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Abstract

To alleviate traffic congestion in the city center, many cities in China restrict non-local vehicles using expressways or entering the central area during the morning peak and the evening peak, such as Shanghai, Beijing and Shenzhen. In Shanghai, the non-local plate vehicle restriction policy started to be implemented in 2002, which banned vehicles without local plates using elevated highways in the central area from 7:30 am to 9:30 am and from 4:30 pm to 6:30 pm. This restriction was firstly tightened in 2015 and further tightened in 2016, with longer restricted hours and expanded banned expressways. However, no relevant research has been found to empirically evaluate these policies from the perspective of macroscopic traffic performance. In this study, the macroscopic fundamental diagram (MFD) approach is used to evaluate the performances of Shanghai's macroscopic traffic under the three different restriction policies. The macroscopic effects of the restriction policy on the restricted expressways are compared with the surface roads without any restrictions. Moreover, the time-varying characteristics of macroscopic traffic performance, e.g., hysteresis loop, during the morning peak and the evening peak, are further investigated in this study.

Keywords

Non-local plate; Vehicle restriction policy; MFD; Macroscopic traffic performance; Time-varying characteristics; hysteresis loop

1. INTRODUCTION

To alleviate traffic congestion in the city center, many cities in China restrict non-local vehicles using expressways or entering the central area during the morning peak and the evening peak, such as Shanghai, Beijing and Shenzhen. Some studies considered that the vehicle restriction is a more quitable way of mitigating road congestion than road pricing (Kornhauser and Fehlig, 2003; Rouwendal and Verhoef, 2006). This policy is not new in the world. Early in the 1970s, a vehicle restriction policy start to implement in Buenos Aires banned one-half of all the cars from entering the city center on a given day depending on whether the last digit of the plate number was odd or even. This method was also used in Caracas in the 1980s and in Athens between 1985 and 1991 (de Grange and Troncoso, 2011). Shanghai is the first Chinese city to implement the driving restriction policy, the non-local plate vehicle restriction policy started to be implemented in 2002, which banned vehicles without local plates using elevated highways in the central area from 7:30 am to 9:30 am and from 4:30 pm to 6:30 pm. This restriction was firstly tightened in 2015 and further tightened in 2016, with longer restricted hours and expanded banned expressways.

Some specialists have argued against the vehicle restriction approach, calling it unjust and inefficient (de Grange and Troncoso, 2011). Using a time-series analysis, Eskeland and Feyzioglu (1995) find that the restriction method actually increases congestion and pollution in the long term, due to the tendency of drivers to acquire an additional car. Other studies evaluate the policy from different perspectives, such as economic activity (Viard and Fu, 2015), air pollution (Viard and Fu, 2015; Huang et al., 2017; Li and Jones, 2015), travel behavior and adaptation mechanisms (Gu and Long, 2017) and travel mode choice (Wang et al., 2014; Liu et al., 2016). However, no relevant research has been found to empirically evaluate these policies from the perspective of macroscopic traffic performance. The main reasons are: 1) lack of reliable network-level data over multiple time periods and 2) lack of a useful tool to represent the crowded conditions in a steady state.

In this study, a Macroscopic Fundamental Diagram (MFD) approach is used to empirically evaluate the non-local vehicle restriction policy in Shanghai. As an alternative to the disaggregate approach, Daganzo (2007) proposed a macroscopic congestion measure called the Macroscopic Fundamental Diagram (MFD), which captures urban traffic states at an aggregate level. MFD is an important tool to monitor a large system and test different control strategies (Geroliminis and Daganzo, 2007). Compared with the traditional forecasting models, MFD can be estimated easily without the full knowledge of the dynamic traffic assignment and the accurate prediction of the micro-level travel behaviors. By knowing and monitoring the state of traffic continuously, transportation managers can now see whether their system in a state that is producing the desired accessibility level for all modes and at all times (Geroliminis and Daganzo, 2008).

The present study was to empirically analyze and quantify how did the non-local restriction policy affect the macroscopic traffic performance in Shanghai. More specifically, the three sub-objective are:

- To evaluate the Shanghai's macroscopic traffic performance at different stages of the restriction policy.
- To analyze and explain the macroscopic traffic performance from the perspective of elevated highways, surface roads, and ramps.
- To explore the time-vary characteristics of macroscopic traffic performance, e.g., hysteresis loop, under the effect of the restriction time.

The reminder of the paper is structured as follows: Section 2 described the data and the research area. Next, the Shanghai MFD is estimated in Section3 and the macroscopic traffic performances at different stages of the restriction policy are compared in this section. Section 4 further discusses the effect of the restriction policy on the elevated highways, surface roads, and the ramp. Finally, conclusions and recommendation are provided in Section5.

2. Data and Research Area

2.1 FCD Data

The FCD data was collected from 2015 to 2016 from Shanghai Qiang-Sheng Taxi Company, one of the largest taxi companies in Shanghai. The entire dataset contains about 13000 taxi drivers' sequential trajectories and operation statuses, including taxi ID, data, measurement time, longitude, latitude, speed (km/h), and operation status identifier (1 for vacant / 0 for hired). The daily dataset has over one hundred million items (more than 10 GB), and records every taxis' ID, speed, location and other operation information in every 10-second interval. The records with the speeds higher than 120km/h and vacant status were removed from the dataset. Additional detailed explanation of the dataset and data cleaning process can be found in Huang et al. (2018).

In order to well evaluate the effect of restriction policy, the data in four time periods was selected to calibrate the MFD. The basic information of the data during the four periods is presented in Table 1.

Table 1. Basic information about the four time periods.

Time Period	Days	Restricted Time	Car Ownership
I: April 1 - April 14, 2015	9 days	AM: 07:30-09:30 PM: 16:30-18:30	Local plate: 1,560,000; Non-local plate: 1,133,300
II: April 16 - April 30, 2015	11 days	AM: 07:00-10:00 PM: 16:00-19:00	Local plate: 1,560,000; Non-local plate: 1,133,300
III: March 18 – March 31, 2016	10 days	AM: 07:00-10:00 PM: 16:00-19:00	Local plate: 1,680,000; Non-local plate: 1,277,500
IV: August 1- August 14, 2016	8 days	AM: 07:00-10:00 PM: 15:00-20:00	Local plate: 1,746,700; Non-local plate: 1,340,000

Notes: (1) Effective days are weekdays; (2) Vehicle with non-local plate cannot enter the elevated highway in the central area during the restricted time in weekdays, vehicle with "Hu C" plate cannot enter the central area at any time

2.2 Research Area

An illustration of research area is shown in Figure 1. Elevated highways and surface roads within the central area were selected as our study site. The total length of the elevated highway network and the surface road network are 64.1 km and 303.0 km, respectively. In Shanghai, most of the elevated highways have 3 lanes and the speed limits are 60 to 80 km/h; most of the surface roads have 2 lanes and the speed limits are 40 to 60 km/h.

Figure 1: Research Area

3. Shanghai MFD

3.1 Estimating the MFD

Using FCD data, the estimation of the MFD is based on Eddie's generalized traffic definition (Edie, 1963). Based on Ambühl and Menendez (2016), the total distance, d_{tot}, and the total travel time t_{tot} spent in the research network during a 10-minute interval, were used to estimate the MFD:

$$\hat{q} = \frac{d_{tot}}{LT\hat{\rho}} \quad (1)$$

$$\hat{k} = \frac{t_{tot}}{LT\hat{\rho}} \quad (2)$$

where, L represents the length of network; T represents 10-minute time slice; $\hat{\rho}$ represent the probe penetration rate.

Previous research used taxi and loop detector data to estimate flow and density, but the loop detector data for each link is not available in this study. Fortunately, Shanghai did a fifth comprehensive transportation survey in 2015, and they have the results for the time-varying network traffic flow based on the loop detector data (Chen et al., 2016). Based on their results, we can estimate the penetration rate at time slice *t* with the following formula:

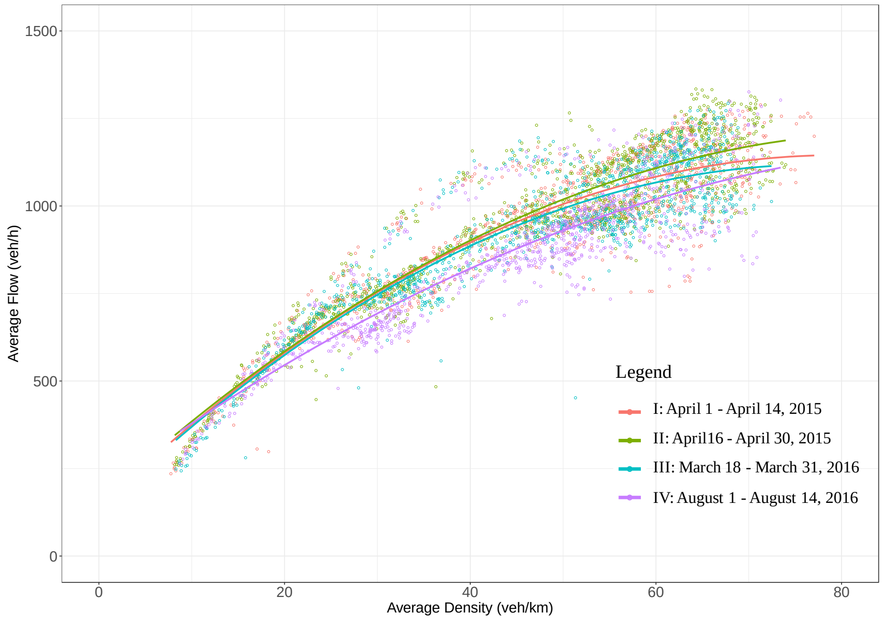
$$\hat{\rho}(t) = \frac{VKT_{taxi} \times P_{taxi}(t)}{VKT_{road} \times P_{road}(t)} = \frac{d'_{tot}(t)}{VKT_{road} \times P_{road}(t)} \qquad (3)$$

where, VKT_{taxi} and VKT_{road} represent the travel distance of taxis in one day and the travel distance of all road traffic in one day, respectively; $P_{taxi}(t)$ and $P_{road}(t)$ stand for the percent of taxi travel distance and the percent for all road traffic travel distance, respectively, for the time slice *t*; $d'_{tot}(t)$ represents the total travel distance for taxi drivers for a time slice *t*. VKT_{road} and $P_{road}(t)$ can be extracted from the 5th Shanghai comprehensive transportation survey (Chen et al., 2016). $d'_{tot}(t)$ can be calculated from the FCD data. Since the network length of the road traffic data is different from the network length in our study area, $d'_{tot}(t)$ is different from the d_{tot} in formula (1).

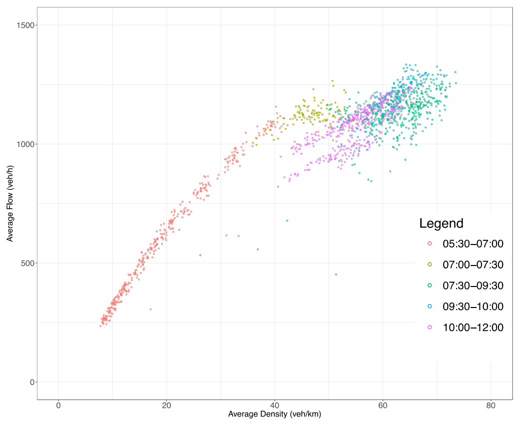
3.2 MFD for the Shanghai central area

Figure 2 (a) shows the average network flow versus density (i.e., MFD) for four time stages. The shapes of MFD in four different time periods are similar, which confirms that the MFD is a steady property of the network (Geroliminis and Daganzo, 2008). The capacity and free flow speed was calculated by the 99th percentile of network flow and speed, respectively. The critical density was calculated from the mean density of all network flow values above the 99th percentile of network flow. From the results, the capacity of the network in Shanghai central area is 1274.8 veh/h (based on each direction of the link, not each lane), the critical density is 65.5veh/km, the critical speed is 19.5km/h, and the free flow speed is 34.9km/h.

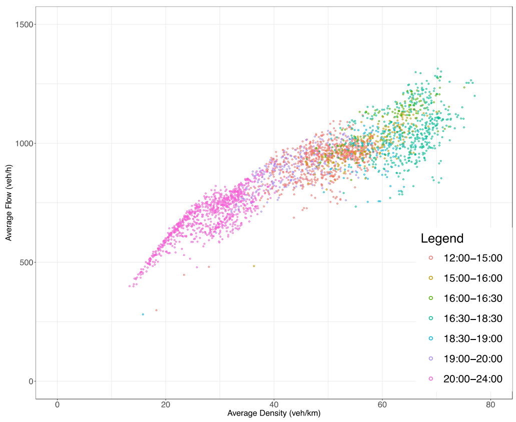
Figure 2: Shanghai (a) MFD in four time periods; (b) MFD during AM peak; (c) MFD during PM peak.



(a)



(b)



(c)

Figure 2 (b) and Figure 2 (c) indicate the shape of MFD in the morning (05:30-12:00) and in the afternoon (12:00-24:00), respectively. The hysteresis loop phenomena exist in both AM peak and PM peak. However, the shapes of the hysteresis loop in the two time periods are totally different: counter-clockwise hysteresis loop is found in the morning and the clockwise hysteresis loop is found in the afternoon. To the best of our knowledge, this is the first empirical finding of the counter-clockwise hysteresis loop. The reasons of the hysteresis loop in Shanghai network is discussed in the Section 4.

3.3 Comparison of the macroscopic traffic performance at different stages of the policy

The MFD can well reflect the supply of the total network. While the traffic demand is various at different time periods due to the restriction policy and the increase of the car ownership, we can use MFD as a steady benchmark to evaluate the macroscopic traffic performance at different stages of the policy.

Some indicators were used to evaluate the macroscopic traffic performance. Maximum volume was calculated as 95th percentile of network flow during the periods, which can be compared with the network capacity. Speed delay was the average of the speed delay compared with the free flow speed. Minimum speed was calculated as the 5th percentile of the speed. VKT was the total driving distance during the periods.

Results of these indicators in different stages of policy are presented in Table 2 to Table 5. It is shown that after the first change of restriction time (April 15, 2015), the macroscopic traffic performance changed slightly. The speed delays were dropped and the minimum speeds as well as the maximum volume were increased. After one year, the car ownership increased about 8%, the macroscopic traffic performance was even worse, in terms of the maximum volume, speed delay, and minimum speed. In terms of the VKT, it seemed that the total travel distance during the morning dropped sharply, while the total travel distance during the PM Peak and non-peak hours were still high. This indicated that some drivers may leave home earlier or bypass the central area in the morning, but the total traffic demand was basically unchanged. After April 15, 2016, the restriction policy was further tightened during the afternoon. The macroscopic traffic performance improved in terms of the speed delay and the minimum speed. The VKT during the PM peak and non-peak hours decreased significantly, which indicated that some drivers may transfer to other traffic modes or bypass the central area. However, the tight restriction policy also has a negative impact on the maximum flow. Tight restriction increased the inhomogeneity of the network flow, which lead to the capacity drop, especially in the PM peak.

Table 2: Indicators of macroscopic traffic performance during April 1 – April 14, 2015

	Maximum Volume (veh/h)	Speed Delay (km/h)	Minimum Speed (km/h)	VKT (in millions)
AM Peak (7:00-10:00)	1256	15.85	16.28	1.26
PM Peak (15:00-20:00)	1220	17.73	14.16	1.88
Non-peak hours	1165	11.14	17.70	2.91
Note: Restricted time: 07:30 - 09:30, 16:30 - 18:30; Car ownership (local-plate vehicle): 1,560,000				

Table 3: Indicators of macroscopic traffic performance during April 16 – April 30, 2015

	Maximum Volume (veh/h)	Speed Delay (km/h)	Minimum Speed (km/h)	VKT (in millions)
AM Peak (7:00-10:00)	1303	15.50	16.68	1.37
PM Peak (15:00-20:00)	1240	17.01	14.95	1.84
Non-peak hours	1172	11.31	17.58	3.67
Note: Restricted time: 07:00 - 10:00, 16:00 - 19:00; Car ownership (local-plate vehicle): 1,560,000				

Table 4: Indicators of macroscopic traffic performance during March 18 – March 31, 2016

	Maximum Volume (veh/h)	Speed Delay (km/h)	Minimum Speed (km/h)	VKT (in millions)
AM Peak (7:00-10:00)	1230	15.64	15.81	1.02
PM Peak (15:00-20:00)	1160	17.36	14.63	1.8

Non-peak hours	1152	11.8	17.95	3.47
Restricted time: 07:00 - 10:00, 16:00 - 19:00; Car ownership (local-plate vehicle): 1,680,000				

Table 5: Indicators of macroscopic traffic performance during August 1 – August 14, 2016

	Maximum Volume (veh/h)	Speed Delay (km/h)	Minimum Speed (km/h)	VKT (in millions)
AM Peak (7:00-10:00)	1253	15.17	16.39	1.3
PM Peak (15:00-20:00)	1031	17.56	13.73	1.71
Non-peak hours	992	12.83	16.53	2.22
Restricted time: 07:00 - 10:00, 15:00 - 20:00; Car ownership (local-plate vehicle): 1,746,700				

4. A deeper look in the effect of plate policy on the Shanghai macroscopic traffic performance

4.1 Road type classification

In Shanghai central area, there exists a large degree of overlap between the area of elevated highways and the adjacent surface roads. Since the FCD data has the limitations of the location accuracy (e.g., lack of height information), it is difficult to distinguish whether the vehicle travels on the elevated highways or the surface roads. However, the restriction policy only restricted non-local vehicle using the elevated highways during the peak hours, it is important to evaluate the effect of restriction policy on the highway and the surface roads separately.

This study proposed a transductive support vector machines (TSVMs) method to identify the travel path in the overlap highway area. TSVMs (Vapnik, 1995) are a group of methods of improving the generalization accuracy of SVMs by using unlabeled data. The concave-convex procedure (CCCP) algorithm, proposed by Collober et al. (2006), was used to implement

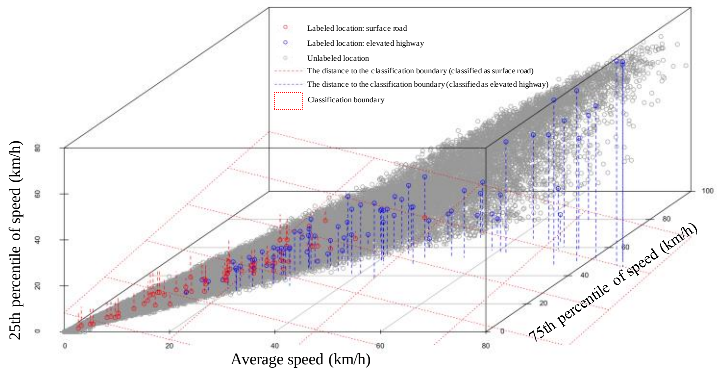
TSVMs. Collober et al. (2006) shown that this algorithm had better performance in dealing with the massive data than other TSVMs algorithm.

The trajectory separation procedures are shown as follows:

1) Create a buffer around the elevated roads, and then select the GPS trajectory within the buffer area as our classification sample.
2) Sort the data by hours as a sub-set.
3) Manually labelled 500-1000 data for each dataset using the characteristic of trajectory, mainly based on the characteristic was chosen based on Xu et al. (2012).
4) Every three moving minutes in one hour was regard as a sample point. The average speed, the 75th percentile of speed, and the 25th percentile of speed were used as features to train the data set.
5) Implement the TSVMs for each sub-set using CCCP algorithm and the linear kernel.
6) Use 7 sample taxis to validate the classification result.

One example of the TSVMs result for one sub-set is shown in Figure 3. The red labeled location connected with red line indicated the accurate classification of the labeled surface load. The blue labeled location connected with blue line indicated the accurate classification of the labeled elevated highway. The validation results shown that the average error rate of identifying the elevated highways and surface roads is 9.7%, which is acceptable

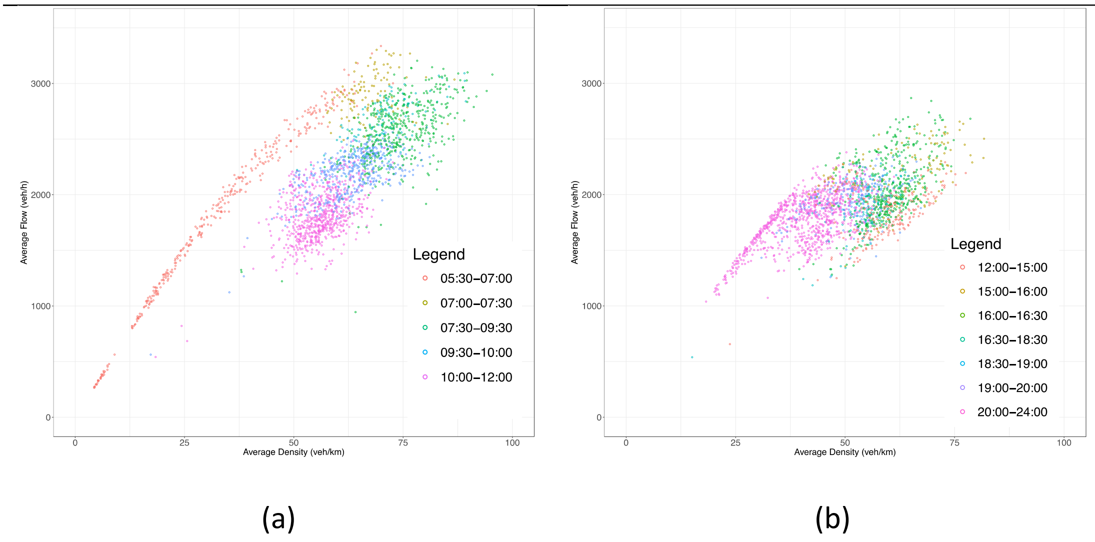
Figure 3: Classification result for one sub-set (8:00 - 9:00).



4.2 The macroscopic performance of elevated highways

The elevated highways MFD is estimated using the same method that have mentioned in Section 2. Figure 4(a) and Figure 4(b) display the highway MFD in the morning and in the afternoon, respectively. The capacity of elevated highway is 3059 veh/h, the critical density is 71.6 veh/km, and the critical speed as well as the free flow speed in the highway are 42.7 km/h and 63.5 km/h, respectively. These estimating results are inline with Shi and Lin (2017) that using loop detector data to estimate the highway MFD in Shanghai. Similar with Shi and Lin (2017), we also found the clockwise hysteresis loop in the morning, which indicated that the traffic within the highway network is moderately unbalanced (Daganzo). However, in the afternoon, there is a distinct capacity drop phenomenon and the points are scattered. The similar capacity drop phenomenon was also found in Chicago freeway network in the afternoon peak period (Seberi and Mahmassani, 2013)

Figure 4: Elevated highway MFD in Shanghai, (a) AM peak; (b) PM peak.



To compare the difference among different time periods, four indicators were used to evaluate the macroscopic traffic performance in Shanghai elevated highways. Critical time I is the first time (5th percentile) density exceeds the critical density (i.e., 71.6 veh/km); critical time II refers to the last time (95th percentile) density exceeds the critical density; speed delay and minimum speed has been described in Section 3.3.

Table 6 shows the results of indicators of highway macroscopic traffic performance at different periods. In terms of the speed delay and the minimum speed, the first change of the restriction policy (from 07:30-09:30 to 07:00-10:00) improved the network traffic performance. The critical time in Stage II was earlier than Stage I, which indicated that many drivers with non-local vehicles left home earlier than before and still use the elevated highway to commute before the restriction time. However, after one year (Stage III), the ownership of cars with local plate increased about 8%, the traffic in the highway was even worse than the Stage I, in terms of the speed delay and minimum speed. At Stage IV, although the restricted time in the morning was unchanged, the traffic in the highway was much better than Stage III, which confirmed our previous assumption that the tight restrict policy in the Stage IV make some drivers with non-local vehicle transfer to other traffic modes. In the PM peak, although the congestion ratio was significantly lower than the AM peak, the total traffic performance was worse than AM peak, from the perspective of speed delay and minimum speed. In terms of the macroscopic indicators, similar conclusion could also be drawn that the traffic performance in Stage II was better than Stage I, but the traffic became even worse in Stage III. After the second adjustment of the restriction policy, the traffic congestion in the highway during the Stage IV was alleviated again.

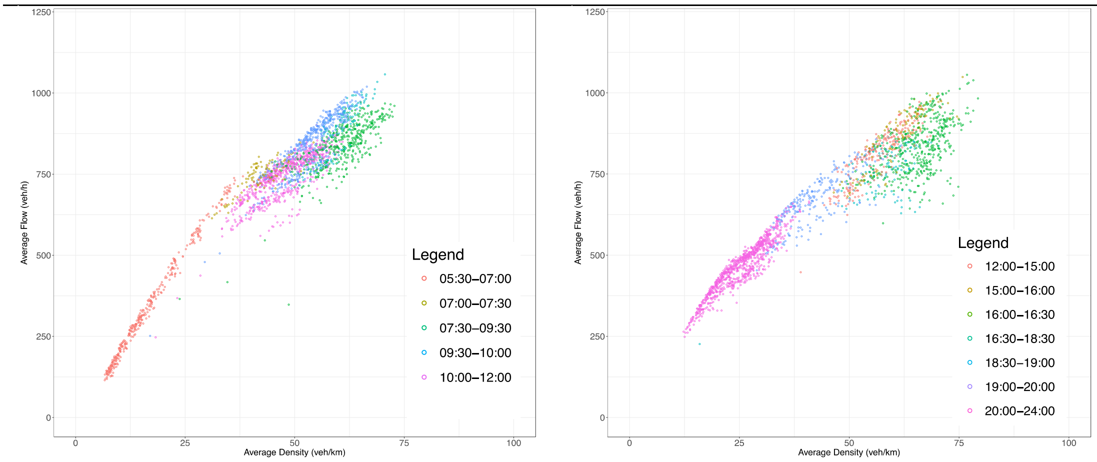
Table 6: Indicators of macroscopic traffic performance at four stages of the policy (Elevated highway)

Time of day	Policy Stage	Restricted time	Speed delay (km/h)	Mini. Speed (km/h)	Critical Time I	Critical Time II
AM 05:30-12:00	I	07:30-09:30	22.73	31.26	07:10	10:40
	II	07:00-10:00	21.75	32.95	06:50	10:40
	III	07:00-10:00	23.83	28.89	07:10	11:40
	IV	07:00-10:00	23.05	31.10	07:20	09:20
PM 12:00-24:00	I	16:30-18:30	26.05	28.36	15:40	16:40
	II	16:00-19:00	25.25	28.92	15:30	16:10
	III	16:00-19:00	26.89	27.52	16:00	16:30
	IV	15:00-20:00	26.16	28.55	NA	NA

4.3 The macroscopic performance of surface roads

Figure 5(a) and Figure 5(b) display the surface road MFD in the morning and in the afternoon, respectively. The capacity of the surface road network is 997.7 veh/h, the critical density is 65.8 veh/km, and the critical speed as well as the free flow speed in the highway are 15.2 km/h and 22.1 km/h, respectively. Counter-clockwise hysteresis loop was found in the morning peak, which indicated that the traffic state in the surface road was very unbalanced in the morning (Gayah and Daganzo, 2011). Under the same network density, the network flow during the restriction periods was lower than the periods without restriction. These results indicated that the restriction policy made the traffic within the surface network more unbalanced and the network traffic flow dropped due to the restriction.

Figure 5: Surface road MFD in Shanghai, (a) AM peak; (b) PM peak.



(a) (b)

Table 7 shows the results of indicators of surface road macroscopic traffic performance at different periods. In terms of the speed and the minimum speed, the first adjustment of restriction policy has little influence on the macroscopic traffic performance of surface roads when comparing Stage I and Stage II. When comparing Stage III and Stage IV, the second adjustment of restriction policy has great impact on the surface roads, the speed delay increased about 17%.

Table 7: Indicators of macroscopic traffic performance at four stages of the policy (Surface Roads)

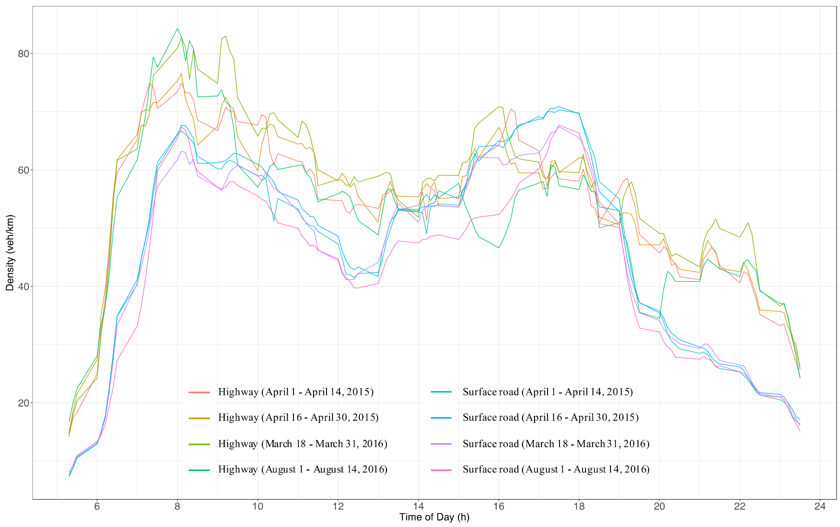
Time of day	Policy Stage	Restricted time	Speed delay (km/h)	Mini. Speed (km/h)	Critical Time I	Critical Time II
	I	07:30-09:30	5.55	13.03	08:00	09:20
AM	II	07:00-10:00	5.57	13.18	07:50	09:50
05:30-12:00	III	07:00-10:00	6.07	13.01	08:20	08:30
	IV	07:00-10:00	6.24	12.86	08:00	08:30
PM	I	16:30-18:30	5.91	12.02	15:50	18:30
12:00-24:00	II	16:00-19:00	5.91	12.48	15:50	18:20

III	16:00-19:00	6.12	12.02	16:00	18:10
IV	15:00-20:00	7.19	11.07	16:50	18:10

4.4 Comparison of elevated highway, surface road, and ramp

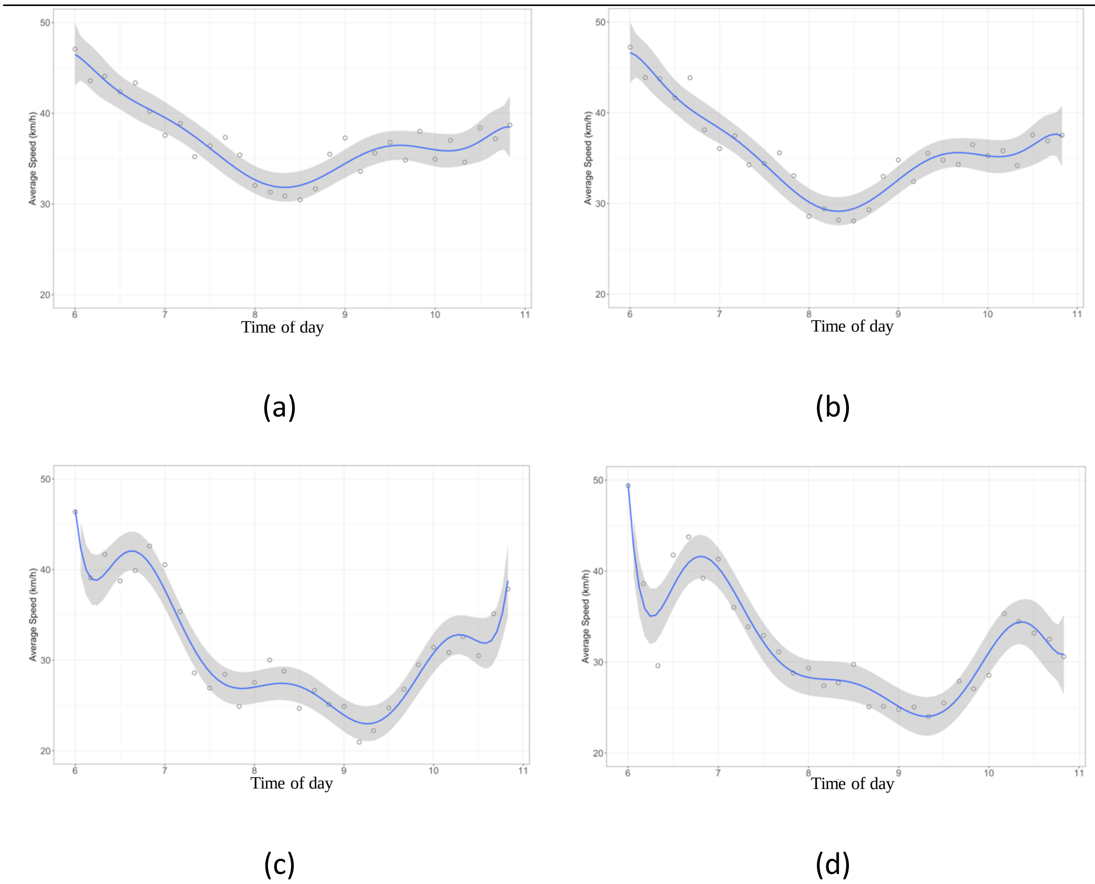
Figure 6 represent the time-series of network density at different stages of the restriction. During the morning peak hours, both elevated highways and surface roads reach the highest density at about 08:00 to 08:30. During the afternoon peak hours, except for Stage IV, the highest density in elevated highway was reached at the end of the unrestricted time and dropped sharply after the restriction time. The tight restriction time in the stage IV significantly lower the traffic on the highway network. The period with highest density in surface roads was from about 17:15 to 17:45. After about 18:00, both elevated highways and surface roads began to recover. As shown in Figure 6, the network density of surface roads in the afternoon did not increase much after the tight restriction policy, which was not as expected. This indicated that the recent tight restriction policy reduced the total road traffic in the central area effectively.

Figure 6: Time-series of network density at different stages of the restriction.



To better understand the connection between elevated highways and surface roads, we further analyzed the average speeds of on-ramp (surface road to highway) and off-ramp (highway to surface road) in the morning at Stage I and Stage II. As shown in the Figure 7, the trend of the average speed for on-ramp was basically consistent with Figure 6 that lowest speed was reached at about 08:00-08:30. However, when we look at the off-ramp, the average speed dropped sharply from 06:30 to 07:30. Meanwhile, the network density on the surface road network was not high during that time. The massive traffic (most of them are non-local vehicle) from the elevated highways made the surface road network extremely unbalanced. This is one of the most important reasons for the counter-clockwise hysteresis loop.

Figure 7: Average speeds of ramp in the morning(a) On-ramp, Stage I; (b) On-ramp, Stage II; (a) Off-ramp, Stage I; (b) Off-ramp, Stage II.



5. Conclusion

In this paper, we used the MFD measures to evaluate the non-local vehicle restriction policy implementation effect on Shanghai's macroscopic traffic. Four stages of the policy were compared, and the macroscopic effects of the restriction policy on the restricted expressways were compared with the surface roads without any restrictions. Moreover, the time-varying characteristics of macroscopic traffic performance, such as hysteresis loop, during the morning peak and the evening peak, were further investigated in this study.

The results in this paper show that the first adjustment of the restriction policy in April 15, 2015, did not achieve the expected results, from the perspective of macroscopic traffic performance. During the early stage of this policy, the macroscopic traffic improved slightly. However, after one year, when the car ownership increased about 8%, the macroscopic traffic performance was even worse, in terms of the maximum volume, speed delay, and minimum speed. It is also shown that the second adjustment of the restriction policy in April 15, 2016, alleviate the traffic congestion in Shanghai central area effectively. Because of the tight restriction policy, many drivers with non-local plates transferred to other traffic modes or bypassed the central area. Therefore, the restriction on the elevated highway did not incur too much traffic on the surface roads. The results also revealed that the restriction policy made the network very unbalanced during the peak hours. This study may be the first empirical finding of the counter-clockwise hysteresis phenomenon in the morning. The possible reasons of the phenomenon are the interactions between the extremely unbalanced traffic within the surface network and the moderately unbalanced traffic within the highway network. The unbalanced traffic within the network lower the maximum flow significantly, which should be taken seriously in the future policy implementation process.

Some limitations exist in this study. First, as mentioned by the previous studies (Ji et al., 2014), taxi FCD data is insufficient for accurate estimation of the car density and must be associated with the loop detector data. In this study, only the LDD data for the total network is available, which has limitations to estimate the spatial heterogeneity of the network, since the route preference of taxi drivers is different from normal drivers. Secondly, the observed data does not exhibit a distinct congested branch, which make it difficult to determine the accurate capacity and critical density. The re-sampling method, introduced by Ambühl et al. (2018), could be used to determine the accurate capacity and critical density and estimate the level of inhomogeneity. Thirdly, due to the limitation of the data, the temporal-spatial distribution of congestion was not investigated in depth. On-going studies need to further explore the temporal-spatial heterogeneity and investigate the relationship among elevated highways, surface roads, and ramps. The deep understanding of the temporal-spatial distribution at different stages of the plate restriction policy will also help implement other type of dynamic control policy, such as road pricing or other perimeter control strategies.

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