Impact of bicycle traffic on the macroscopic fundamental diagram
Some empirical findings in Shanghai

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Impact of Bicycle Traffic on the Macroscopic Fundamental Diagram: Some Empirical Findings in Shanghai

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ABSTRACT

Interactions between bicycles and cars have begun to attract increasing attention. This paper aims to investigate network-level car-bicycle interactions by quantifying the impact of bicycle traffic on empirical macroscopic fundamental diagrams (MFDs). First, the stratified re-sampling method is used to analyze the impact of bicycle-related facilities on network capacity and critical density. Then, the $\lambda$-trapezoidal MFD function is applied to investigate the relationship between network bicycle flow and upper-bound MFD. The results show that car-bicycle mixed roads can have a negative marginal effect on network capacity and critical density, regardless of separation and road type. However, difference of capacity reduction in networks with various percentages of car-only roads is not substantial. To reduce car-bicycle interactions at the network level, it is more efficient to improve bicycle network capacity and build more exclusive bicycle facilities than restrict roads for bicycle users in central areas. Based on these results, various traffic management strategies can be applied, such as adjusting the share of car-only roads, changing separation type, redistributing road space among different modes and extending bicycle priority in certain areas.

Keywords: Macroscopic Fundamental Diagram (MFD); Car-bicycle interaction; Bicycle traffic; Network level; Car-only road; Separation type
1 INTRODUCTION

Urban street networks are typically shared by different modes, including cars, buses, bicycles and pedestrians. These modes interact with each other and compete for limited road space, as well as government financial subsidies. As one of the largest and most populous cities in China, Shanghai implemented a traffic separation scheme and started to restrict bicycles on some main roads in the central city area in 1996 [1], aiming to reduce bicycle-car conflicts. However, these schemes are controversial; many cyclists in Shanghai need to dismount and walk their bicycles or make a detour to avoid these car-only roads. Besides, according to [2], both car and bicycle volume declined significantly after implementing the separation scheme in Shanghai. It is crucial to understand multi-modal interactions and quantify the impact of such separation schemes on overall road traffic.

Interactions between bicycles and cars have attracted increasing attention recently. Cars generally go faster and have a negative impact on bicyclists’ perceptions of their safety and quality of service on on-street bicycle lanes [3]. Although bicycles are more flexible, they can frequently spill into motor vehicle lanes, slowing down cars. Previous studies explored conflicts between car and bicycle from different perspectives, including road safety [4-6], intersection interaction [7, 8], decision processes [9, 10], bicycle and car dynamic positions detection [11] and bicycle lane spilling behavior [12, 13]. Most of these studies aimed at improving traffic safety in mixed traffic flow, or traffic efficiency at the link or intersection level. Although a car-bicycle model was presented for both link level and intersections using cellular automata simulation [14], car-bicycle conflicts at the network level were seldom investigated.

This study evaluates the impact of bicycle traffic on network traffic performance using an aggregated approach. [15] proposed a macroscopic traffic modeling approach, the macroscopic fundamental diagram (MFD), which is a reproducible curve that relates traffic production and accumulation within a network. MFD is a property of the urban network and independent of dynamic traffic demand [16]. MFD’s existence was first verified in 2007 by simulation [17] and examined by the empirical data in Yokohama in 2008 [16]. So far, empirical MFDs have been observed in many cities. For example, China, Shanghai [18], Shenzhen [19], and Changsha [20] and Switzerland, Zurich [21] have observed empirical MFDs in urban networks. Based on MFD results, many traffic operation-related strategies, such as perimeter control [22], road pricing [23], plate policy evaluation [24] and parking control [25] have been proposed and evaluated. To consider bi-modal interaction within car-bus networks, [26], [27] and [28] extended the single-mode MFD to bi-modal MFD model, known as three-dimensional macroscopic fundamental diagram (3D-MFD). Using simulation methods, the 3D-MFD has been applied to road space distribution [26], parking pricing [29], and perimeter flow control [30]. The empirical 3D-MFD model helps understand interactions between cars and buses at an aggregated level, which has also been verified with empirical data in Zurich [28] and in a large-scale network in Shenzhen, China [28].

Although the MFD idea is mode-abstract and could be applied to different single networks or multi-modal urban networks [15], empirical MFDs so far have only considered pedestrians [31] and motorized traffic, e.g., car and bus. Bicycle traffic impact on the MFD has received little attention in literature. The main reasons are: 1) lack of bicycle flow-related sensor data, 2) difficulty simulating cyclists’ behavior and 3) rarity of congested bicycle traffic at the network level. With the emergence of innovative mobility services in the last few years, such as dockless
bike-sharing, a tremendous amount of bicycle GPS data can now be obtained to explore bicycle traffic impact on the MFD.

This paper aims to explore the interaction between cars and bicycles at the network level. More specifically, the study includes the following two tasks: (1) analyze bicycle-related network features on the MFD and (2) quantify bicycle traffic impact on the upper-bound MFD. The remainder of the paper is structured as follows: Section 2 presents empirical data used and explains the MFD estimation method. In Section 3, impact of bicycle-related facilities on the empirical MFD is investigated. In Section 4, the $\lambda$-trapezoidal MFD function is introduced to investigate the relationship between bicycle traffic and upper-bound MFD. Finally, conclusions and findings are discussed in Section 5.

2 DATA AND MFD ESTIMATION

This section shows the available dataset used in this study and presents the MFD estimation method. This empirical dataset includes taxi floating car data (FCD), loop detector data and GPS data from dockless shared bicycles.

2.1 Research Area

![Figure 1 The study network in Shanghai (Source: OpenStreetMap)](image)

As a global commercial and financial center, Shanghai has over 24 million residents. The inner central area of Shanghai, with a scale around 80 km$^2$, was chosen as the study area (See Figure 1). The network contains 177 secondary roads and 110 arterial roads. Residential roads and highway systems are not included in this study.

In Shanghai, to improve the mobility of motorized modes (individual cars, bus, etc.) and reduce the car-bicycle conflicts, a certain number of roads in the inner central area are operated as car-only roads; their distribution in the central area is shown in Figure 1.

2.2 Data

2.2.1 Car data
car data (FCD) from Shanghai Qiang-Sheng Taxi Company contains about 13,475 taxis’ sequential trajectories from Aug. 1 to 31, 2016. Each order contains taxi ID, date, measurement
time, longitude, latitude, speed (km/h) and operation status (1 for vacant /0 for hired). The daily
dataset has over one hundred million records in 10-second intervals (more than 10 GB); those
with the speeds higher than 120 km/h and vacant status were removed from the dataset.

Loop detector data (LDD) was collected from 326 loop detectors by Shanghai traffic
authorities. Loop detectors are mainly installed on highways or ramps for traffic control
purposes. The LDD dataset contains attributes like location (e.g., from one ramp to the other),
road type (highway, on-ramp, or off-ramp), direction, hourly flow and daily flow.

2.2.2 Bicycle Data

Bicycle data was obtained from Beijing Mobike Technology Company, one of the largest
bike-sharing companies in China. As presented by Zhang and Mi [32], Mobike receives about 20
million orders per day, accounting for nearly 60% market share of bike sharing. The dataset
contains more than 1,000,000 bike-sharing orders in Shanghai from Aug. 1 to 31, 2016. Each
record contains order-ID, bicycle-ID, user-ID, date, start-time, start-location, end-time, end-
location and track points.

Because each track point does not have a time stamp in the raw dataset, the true order of
one bicycle track was estimated by calculating and comparing relative distance between start and
end locations. Average speed of each trip was estimated by dividing the sum of adjacent
distances by travel time. Records with average speeds less than 5 km/h and higher than 25 km/h,
or those with travel distance less than 500 meters, or more than 10 km, were removed from the
dataset.

2.3 MFD Estimation Method

Using the FCD of taxi trajectories, MFD estimation is based on Edie’s generalized traffic
definition [33, 34]. The total distance, \( d_{FCD_{tot}} \), and the total travel time, \( t_{FCD_{tot}} \), spent in the
network during a 10-minute interval, were used to estimate the MFD:

\[
q_{FCD} = d_{FCD_{tot}} LT10 \rho \quad (1)
\]

\[
k_{FCD} = t_{FCD_{tot}} LT10 \rho \quad (2)
\]

where \( L \) represents network length, \( T10 \) represents a 10-minute time slice and \( \rho \) represents probe
penetration rate.

Taxi probe penetration rate \( \rho \) was determined by the LDD for the same time slice. For each
road segment \( i \), loop detectors measured total traffic flows for each hour, which were then
weighted by segment length \( l_i \) to calculate overall network flow.

\[
q_{LDD} = \sum_{i} l_i q_i \quad (3)
\]

For each hour, total network flow \( q_{LDD} \) estimated by LDD can also be expressed by the
average of total network flow \( q_{FCD_j} \) estimated by FCD during the \( j^{th} \) 10-minute slice as:

\[
q_{LDD} = q_{FCD} = \frac{1}{6} \sum_{j=1}^{6} q_{FCD_{j}} = \frac{1}{6} \sum_{j=1}^{6} d_{FCD_{tot}} j LT10 \rho j \quad (4)
\]

Notice that as the value of taxi penetration rate \( \rho_j \) changes with time, penetration rate was
assumed to change linearly between two adjacent hours. Then, taxi penetration rate for each time
slice could be estimated based on Eqs. (3) and (4).
Another study [35], based on 40 selected arterial/secondary roads in Shanghai, shows that average taxi penetration rate on surface roads is 12.9%, with no large differences across the zones and road types. However, the result is based on all 49,788 taxis. After modification for overall number of taxis, our estimate of the average surface road penetration rate (3.65%*49788/13475=13.5%) is very close to that value (12.9%). Investigation details are found in [35].

3 IMPACT OF BICYCLE-RELATED FACILITIES

This section focuses on effects of bicycle-related facilities on the empirical MFD. Notice that macroscopic fundamental car diagrams can now be estimated incorporating buses’ impact [26]. It is also worth relating the MFD shape to bicycle-related facilities.

3.1 Stratified re-sampling method

The stratified re-sampling method is developed from the method used for empirical MFD estimation [36]. It is shown that re-sampling can effectively determine network capacity and critical density, even if no distinct congested branch was observed [36]. Additionally, for each subsample, various empirical MFD groups and corresponding road network features can be obtained.

First, the network is stratified into sub-networks \( i \) (strata). The selection of each sub-network \( i \) is based on road attributes, such as number of lanes and road type, which may help supply information about specific road types, even with a small percentage in the network. Then, each sub-network \( i \) is randomly re-sampled \( j \) times without replacement. The sample time \( j \) for each network \( i \) is based on the number of links. For example, if total sample time is 500, sample time for network \( i \) is \( 500*\frac{N_i}{N} \), where \( N_i \) is the number of links in the sub-network \( i \) and \( N \) is the total number of study network links. Finally, results from each re-sampled network are combined to assess the relationship between network features and corresponding empirical MFDs. The capacity of each re-sampled MFD is determined by the 99\textsuperscript{th} flow percentile and critical density. Similar to [36], four network shares (20\%, 40\%, 60\%, and 80\%) are chosen to re-sample sub-networks and total sample time \( N \) is set to 500. Since road attributes in each sub-network are more homogeneous, re-sampled MFDs should have less heterogeneity-related capacity reduction than the un-stratified network [37].

3.2 Empirical MFD and upper-bound MFD

We first compare empirical MFDs for each sub-network with various road types: arterial roads with 2-4 lanes, with 5-6 lanes and with 7-10 lanes, secondary roads with 2-4 lanes and with 5-6 lanes. Results are presented in Figure 2(a) and show that empirical MFDs for arterial roads with 7-10 lanes and secondary roads with 5-6 lanes have higher capacity reduction compared to other sub-networks. Notice that empirical MFDs do not exhibit a distinct congested branch and that plots are rather scattered due to the spatial heterogeneity of each link within sub-networks. It is worth avoiding the scatters and identifying distinct congested branches for each MFD.

Following [36], we identify stable upper-bound MFD by re-sampling each sub-network 500 times (network share 20\%) and using the median of the top 50 flow values per density bin as upper-bound flow. Figure 2(b) shows upper-bound MFDs for different road types. Since the congested branch for each upper-bound MFD is distinct, we can easily identify capacity and critical density for each MFD: arterial roads with 2-4 lanes (\( Q_{\text{max}} \)= 603.0 veh/h-lane,
\( Kc_i = 39.5 \text{veh/km-lane} \), arterial roads with 5-6 lanes \( (Q_{max}=580.8 \text{veh/h-lane}, Kcri=48.0 \text{veh/km-lane}) \), arterial roads with 7-10 lanes \( (Q_{max}=398.4 \text{veh/h-lane}, Kcri=28.5 \text{veh/km-lane}) \), secondary roads with 2-4 lanes \( (Q_{max}=525.2 \text{veh/h-lane}, Kcri=43.5 \text{veh/km-lane}) \) and secondary roads with 5-6 lanes \( (Q_{max}=436.3 \text{veh/h-lane}, Kcri=34.0 \text{veh/km-lane}) \). Similar to Figure 2(a), arterial roads with 7-10 lanes and secondary roads with 5-6 lanes have larger capacity reduction than other networks.

![Figure 2 Relationship between facility type and MFDs: (a) Empirical MFDs for various road types; (b) Upper-bound MFDs for various road types; (c) Empirical MFDs for various separation types; (d) Upper-bound MFDs for various separation types;](image)

Another bicycle-related factor that should be taken into account is separation type between motorized traffic and bicycle. According to separation type, facilities can be classified into three categories [3]:

- **Bicycle lane**: A portion of a roadway designated by striping, signing and pavement markings for preferential or exclusive use of bicycles.
- **Bicycle path**: A bikeway physically separated from motorized traffic by an open space or barrier, either within the highway right-of-way or within an independent right-of-way.

- **Shared lane**: A facility where bicycles share a travel lane with motorized vehicular traffic.

In this study, we mainly focus on roads with physically separated facilities (bicycle paths) and roads without physical separation (bicycle lanes and shared lanes). Similar to previous analysis, we account for number of lanes (5-6 lanes for two directions) and compare empirical MFDs and upper-bound MFDs for different separation types. Results are shown in Figure 2(c) and Figure 2(d). As expected, both two figures reflect that networks permitted for bicycle traffic have a distinctly lower capacity compared to car-only roads. For the same density bin, traffic flow for networks with physically separated facilities is higher than networks without physically separated facilities.

### 3.3 Impact of bikeway and road type

We now discuss the impact of bikeways on different types of motorized roads. To control the effect of car lanes on results, the independent variable, *Road type*, is coded in the dummy variables: $A_{2-4}$ (Arterial road, 2 <= lanes <= 4), $A_{5-6}$ (Arterial road, 5 <= lanes <= 6), $A_{7-10}$ (Arterial road, 7 <= lanes <= 10), $S_{2-4}$ (Secondary road, 2 <= lanes <= 4), and $S_{5-6}$ (Secondary road, 5 <= lanes <= 6). Another independent variable, *Separation type*, is modeled as a continuous variable: $P0N$ (Percentage of roads without physical separation in the network), $P0P$ (Percentage of physically separated roads in the network), and 1-$P0$ (Percentage of car-only roads in the network). Interaction effect between bikeway percentage ($P0$) and road type is also analyzed.

Table 1 presents linear regression results (20% network share). Networks with bikeways ($P0N$ and $P0P$) significantly decrease network capacity and critical density ($p<0.01$). Compared to arterial roads with 2-4 lanes, arterial roads with 5-6 lanes and secondary roads with 2-4 lanes have no less network capacity or decreased critical density. Meanwhile, arterial roads with 7-10 lanes and secondary roads with 5-6 lanes have substantially less capacity and a critical density ($p<0.001$), in line with Figures 2(a) and 2(b). The moderation effect of number of lanes on the bikeway impact is significant only for arterial roads with 7-10 lanes.

### TABLE 1 Relationship between $P0$, road type and two indicators of MFD ($Q_{max}$ & $K_{cri}$) for 20% network share

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$Q_{max}$ Estimate (S.E.)</th>
<th>$Q_{max}$ p</th>
<th>$K_{cri}$ Estimate (S.E.)</th>
<th>$K_{cri}$ p</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta0'$ Intercept</td>
<td>475.499(25.296)</td>
<td>&lt;0.001</td>
<td>39.301(3.010)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Separation type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-$P0$ (Car-only road)</td>
<td>0^a</td>
<td></td>
<td>0^a</td>
<td></td>
</tr>
<tr>
<td>$P0N$ (Non-physical separation)</td>
<td>-109.972(40.175)</td>
<td>0.006</td>
<td>-12.826(4.503)</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Original paper submittal – not revised by author
After analyzing the impact of bicycle-related facilities on the MFD, this section focuses on effects of bicycle flow. Notably, relationships between bicycle flow and MFD for different network features are investigated.

### 4.1 Bicycle V/C ratio and MFD

The first objective is to identify whether MFD shape will be affected by bicycle flow. An existing bike-sharing trajectories dataset is used, which has limitations representing total bicycle flow without information about service penetration rate. In this section, we quantify bicycle network flow characteristics by using the V/C ratio:

\[
V = \frac{V_{bike}}{C_{bike}} = \frac{Q_{shared \cdot bike\cdot penetration}}{Q_{shared \cdot bike\cdot penetration \cdot 99th \cdot percentile}}
\]

where, \(V_{bike}\) and \(C_{bike}\) are network volume and network capacity for bicycles; \(Q_{shared \cdot bike}\) and \(Q_{shared \cdot bike\cdot penetration \cdot 99th \cdot percentile}\) are network flow of shared bicycles and the 99\(^{th}\) percentile of shared bicycle volume; \(penetration\) is penetration for shared bicycles; \(penetration\) is penetration when volume of shared bicycles reaches its peak.
The V/C ratio is widely used to reflect the level of facilities service [3]. Note that empirical network capacity for bicycles is seldom observed, since bicycles can spill into the motorized lane if the bicycle lane is crowded enough. Here, we used the 99th percentile of shared bicycle flow as the maximum shared-bicycle flow. penetration and penetration are assumed to be constant in this paper.

We compare network density-flow relationship and network density-speed relationship while controlling for the bicycle V/C ratio (See Figure 3(a) and Figure 3(b)). It turns out that bicycle flow has a negative impact on car MFD. High bicycle V/C ratio reduces capacity substantially and slows cars. This is also confirmed by Figures 3(c) and 3(d), contour plots of bicycle V/C ratio and car density. Figure 3(c) also presents critical density of cars for different values of the bicycle V/C ratio. Maximum network flow value occurs when network density is around 45 veh/km-lane and bicycle V/C ratio is approximately 0.3. It can be seen in Figure 3(d) that network car speed decreases as car density and bicycle V/C ratio increases, in line with car-bicycle conflicts for the link level [13].

![Figure 3 Car MFDs for various bicycle V/C ratios: (a) density-flow relation; (b) density-speed relation; (c) Contour plot of network car flow; (d) Contour plot of network car speed](image-url)

4.2 The functional form of MFD
To quantify the impact of bicycle flow on car MFD, we should seek a functional form that captures capacity reduction dynamics due to bicycle traffic. Currently, most empirical MFD studies choose exponential-family or polynomial functions as the functional form of \( q(k) \). However, parameters of these methods do not have a strong physical meaning. Recently, Ambühl et al.[38] proposed a new functional form of MFD that quantifies capacity reduction level. We followed their work and used the \( \lambda \)-trapezoidal MFD function to investigate the relationship between bicycle traffic and MFD. The functional form is proposed as follows:

\[
q_c = -\lambda vbcb lnexp - \mu fc k c vc + exp - Q c k e + exp - k c k c w c \lambda v c b c b
\]  

(6)

where, \( q_c \) is network flow for car traffic; \( \lambda vbcb \) determines how far empirical MFD lies beneath the trapezoidal MFD, which is assumed to be related to bicycle V/C ratio in this study; \( \mu fc \) is free flow speed (car); \( k e \) is network density (car); \( Q c \) is intersection capacity (car); \( k c \) is jam density (car); and \( wc \) is backward wave speed (car). Technical parameters for trapezoidal MFD (\( \mu fc, Q c, k c, \) and \( wc \)) are estimated by empirical data or given by the local transportation authority. We estimated free flow speed \( u f,c \) by using the 85th percentile of network taxi speeds for non-rush hours. Intersection capacity \( Q c \) is calculated based on the equation given by [39]. Average ratio of green time/cycle length (G/C) is given by [40]. Jam density \( k c \) can be estimated by average vehicle length. Here, we assume that average vehicle length in Shanghai is similar to London and Marseille, where the value of \( k c \) is given by [38]. Backward wave speed \( wc \) is provided by the local transportation authority. Technical parameters used in this paper are summarized as: \( u f,c = 5.460 \text{ m/s}; wc = 1.614 \text{ m/s}; k c = 0.150 \text{ veh/m}; Q c = 0.175 \text{ veh/s}. \)

To obtain empirical MFDs with different values of the bicycle V/C ratio, we estimated Eq. (6) using the non-linear quantile regression method, which allows us to estimate the conditional quantiles of a response variable distribution. To avoid outliers’ influence, we apply this method to estimate the upper-bound MFD (the 97.5\(^{th}\) quantile). The pseudo-\( R^2 \) for the quantile regression estimation was calculated based on [41].

Estimation results of \( \lambda \) for different bicycle V/C ratio and sensitivity to the network share are shown in Table 2. Value of \( \lambda \) for each group is between 0.03 to 0.07, which is reasonable according to [38]. Similar to results in Figure 3, \( \lambda \) is highly related to the bicycle V/C ratio, indicating that high bicycle flow may lead to large capacity reductions in the MFD. pseudo-\( R^2 \) values of 0.85-0.95 (close to 1) indicate a decent model fit for different bicycle V/C ratios and network shares.

<table>
<thead>
<tr>
<th>Network share</th>
<th>Bicycle V/C Ratio</th>
<th>( \lambda )</th>
<th>( t ) value</th>
<th>( p )</th>
<th>pseudo-( R^2 )</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>0.0 - 0.2</td>
<td>0.033</td>
<td>245.478</td>
<td>&lt;0.001</td>
<td>0.901</td>
<td>505,932</td>
</tr>
<tr>
<td></td>
<td>0.2 - 0.4</td>
<td>0.041</td>
<td>447.777</td>
<td>&lt;0.001</td>
<td>0.895</td>
<td>376,038</td>
</tr>
<tr>
<td></td>
<td>0.4 - 0.6</td>
<td>0.048</td>
<td>509.341</td>
<td>&lt;0.001</td>
<td>0.858</td>
<td>155,352</td>
</tr>
<tr>
<td></td>
<td>0.6 - 0.8</td>
<td>0.054</td>
<td>431.923</td>
<td>&lt;0.001</td>
<td>0.862</td>
<td>59,994</td>
</tr>
<tr>
<td></td>
<td>0.8 - 1.0</td>
<td>0.056</td>
<td>238.702</td>
<td>&lt;0.001</td>
<td>0.862</td>
<td>24,576</td>
</tr>
</tbody>
</table>

**TABLE 2** Estimation results of \( \lambda \) for different bicycle V/C ratios.
<table>
<thead>
<tr>
<th></th>
<th>0.0 - 0.2</th>
<th>0.2 - 0.4</th>
<th>0.4 - 0.6</th>
<th>0.6 - 0.8</th>
<th>0.8 - 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>0.035</td>
<td>0.044</td>
<td>0.049</td>
<td>0.058</td>
<td>0.062</td>
</tr>
<tr>
<td></td>
<td>312.826</td>
<td>726.049</td>
<td>653.767</td>
<td>642.822</td>
<td>546.240</td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
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</tr>
<tr>
<td></td>
<td>0.907</td>
<td>0.905</td>
<td>0.861</td>
<td>0.863</td>
<td>0.860</td>
</tr>
<tr>
<td></td>
<td>456,960</td>
<td>392,700</td>
<td>173,424</td>
<td>69,288</td>
<td>30,288</td>
</tr>
<tr>
<td>60%</td>
<td>0.035</td>
<td>0.044</td>
<td>0.049</td>
<td>0.060</td>
<td>0.065</td>
</tr>
<tr>
<td></td>
<td>259.024</td>
<td>696.753</td>
<td>789.326</td>
<td>796.774</td>
<td>796.774</td>
</tr>
<tr>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>0.909</td>
<td>0.906</td>
<td>0.862</td>
<td>0.864</td>
<td>0.859</td>
</tr>
<tr>
<td></td>
<td>446,016</td>
<td>390,540</td>
<td>181,656</td>
<td>72,444</td>
<td>32,004</td>
</tr>
<tr>
<td>80%</td>
<td>0.036</td>
<td>0.045</td>
<td>0.050</td>
<td>0.061</td>
<td>0.067</td>
</tr>
<tr>
<td></td>
<td>299.599</td>
<td>851.112</td>
<td>831.540</td>
<td>1,106.305</td>
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<td>476,022</td>
<td>179,346</td>
<td>69,282</td>
<td>30,324</td>
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</table>

### 4.3 Relationship between bicycle flow and \( \lambda \)

The variation of \( \lambda \) can be used as a measure of capacity reduction in the network given the respective upper-bound MFD. In this section, the evolution of \( \lambda \) with respect to bicycle V/C ratio under different conditions is investigated, with the value of \( \lambda \) estimated in each bicycle V/C ratio interval (0.01) from corresponding car density and flow. Non-linear quantile regression method (the 97.5th quantile) is applied to estimate \( \lambda \) for the same shape parameters of trapezoidal MFD.

#### 4.3.1 Network share

We first compare the relationship between bicycle flow and \( \lambda \) for different network shares (20%, 40%, 60%, 80%) shown in Figure 4(a). As expected, the value of \( \lambda \) with low network shares is slightly smaller than the value with high network shares for the same level of bicycle V/C ratio, because smaller sampled networks can identify road combinations with homogeneous traffic more easily and show less capacity reduction.

The results confirm that growth of bicycle V/C ratio can sharply increase the value of \( \lambda \), indicating that car infrastructure is increasingly inefficiently used due to bicycle traffic interference. When the bicycle V/C ratio is large enough (around 0.75), the value of \( \lambda \) becomes relatively stable. This is in line with [13], who conclude that bicycle density impact on car delays becomes stable when bicycle density reaches a certain level. The trend of \( \lambda \) is similar for different network shares; the following analysis uses the 20% network share.

#### 4.3.2 Number of lanes and percentage of can-only roads

We now assess the effect of number of lanes and percentage of car-only roads on the relationship between bicycle V/C ratio and \( \lambda \). Figure 4(b) shows \( \lambda \) evolution for bicycle V/C ratio and number of lanes (2-4 lanes; 5-6 lanes; and 7-10 lanes). As bicycle V/C ratio increases, \( \lambda \) for the 2-4 lanes soars to approximately 0.06 when bicycle V/C ratio is around 0.50. Meanwhile,
value of $\lambda$ for networks with larger number of lanes increases much more slowly for the same level of bicycle V/C ratio. Figure 4(c) compares the relationship for different percentages of car-only roads. Note that 25.6% is the average percentage of car-only roads in the Shanghai central area sampled network; 16.4% and 34.4% are the 25th percentile and 75th percentile, respectively. It is interesting to notice that the difference in $\lambda$ between networks with less car-only roads and networks with a large percentage of car-only roads is not large (average difference of $\lambda$ between the 25th percentile and 75th percentile of car-only roads percentage is 0.0023). Networks with a high percentage of car-only roads have slightly smaller $\lambda$ only when the bicycle V/C ratio is between around 0.3 to 0.7. When network bicycle flow is large enough (V/C ratio larger than around 0.7), restricting bicycles cannot increase network car flow, possibly because when bicycle network flow is large, some cyclists will illegally spill into the car-only roads.

4.3.3 Separation type

Figure 4(d) and Figure 4(e) present separation type influence on the relationship between bicycle V/C ratio and car traffic capacity reduction. Figure 4(d) highlights the impact for different percentages of roads with physical separation type; Figure 4(c) shows the influence of different percentages of shared roads. As expected, high percentage of roads with physical separation (larger than 66.5%, 75th percentile of sampled networks) have less capacity reduction than networks with fewer physically separated roads. Similarly, higher percentages of shared roads (more than 7.8%, 75th percentile) have more capacity reduction than networks with more bicycle facilities. Average difference of $\lambda$ between the 25th percentile and 75th percentile of physically separated roads is 0.0056 and the value is 0.0058 for shared roads. Compared to increasing car-only roads, it is more efficient to decrease the average value of $\lambda$ by building more physical bicycle facilities, e.g., open space or barriers, and by reducing the percentage of shared roads in the network. As in previous results, when bicycle flow is large enough, $\lambda$ value becomes relatively stable and difference in $\lambda$ between different shares of separation type is not substantial.
Figure 4 Evolution of $\lambda$ for bicycle V/C ratio and (a) network share; (b) number of lanes; (c) percentage of car-only roads; (d) percentage of physical separation; (e) percentage of shared roads.

4.4 Case study for three complete networks

In this section, we extend re-sampled network results to three complete networks in the Shanghai central area (See Figure 5). These networks are selected for several reasons. First, they do not violate the spatial homogeneity assumption of MFD, because the area size is similar to that analyzed in Yokohama [16] and smaller than the partitioning area in Shenzhen [19]. Second, the three selected networks are all popular regions in Shanghai, with sufficient bike-sharing data and taxi trajectories to estimate empirical MFDs. Third, the three networks have various shares of bicycle lanes, bicycle paths, shared lanes, and car-only roads, shown in Figure 5. Network 1 (Yangpu District) has 97.6 km-lanes for bicycles, with no car-only roads. Length of car-bicycle shared lanes in Network 1 is 20.3 km, the longest among the three networks. Network 2 (Huangpu District) has 63.2 km-lanes for cycling. Cyclists are forbidden to use 7.5 km roads in one direction and 6.2 km roads for both directions within Network 2. Network 2 also has a small percentage of bicycle path (with physical separation facility) and most roads are separated by ...
traffic marking (40.4 km). Network 3 (Xuhui District) has 77.1 km-lane bikeways and 0.7 km bi-
direction roads are restricted for cycling. Most roads within Network 3 are physically separated
between car and bicycle traffic (52.1 km).

<table>
<thead>
<tr>
<th></th>
<th>Network 1</th>
<th>Network 2</th>
<th>Network 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicycle Length</td>
<td>97.6</td>
<td>63.2</td>
<td>77.1</td>
</tr>
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<td>km-lane</td>
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<tr>
<td>Car-only Road</td>
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<td>7.5</td>
<td>0.7</td>
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<td>[km]</td>
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<td>6.2</td>
<td>2</td>
</tr>
<tr>
<td>Bicycle Path</td>
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<td>22.8</td>
<td>52.1</td>
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<tr>
<td>Bicycle Lane</td>
<td>27.8</td>
<td>40.4</td>
<td>18.5</td>
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<tr>
<td>[km-lane]</td>
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<tr>
<td>Shared Lane</td>
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<td>6.5</td>
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<td>[km-lane]</td>
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<tr>
<td>Car Length</td>
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<td>Arterial Road</td>
<td>37.4</td>
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<td>[%]</td>
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<td>50.9</td>
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</table>

Figure 5 Three study networks.

Note: 1 Single direction is restricted for bicycle use; 2 Two directions are restricted for bicycle use.

Figure 6 presents $\lambda$ evolution in the bicycle V/C ratio for the three study networks. Results
confirm that growth of bicycle V/C ratio can increase $\lambda$ value and reduce network capacity,
which is in line with the results from re-sampled networks in Section 4.3. As shown in Figure 6,
Network 3, with the highest percentage of physical separation facilities among the three
networks, has less capacity reduction compared to Networks 1 and 2. Network 2 has more car-
only roads than Network 3, but only around one-third of bikeways are physically separated. The
result of Figure 6 is also in line with Figure 4(c) and Figure 4(d), indicating that the difference of
capacity reduction among networks with various percentage of car-only roads is not as
substantial as networks with various percentage of physically separated facilities. Figure 6 also
shows that the value of $\lambda$ for Network 2 is lower than Network 1 when bicycle V/C ratio is larger
than around 0.2. As network 1 has far more car-bicycle shared lanes than Network 2, the result
indicates that high percentage of shared road can result in substantial capacity reduction when
the bicycle flow increases, in line with Figure 4(e).
5 CONCLUSIONS AND DISCUSSIONS

This paper presents an empirical study of car-bicycle interaction at the network level. The impact of bicycle facilities and bicycle flow on car MFD was evaluated based on taxi FCD data, loop detector data and bicycle GPS data. The stratified re-sampling method and a linear model were used to investigate the impact of bicycle-related facilities on the network capacity and critical density. Then, $\lambda$-trapezoidal MFD functions were estimated to investigate the relationship between bicycle traffic and car MFD. We observe that percentage of roads with bicycle traffic can have a negative marginal effect on network capacity and critical density, regardless of separation type between bicycle and car. However, when adding the bicycle flow into the functional form of MFD, we observe that flow reduction difference among networks with various percentage of car-only roads is not large (average difference of $\lambda$ between the 25th percentile and 75th percentile of car-only roads percentage is 0.0023). If some road segments are car-only, other road segments would be more crowded for bicycles, which is more likely to increase interactions between bicycle flow and car flow [12]. Meanwhile, a small number of cyclists would illegally use car-only roads, which also reduces the car flow. These results are in line with an earlier study showing that the total vehicle flow of 55 streets in Shanghai decreased by 24% after the implementation of the separation scheme [2]. The average difference of $\lambda$ between the 25th percentile and 75th percentile of physically separated roads is 0.0056, with a value of 0.0058 for shared roads. Compared to setting car-only roads, it is more efficient to decrease capacity reduction by building more physical bicycle facilities and reducing the percentage of shared roads in the network. If bikeways are not physically separated, many factors, such as on-street parking occupancy [3] and presence of a stopped bus [42], can frequently cause bicycles to spill into the motorized lane and interfere with car flow. These results are also confirmed by empirical analyses of three complete networks in Shanghai.

The results also indicate that the interference effect can be moderated by number of car lanes. For the same level of bicycle network flow, networks with wider motorized roads have lower capacity reductions due to bicycle flow. This is in line with that most cyclists only interact with cars on the adjacent motorized lane [12]. Another study [13] also confirmed that most conflicts between bicycles and cars on wide roads are frictional conflicts, while many on narrow
roads are blocking conflicts. However, widening roads can also lead to frequent lane-changing behaviors, possibly decreasing network traffic flow [43]. Thus, it is not generally productive to reduce bicycle interference by widening links.

Although results are promising, this study is limited somewhat by data and approach. First, the dataset used to estimate bicycle flow is bike-sharing data, which is insufficient to fully estimate density or volume of overall bicycle traffic. Future studies should incorporate bike-sharing data with supplementary data sources, like video data, to estimate penetration rate. Second, the proposed approach is empirically data-driven, with limited range, which may not adequately represent the distinct congested branch of the MFD. Furthermore, some important factors, such as E-bikes and buses, are not covered in this study. Further research could extend this work to E-bikes and buses with additional field data.

The case is particularly important because Shanghai is often regarded as a model for urban transportation development in China [2]. This study offers an approach for investigating impact of bicycle traffic on MFD on the existing car-bicycle network and evaluating traffic separation schemes in Shanghai. Features of mixed traffic flow observed in this work may assist traffic engineers to better understand operational principle of mixed car-bicycle traffic at the network level. Based on the results, various traffic management strategies may be proposed, such as adjusting share of car-only roads, changing separation type, redistributing road resources among different modes and extending bicycle priority in certain areas. Furthermore, results of this study may also shed light on future 3D-MFD studies on car-bicycle interactions.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm the contributions to the paper as follows: study framework and model design: Yizhe Huang, Daniel(Jian) Sun, Aoyong Li, Kay W. Axhausen; data collection and pre-processing: Yizhe Huang, Aoyong Li; analysis and interpretation of results: Yizhe Huang, Daniel(Jian) Sun; draft manuscript preparation: Yizhe Huang, Daniel(Jian) Sun, and Kay W. Axhausen. All authors reviewed the results and approved the final version of the manuscript.
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