Exploring the relationship between the features of macroscopic fundamental diagram and congestion pattern for expressway networks: A case study of Tokyo metropolitan expressways

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This paper aims to explore the relationship between the features of Macroscopic Fundamental Diagram (MFD) and the congestion pattern for expressway networks. To achieve this, we used the observed data of 1-min periods for Tokyo metropolitan expressway networks (Japan) throughout one year (1/1/2014-12/31/2014) to analyze the characteristics of MFD and the congestion pattern. The empirical result demonstrates that for *Inner Circular Route* and *Central Circular Route* of Tokyo metropolitan expressway: (1) the congested regime and hysteresis loop always occur in MFDs, especially, triangular shaped MFDs with a low scatters can be observed in the *Inner Circular Route* on some sunny weekdays (about 25%); (2) congested regime occurs gradually in an MFD with the increase of number of queue-spillbacks; (3) the relationship between the traffic production and the number of queue-spillbacks or congested destinations (destinations where the queue forms) under the same accumulation is almost negative linear; (4) the large number of queue-spillbacks are caused by the congestion spreading in some parts of the expressway network.

Key Words: *macroscopic fundamental diagram, hysteresis loop, congested regime, congestion pattern, traffic data, Tokyo metropolitan expressway*

1. INTRODUCTION

Recently, in order to directly evaluate network wide traffic states or network performance, Daganzo (2007)[4] proposed a aggregative macroscopic observation-based model called *Macroscopic Fundamental Diagram* (MFD) that relates the number of vehicles and area's traffic production. Using the simulated result of San Francisco Business District (SFBD), Geroliminis and Daganzo (2007)[5] showed that the well-defined MFD exists in homogeneously congested areas. Then, Geroliminis and Daganzo (2008)[6] demonstrated that the well-defined MFD which is reproducible and invariant when the demand changes both within-day and day-to-day exists in real world with a field experiment in downtown Yokohama.

Furthermore, Geroliminis and Sun (2011a)[7] showed that a well-defined MFD with a low scatter exists if the spatial distribution of traffic density (for per lane) is the same for two different time intervals with the same average network density. However, the well-defined MFD is not always observed for urban or expressway networks. For example, Buisson and Ladier (2009)[1] found that the hysteresis loop forms in an MFD for the expressway networks in Toulouse (France) when the spatial distribution of traffic density is heterogeneous. Moreover, using the loop detectors data from the freeway networks of Minneapolis (USA), Geroliminis and Sun (2011b)[8] indicated that the difference of spatial distribution of traffic density between the onset and offset of congestion is an important reason for the formation of hysteresis loop in an MFD. However, these studies only explored the relationship between the MFD features and the spatial distribution of traffic density, it is still difficult to understand the occurrence mechanism of the MFD features (e.g., the occurrence of congested regime and the formation of hysteresis loop).

In addition, some studies[12), 13), 14)] explored the relationship between the space-mean flow and standard deviation of traffic density using the simulated data. These studies reported that under the same space-mean density, the space-mean flow decreases with the increase of standard deviation of traffic density. Geroliminis and Skabardonis (2011)[9] found that the congested regime occurs in an MFD if the number of spillovers exceed its critical value based on the simulated result of SFBD. However, to our knowledge, there is no study reported that these findings above are established robustly in real road networks. Therefore, it needs more empirical studies to verify these important conclusions are whether established for real road networks or not.

Although recent results from field experiments for expressway networks[1), 2), 8), 10), 12), 15), 22)] and urban road networks[1), 11), 17), 18), 19), 20), 21)] have revealed useful insights on the MFD features. However, it is much less than the number of theoretical and simulated studies. Furthermore, most of these studies (excluding some studies[19), 20), 21)]) used data for only several days at most, which may be insufficient to investigate the robust features of MFD. Especially, using long-term detector data to investigate the MFD features for expressway network has not been reported in previous works. For example, we do not know the MFDs with a low scatter exist in expressway network or not though some previous studies (e.g., Cassidy et al., 2011[2)], Geroliminis and Sun, 2011b[8)]) pointed out that it do not exist. Furthermore, these studies do not explore the occurrence mechanism of the MFD features, for example, they do not examine the relationship between the MFD features and the congestion pattern.

Therefore, the first purpose of this study is to use a long-term detector data (one year) to analyze the robust features of the MFD for Tokyo metropolitan expressway networks (Japan). The second objective is to explore the relationship between the MFD features (in this study, we focus on the occurrence of congested regime and the formation of hysteresis loop in an MFD) by investigating the characteristics of congestion pattern.

The remainder of this paper is organized as follows: First, we introduce the network of Tokyo metropolitan expressway and detectors data in Section 2. Then, Section 3 examines the MFD features during the entire year. Next, Section 4 explores the relationship between the MFD features and congestion pattern. Finally, Section 5 summarizes the findings of this study and suggests some directions for future research.

2. DATA DESCRIPTION

(1) Detector data

Tokyo metropolitan expressway (hereafter, we call it *MEX* simply) is a vital road infrastructure for people' mobility and the economy. It carries approximately 1.1 million vehicles per day[23)]. The length of road network is about 300 [km], and a part of the expressways with 23 [km] called *Shinagawa Route*[1]is under construction (blue dotted line in Fig.1 (b)). The road sections in the road network have 2-4 lanes in each direction and the speed limit is about 80 [km/h]. The average length of road section[2] is about 250 [m].

(a) Inner Circular Route (b) Central Circular Route

Fig.1 Analysis areas of MEX networks[23)]

In this study, we use the *Inner Circular Route* and *Central Circular Route* (hereafter, we call them *Area 1* and *Area 2*, respectively) of MEX networks for analysis (the areas within the red dotted line in Fig.1), and the area of these two analysis areas are approximately 9.6 [km^2] and 193.6 [km^2] respectively (Fig.1). Traffic flow and traffic density are collected for each road section by 149 and 1129 detectors (road sections) in these two analysis areas. The analysis period is one year, from 1/1/2014 to 12/31/2014. These detectors record the value for each 1-min period during each 24-h day, producing a total of 1439 periods (T=1439) for each day. Detector i records the traffic flow q_t^i and the vehicle speed v_t^i for road section i in each time period t. The traffic density k_t^i is calculated by $k_t^i = q_t^i / v_t^i$.

(2) MFD definition

We then define the MFD and illustrate the method for drawing the MFD using an example shown in Fig.3. The horizontal axis in figure represents the traffic production P_t and the vertical axis represents the accumulation N_t. Each plotted point is the data pair (accumulation, traffic production) observed during each time period for each day. The traffic production P_t and accumulation N_t can be calculated using Eq.(1) and Eq.(2), respectively:

$$N_t = \sum\nolimits_{i \in I} k_t^i l^i = \sum\nolimits_{i \in I} (q_t^i / v_t^i) l^i \quad (1)$$

$$P_t = \sum\nolimits_{i \in I} q_t^i l^i \quad (2)$$

where I is the detector (road section) set for any analysis area and l^i is the length of road section i. In

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[1] *Shinagawa Route* has been completed in March, 2015. The analysis period in this study is 1/1/2014-12/31/2014.
[2] Here, the road section is defined as the distance between the adjacent detectors.

addition, as shown in Fig.3, we divide the 24 hours in each day into six time periods as indicated by six different symbols and colors.

3. MFD CHARACTERIZATION

(1) MFD classification

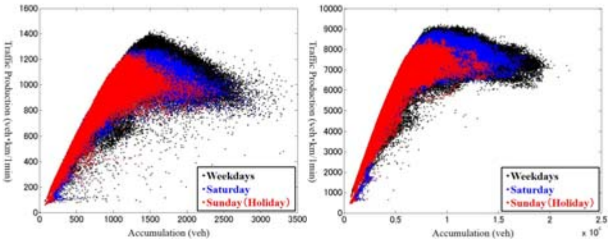
Firstly, we draw MFDs for the entire year using the detector set I_1 and I_2 (the sets of detector in Area 1 and Area 2). The result (Fig.2) shows that the congested regime occurs on most weekdays, Saturdays, and Sundays (and holidays). This means that the occurrence of congested regime is a common phenomenon for MEX networks. Furthermore, examination of a large number of MFD observations reveals that the daily MFDs throughout the entire year can be classified into several types depending on the traffic demand (weekdays vs. weekends) and network supply level (sunny days vs. bad weather days).

By observing the MFDs for bad weather days (rainy or snowy days) for the entire year, we find that the MFD shape is different from that on sunny days. Furthermore, the difference may occur during the time periods of rainfall or snowfall (see some previous studies[19), 20), 21)]). Therefore, in the following sections, we only focus on the sunny days to analyze the MFD features in more detail.

(2) MFD features on sunny days

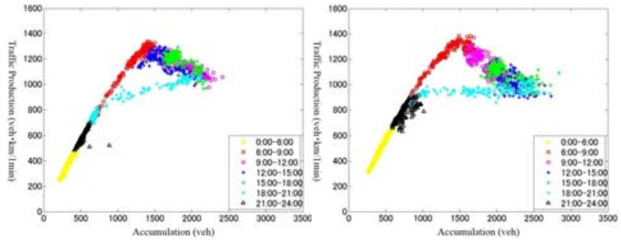
Throughout the observation during the entire year, we find that for sunny weekdays, the congested regime always occur (occurrence frequency is about 95% for Area 1 and 70% for Area 2) in MFDs for the two analysis areas, especially, triangular shaped MFDs (Fig.3 (a)-(d)) with hysteresis loop and a low scatters sometimes be observed in the Area 1 (about 25%). This result means that a well-defined MFD exits in expressway network and this is a new finding that has not been reported in previous works. Then, for Area 2, the MFD with a hysteresis loop (as shown in Fig.4 (a)-(b)) does not always form (only about 10%), on the contrary, the MFD with multiple hysteresis loops (as shown in Fig.4 (c)-(d)) are often observed. In addition, for sunny weekends, the congested regime may occur (Fig.4 (e), Fig.5 (e)), or it may not (Fig.4 (f), Fig.5 (f)) for two analysis areas.

For the observational result above, we want to know that why the triangular shaped MFDs (Fig.3 (a)-(d)) with a low scatters can be observed in Area 1 sometimes. Here, we suppose that the network structure of Area 1 is an important reason for this phenomenon. It is quite different from the urban road networks (it can be seen as a parallel network with independent two routes), because that the users can not select a new route to avoid the congestion from the downstream. Once the traffic congestion occurs somewhere, it can spread to upstream rapidly. Any user can not avoid

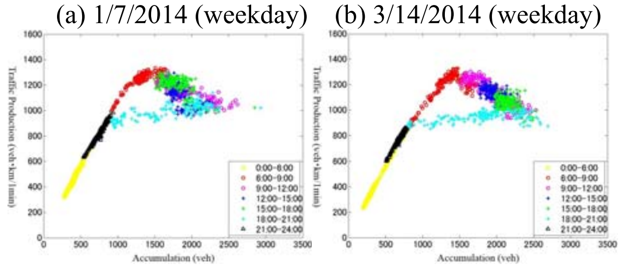


(a) Area 1 (b) Area 2

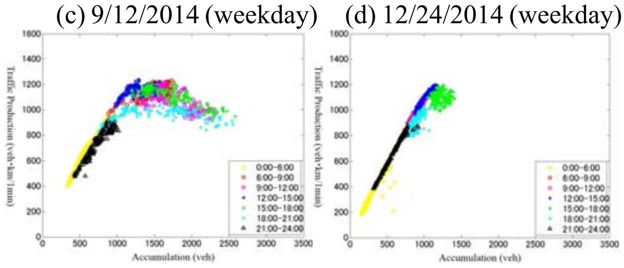
Fig.2 MFDs for the entire year



(a) 1/7/2014 (weekday) (b) 3/14/2014 (weekday)

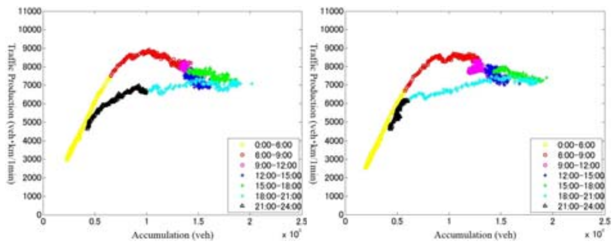


(c) 9/12/2014 (weekday) (d) 12/24/2014 (weekday)

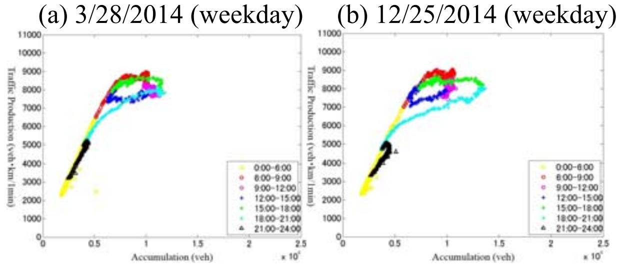


(e) 3/8/2014 (Saturday) (f) 11/24/2014 (holiday)

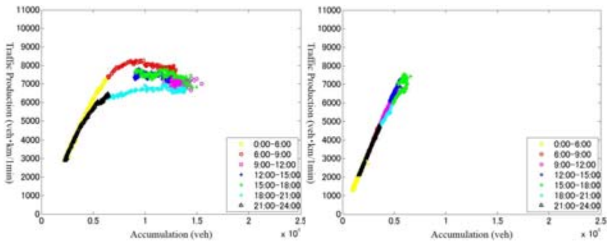
Fig.3 MFDs on sunny days for Area 1



(a) 3/28/2014 (weekday) (b) 12/25/2014 (weekday)



(c) 6/19/2014 (weekday) (d) 10/9/2014 (weekday)



(e) 3/21/2014 (holiday) (f) 1/5/2014 (Sunday)

Fig.4 MFDs on sunny days for Area 2

this congestion unless he/she leaves the network from a off-ramp/JCT where has not been involved in congestion. This means that the duration of heterogeneous traffic states (congested links and uncongested links) in Area 1 is short, then a well-defined MFD with a low scatters can be observed on some sunny weekdays.

On the other hand, when there are many routes can be selected for users to avoid the congestion such as Area 2. Then, the duration of heterogeneous traffic states would become longer than that in Area 1, therefore, the MFDs with high scatters and multiple hysteresis loops exists in Area 2 (Fig.4 (c)-(e)). To test the hypothesis above is a research topic for future works. In addition, we can also explain these phenomena as follows. Based on the observation, we find that the MFD for each route are triangle. Since the congestion spreading level for each route at the same time period is different from each other, so we can see that the high scatters and multiple hysteresis occur for Area 2 after their combination[3].

4. CONGESTION PATTERNS

(1) Number of queue-spillbacks

Before analyze the spatial distribution of congested links, we use an aggregated value, the number of queue-spillbacks S_t which expresses the deviation of congestion pattern to explore the relationship between the MFD features and the congestion pattern. Then, the number of queue-spillbacks during time period t is defined as follows.

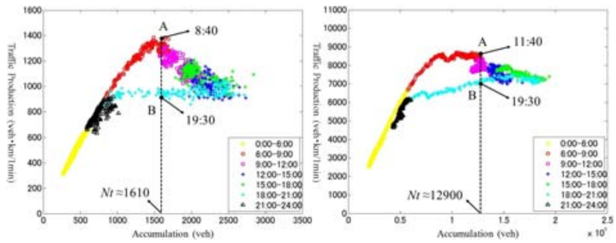
$$S_t = \sum_{k\in K} S_t^k = \sum_{k\in K} \sum_{u\in IN(k)} \sum_{d\in OUT(k)} s_t^{k,(u,d)} \qquad (3)$$

$$\begin{cases} s_t^{k,(u,d)} = 1 \; if \; v_t^{k,u} \le 20 \, and \, v_t^{k,d} \le 20 \\ s_t^{k,(u,d)} = 0 \; otherwise \end{cases} \qquad (4)$$

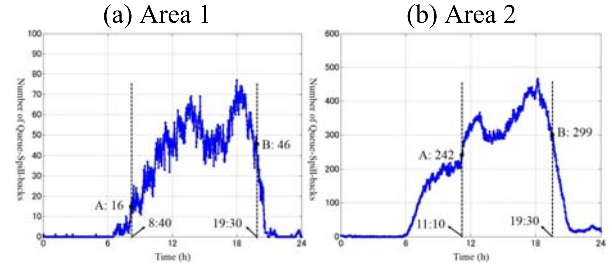
where K is the set of node k, $IN(k)$, $OUT(k)$ are the upstream and downstream road section for the node k, $v_t^{k,u}$ and $v_t^{k,d}$ are the vehicle speed for the upstream and downstream road section, S_t^k is the number of queue-spillbacks for the node k during time period t.

Using the definition above, we first compare the number of queue-spillbacks between the upper and lower curve on hysteresis loop under the same accumulation for some typical days (Fig.5). The plots A and B in Fig.5 are the same accumulation and the number expresses the number of queue-spillbacks. The results demonstrate that under the same accumulation level, the number of queue-spillbacks during the loading process (upper curve of hysteresis loop) is lower than that during the recovery process (lower curve of hysteresis loop). Then, we can also see that the number of queue-spillbacks in the uncongested regime is much lower than that in the congested regime. This means that the congested regime in an MFD occurs gradually with the increase of the number of queue-spillbacks.

In order to test the robustness of the former conclusion above, we analyze the relationship between traffic production and the number of queue-spillbacks under the same accumulation level for the two analysis areas during the entire year (365 days). The horizontal axis in Fig.6 represents the traffic production and the vertical axis represents the number of queue-spillbacks, and the plots in this figure with different colors express the different same accumulation level. Fig.6 shows that the relationship between the traffic production and the number of queue-spillbacks for each accumulation level is almost navigate linear. This means that the conclusion

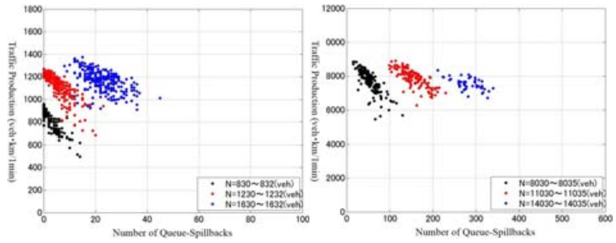


(a) Area 1 (b) Area 2



(c) Area 1 (d) Area 2

Fig.5 MFD and Time-series of the number of queue-spillbacks



(a) Area 1 (b) Area 2

Fig.6 The relationship between the traffic production and the number of queue-spillbacks under the same accumulation

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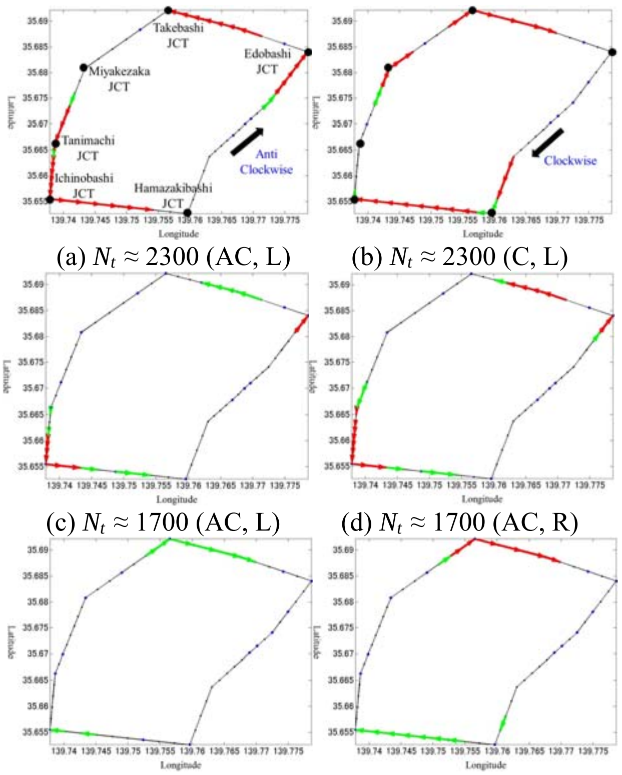
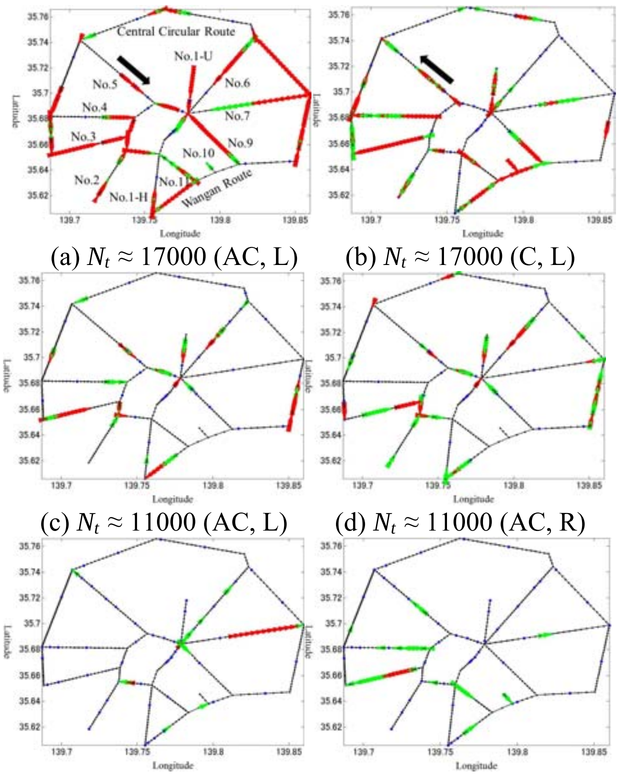
[3] Due to the limited space, we do not show the MFD for each route here.



(a) $N_t \approx 2300$ (AC, L) (b) $N_t \approx 2300$ (C, L)
(c) $N_t \approx 1700$ (AC, L) (d) $N_t \approx 1700$ (AC, R)
(e) $N_t \approx 1700$ (C, L) (f) $N_t \approx 1700$ (C, R)

Fig.7 Congestion pattern for Area 1



(a) $N_t \approx 17000$ (AC, L) (b) $N_t \approx 17000$ (C, L)
(c) $N_t \approx 11000$ (AC, L) (d) $N_t \approx 11000$ (AC, R)
(e) $N_t \approx 11000$ (C, L) (f) $N_t \approx 11000$ (C, R)

Fig.8 Congestion pattern for Area 2

which have been explored using simulated data (see, Mazloumian et al., 2010[14)]) is also established in expressway network (Wang et al., 2016[20)] have explored the "navigate linear" exists in urban road network).

(2) Spatial distribution of congested links

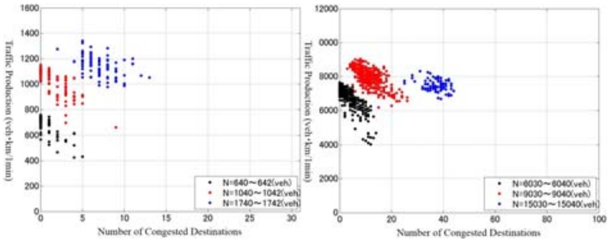
This section aims to analyze the characteristics of spatial distribution of congested links. Here, we show the evolution of congestion pattern in anti-clockwise ("AC" in Figs.7-8) and clockwise ("C" in Figs.7-8) during the traffic loading process ("L" in Figs.7-8) and traffic recovery process ("R" in Figs.7-8) for some accumulation level. The arrows with different colors represent the occurrence frequency for each link during the 7:00-21:00 (e.g., green: 50%-75%; red: 75%-100%)[4]. The accumulation in Figs.7-8 expresses the number of vehicles (e.g., $N_t \approx 2300$) in Area 1 or Area 2, *not only* in the clockwise or anti-clockwise network.

By observing the congestion pattern[5] in Area 1, we first find that the congested regime occurs gradually with the increase of the number of queue-spillbacks which caused by the congestion spreading for different position in clockwise and anti-clockwise network. For example, for anti-clockwise network (Fig.7 (a)), the congested links exist in the upstream of *Takebashi JCT* and *Edobashi JCT*, periphery of *Ichinobashi JCT* and *Tanimachi JCT*. On the contrary, for clockwise network (Fig.7 (b)), the congested links are always concentrated between the *Ichinobashi JCT* and *Hamazakibashi JCT*, the periphery of *Takebashi JCT* and *Miyakezaka JCT*.

Then, we also find that under the same accumulation, the spatial distribution of congested links during the traffic loading process (Fig.7 (c), (e)) are similar to the traffic recovery process (Fig.7 (d), (f)). However, the congestion spreading level (the number of queue-spillbacks) during the two process are much different from each other, for example, we can see more queue-spillbacks during the traffic recovery process. In addition, the result also indicates that it is difficult to observe the congested links in some positions of clockwise and anti-clockwise networks though the accumulation reaches its maximum value (e.g., $N_t \approx 2300$). Such as the periphery of *Shiodome JCT* and *Kyobashi JCT* which connect the *KK Route* and *Yaeshu Route*.

4 The purpose of this study is to analyze the relationship between the MFD features and the typical congestion pattern that appears frequently on weekdays. Therefore, it is necessary to eliminate some congested links (congestion pattern) that are occasionally observed for only several weekdays in these two analysis areas due to some reasons (e.g., bad weather, traffic accidents or road construction).

5 Due to the limited space, in this paper, we only show the congestion pattern for maximum accumulation and for one accumulation level. Using such congestion pattern, we can clearly find that where the congestion spreading occurs.



(a) Area 1 (b) Area 2

Fig.9 The relationship between the traffic production and the number of queue-spillbacks under the same accumulation

Furthermore, throughout the observation for the congestion pattern in Area 2, we find that the spatial distribution of congested links are different from the clockwise and anti-clockwise networks. For example, for anti-clockwise network, we can see that the congestion spreads in *Route No.1-U*, *No.3*, *No.6*, *No.7*, *No.9*, *No.11*, and the east/west of *Central Circular Route* (Fig.8 (a)). On the other hand, for clockwise network, the *Route No.1-U*, *No.3*, *No.4*, *No.9*, *No.10*, and the west of *Central Circular Route* become congested with the increase of the accumulation (Fig.8 (b)). Then, we also find that under the same accumulation, the spatial distribution of congested links during the traffic loading process are similar to that during the recovery process, but the congestion spreading level are much different from the two processes (this conclusion is consistent with that of Area 1). In addition, the result also indicates that it is difficult to see that the congested links in some positions in clockwise and anti-clockwise networks, though the accumulation reaches its maximum value. Such as the north of the *Central Circular Route*. We suppose that these phenomena mentioned (congested and uncongested sections exist) for Area 1 and Area 2 are strongly related to the spatial distribution and inflow of on-ramps/JCTs, because that the merging of vehicles in on-ramps/JCTs is easy to cause congestion for expressway network. To test the hypothesis above is a research topic for future works.

(3) Number of congested destinations

From the perspective on spatial connection of congested links, Section 4(2) explored the relationship between the spatial distribution of congested links and the MFD features. This section aims to investigate the relationship between the MFD features and the congested destinations (destinations where the queue forms consists of the off-ramps and the outflow links in JCT), because that if the congested links are connected to the destinations, it can obviously affect the network performance (outflow of the network)[6].

Based on this motivation, we investigate the traffic production and the number of congested destinations under the same accumulation level. The horizontal axis in Fig.9 represents the traffic production and the vertical axis represents the number of congested destinations, and the plots in this figure with different colors express the different same accumulation level. Fig.9 shows that the relationship between the traffic production and the number of congested destinations for each same accumulation is almost navigate linear. It means that if the number of congested destinations increase, to leave the network for users would become more difficult, then the congestion spreads, the traffic production decreases.

5. CONCLUSION

In this paper, we explored the relationship between the features of Macroscopic Fundamental Diagram (MFD) and the congestion pattern for Tokyo metropolitan expressway networks. The empirical result demonstrated that for two analysis areas of Tokyo metropolitan expressway: (1) the congested regime and hysteresis loop always occur in MFDs, especially, triangular shaped MFD with a low scatters can be observed in the *Inner Circular Route* on some weekdays (about 25%); (2) congested regime occurs in an MFD with the increase of number of queue-spillbacks; (3) the relationship between the traffic production and the number of queue-spillbacks or congested destinations (destinations where the queue forms) under the same accumulation is almost the negative linear; (4) the large number of queue-spillbacks are caused by the congestion spreading in some parts of the expressway network.

As the first step in future works, it is necessary to establish a model to explore the occurrence mechanism of MFD features (e.g., hysteresis loop, congested regime). Then, based on the analysis of the congestion pattern, we clearly know the position of "bottlenecks" for MEX networks. Then, we can employ some traffic control methods (e.g., ramp metering control, TBP) to reduce the congestion of MEX networks and evaluate the network performance using MFD features before and after the implementation. In addition, we are also interested in investigating the relationship between the MFD and network performance (outflow) because we can understand the outflow for MEX networks (excluding Geroliminis and Daganzo, 2008[6]), no empirical research focus on this point). The detail of these re-

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[6] Some previous theoretical studies[4)] also pointed out that (1) it is necessary to prevent queues from forming where the destinations are, (2) maximize flow where exit rates are high is an efficient strategy for storing queues in congested roads.

searches are on progress.

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