteresis loop and the drop of network flow are used to describe the shape of the loop. The length of the hysteresis loop (ΔO) indicates the difference between the maximum and minimum average network occupancies ($O_{\max}$, $O_{\min}$), and the drop of network flow (ΔQ) is the difference between the two network flows whose occupancies are the same. One flow is the maximum flow $Q_{\max}$, the other is the minimum flow $Q_{\min}$. The formulae are in the following and the schematic illustration is shown in Fig. 7.

$$\Delta Q = Q_{\max} - Q_{\min}, \quad \Delta O = O_{\max} - O_{\min}$$

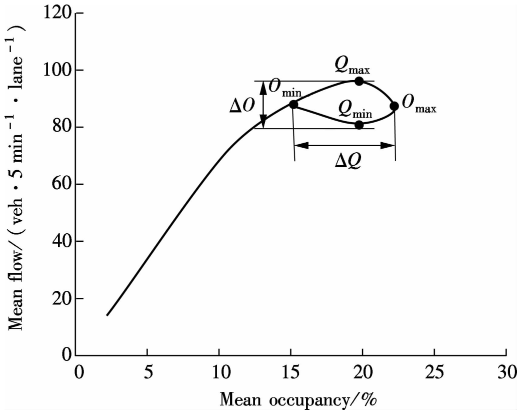

Fig. 7 Schematic illustration of ΔQ and ΔO in the hysteresis loop

It is clear that the two parameters differ much across days, as shown in Tab. 1. To verify the relationship between the two parameters with the traffic situation, the index of congestion $\bar{\alpha}_{ab}$ is used to express the severity of the congestion; $\bar{\alpha}_{ab}$ refers to the mean value of α_t during the time interval from a to b; α_t is the proportion of the congested points at time t. If the average speed of links on the urban expressway network in Shanghai is below 40 km/h, drivers will be told that the road is congested. Hence, congestion detectors are defined as those with a speed below 40 km/h. n_j is the number of the congested detectors.

$$\alpha_t = \frac{n_j}{N}, \ \bar{\alpha}_{ab} = \frac{\sum_{t=a}^{b} \alpha_t}{b - a + 1}$$

Tab. 1 The shape of hysteresis loops

Date	ΔQ/(veh · 5 min^{-1} · lane^{-1})	ΔO/%
2009-09-27 (morning)	8.98	4.19
2009-09-27 (evening)	13.93	4.86
2009-09-28 (morning)	13.33	6.51
2009-09-28 (evening)	13.37	2.82
2009-09-29 (morning)	8.31	5.74
2009-09-29 (evening)	18.06	2.67
2009-09-30 (morning)	13.02	5.24
2009-09-30 (afternoon)	13.02	10.77
2012-09-24 (morning)	12.23	11.42
2012-09-24 (evening)	11.27	2.88
2012-09-25 (morning)	9.52	6.80
2012-09-25 (evening)	7.90	2.93
2012-09-26 (morning)	13.72	6.12
2012-09-26 (evening)	6.04	3.65
2012-09-27 (morning)	10.25	7.59
2012-09-27 (evening)	6.90	3.28
2012-09-28 (morning)	13.75	6.80
2012-09-28 (evening)	3.98	4.06
2012-09-29 (morning)	12.69	4.05
2012-09-29 (afternoon)	5.76	10.84

The correlation between the length of the loop and the congestion situation are shown in Fig. 8(a). The direct correlation between the length of a hysteresis loop and the index of congestion proves that longer loops form when the congestion is heavier. However, the network flow drops and the congestion has no correlation (see Fig. 8(b)). Factors that affect the flow drop need to be analyzed further.

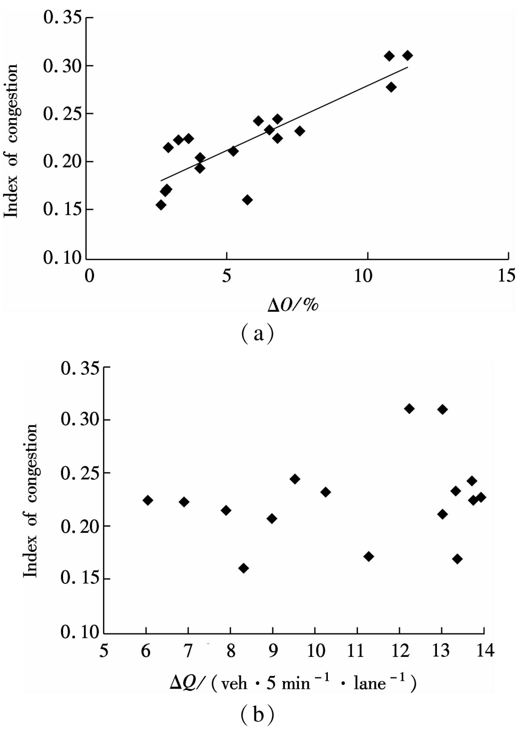

Fig. 8 The correlation between the shape of loop and index of congestion. (a) Index of congestion vs. ΔO; (b) Index of congestion vs. ΔQ

5 Conclusion

This paper aims to characterize and compare different types of days' MFD for the Shanghai urban expressway network. The main contributions of this paper are summarized as follows. First, the existence of MFD in the Shanghai urban expressway network can be proved on different types of days. The hysteresis loops exist on most days and loops coincide with the real traffic situation. On weekdays, there are two loops coinciding with the morning and evening peaks. There is only one irregular loop on weekends. On holidays, there is no loop due to the free-flowing traffic situation. Secondly, the standard deviation of occupancy is used to confirm the statement of Geroliminis and Sun[11], that the inhomogeneity of traffic distribution leads to the hysteresis phenomena. The hysteresis loop still existed in 2012 which further verifies the existence of the hysteresis phenomenon. The shape and size of loops in 2012 were a little different from those in 2009. There are more scatters in the afternoon (14:00 and 15:45). Finally, the positive correlation between the length of a hysteresis loop and the congestion severity is proved. The network flow drop is variable and has no correlation with congestion. Factors that affect the flow drop need to be further analyzed in the future.

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上海快速路网宏观交通流基本图研究

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摘要: 为了得到城市整体交通状况,研究了宏观交通流基本图.试图探索上海快速路网的宏观交通流基本图(MFD)的存在性和不同天的 MFD 图像特征.通过分析上海快速路网 2 周的数据,宏观交通流基本图确实存在.并且大部分天的 MFD 图像存在磁滞现象,在不同的交通状况下呈现不同的磁滞圈.验证了磁滞现象和交通状况的不均匀程度的关系.比较了 2009 年和 2012 年间 MFD 的变化,2012 年 MFD 磁滞现象依然存在.最后,验证了磁滞圈的长度和交通拥堵的相关性,而磁滞圈的宽度即流量下降的程度与拥堵状况没有关系,它会随着不同天不同的交通状况产生变化.

关键词: 宏观交通流基本图;磁滞现象;城市快速路网;拥堵指数

中图分类号: U491.12