Estimating Capacity of Bicycle Path on Urban Roads in Hangzhou, China

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ABSTRACT

Bicycle path capacity is of significance for bicycle facilities planning, design and management. With the rapid increase of electric bicycles (e-bikes), the heterogeneous traffic composed with conventional bikes and e-bikes, which use conventional bicycle path, will bring some efficiency issues. This paper proposed a method to derive bicycle path capacity by fitting a relationship between the three fundamental traffic variables: flow, speed, and density. The field data of eleven bicycle path sections were collected in Hangzhou, China in the case study. The results indicated that the mean capacity is about 2512 bicycles/h per meter, and the capacity per meter is not related to bicycle path width. Four important factors of mixed bicycle traffic, e-bikes percentage, male percentage, young rider percentage, and carrying things percentage were introduced to analyze their effect on capacity. It is found that the estimated bicycle path capacity will increase with the increase of the e-bikes percentage or the decrease of carrying things percentage. These findings are valuable to support future studies for design and management of bicycle path under the condition mixed with bicycles and e-bikes traffic flow.

Keywords: Capacity, Electric bicycle, time interval, density-speed model

INTRODUCTION

Non-motored traffic trip is one of the main trip modes in developing countries, especially in Southeast Asian such as China, Indian, and Vietnam *(1)*. In recent years, because of the low-cost, convenient, and relatively energy-efficient, electric bicycles (e-bikes) are quickly becoming one of the dominant non-motored travel modes in the country. E-bikes ownership of China reached approximately 200 million in 2013 *(2)*. Therefore, due to the same classification and management of bikes and e-bikes, the heterogeneous traffic mixed with e-bikes and slower-moving bicycles, which uses conventional bicycle path, is and will be very common in Chinese cities. The heterogeneous traffic composed with bikes and e-bikes will bring some efficiency and safety issues. The size and speed differences between these two modes will lead to more complicated characteristics and higher risk of traffic collisions.

Based on above reasons, in this paper, we focus on estimation of the capacity of traditional bicycle path under mixed bikes flow. The bicycle path capacity is the most significant in transportation engineering and vary according to traffic conditions (e.g., volume, speed, e-bike percentage), road geometries (e.g., path width, grade), driver characteristics (e.g., age, gender), or weather conditions. The purpose of this paper is to comprehensively analyze the affecting factors of capacity and accurately estimate bicycle path capacity based on a large number of field survey data in Hangzhou, China. We think this research will have great theoretic and practical significance for the planning and management of non-motored traffic facilities.

LITERATURE REVIEW

The development course of bicycles and e-bicycles, which are one of primary trip modes in developing countries especially in China, is the key pathway to understand and research the motorization and transform of travel mode. Zhang, Shaheen, and Chen *(2)* examined four phases in bicycle evolution in China from initial entry and slow growth (1900s to 1978), to rapid growth (1978 to 1995), bicycle use reduction

(1995 to 2002), and policy diversification (2002 to present). They also explored two bicycle innovations, e-bikes, and public bike-sharing (the shared use of a bicycle fleet), and proposed detailed description of the characteristics of two new forms of bicycle. Weinert, Ma, and Cherry *(3)* examined how and why e-bikes developed so quickly in China with particular focus on the key technical, economic, and political factors involved. This case study provides important insights to policy makers in China and abroad on how timely regulatory policy can change the purchase choice of millions and create a new mode of transportation.

The capacity of bicycle path section can be defined similar with the capacity of a freeway or multilane highway section which proposed in the Highway Capacity Manual (HCM 2010) *(4)*. Therefore, the capacity of bicycle path section is referred to as the maximum hourly rate at which bicycles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions. Related research of bicycle path capacity focuses on two aspects. One is the capacity under uninterrupted-flow conditions which is the main research object of this paper. The other is about the capacity under interrupted-flow conditions, especially saturation flow rate or capacity of bicycles and effect of bicycles on capacity at signalized intersections.

Due to the reason that capacity is rarely observed on bicycle facilities in the United States, values for capacity therefore reflect sparse data, generally from Europe, Asian countries, or simulations. The American Association of State Highway and Transportation Officials (AASHTO) recommend that separated bicycle paths be 3.0 m wide with a minimum width of 2.4 m in low-volume conditions, where a standard width for a bicycle lane is approximately 1.2 m *(5)*. The HCM, which used results from Europe, reports capacity values of 1,600 bicycles/h/ln for two-way facilities, and 3,200 bicycles/h/ln for one-way facilities under uninterrupted-flow conditions *(4)*. The Swedish Capacity Manual (SCM) *(6)* suggests 1,500 bicycles/hr as the planning capacity of a 1.2-m bicycle lane. The ministry of housing and urban-rural Development of China (MOHURD) *(7)* recommends that a standard width for a bicycle lane is 1.0 m, and a bicycle path must contain two lanes and be not less than 2.5 m. MOHURD also recommends the capacity of bicycle path for one-way facilities is about 1600~1800 bicycles/h/ln with physical separation, and 1400~1600 bicycles/h/ln without physical separation.

Some studies also focus on the bicycle path capacity. Homburger *(8)* reported that bicycle facility capacity was reached at approximately 2,600 bicycles/hr per 1-m lane in Davis, California. Navin's study *(9)* reported the capacity of a 2.5-m bicycle path as 10,000 bicycles/hr. This translates into approximately 4,000 bicycles/hr per 1-m lane in Canada. Botma *(10)* eported the bicycle capacity was about 3,200 bicycles/hr per 1-m lane in Holand. Liu *et al (11)* found bicycle capacities of between 1,800 and 2,100 bicycles/ hr per 1-m lane in Beijing, China. Another study in Beijing reported a bicycle lane capacity of 2,344 bicycles/hr for uninterrupted facilities separated from motor vehicle traffic *(12)*. Li *(13)* reported that theoretical and practical capacities of a bicycle lane are about 2000 bicycles/h/ln and 1280 bicycles/h/ln, respectively.

In summary, the capacity for a single 1-m to 1.2-m bicycle lane has great difference in different studies which can be due to different methods, different bicycle facilities, different characteristics of cyclists, and different travel purposes. The majority of estimated capacity results fell between 2,000 and 3,500 bicycles/hr/ln *(14)*.

As described, the previous research focused on the bicycle path capacity with conventional bicycles. However, very little research has been conducted regarding the bicycle path capacity mixed with conventional bicycles and e-bikes. Therefore, this paper presents a methodology in estimating capacity at bicycle path segments and analyzes the influence factors of capacity quantitatively.

FIELD DATA COLLECTION

Data Survey

Field data collection is crucial for capacity estimation. Data quality determines the estimation results and leads to whether the conclusions are correct. In this paper, field surveys were designed for collecting cyclist characteristics (e.g. age, gender) of bicycles and e-bikes and mixed traffic flow parameters (e.g. volume, speed, type). Eleven bicycle path sections from 11 roads in Hangzhou, China, which is a very famous tourism Chinese city with a population of 8.84 million by the year of 2013, were selected for data collection. These bicycle paths are located in the downtown area of Hangzhou, as shown in Figure 1.

All sections locate in the middle of road links, away from intersections, which will lead to the least effect of traffic signal and pedestrian crossing. All bicycle paths have zero grades and are separated from motor vehicle lanes by barriers. Hence, the traffic flow of bicycles are without interruption from pedestrians and motor vehicles, and the adjustment factors for lateral motor vehicles, pedestrians, and traffic signal could be ignored in estimating and analyzing the capacity of bicycle path. Due to reconstruction of old bike paths and difference of road planning and design standards, the bicycle paths in Hangzhou cover a wide range width, which provided a chance for analyzing the path width effect on capacity.

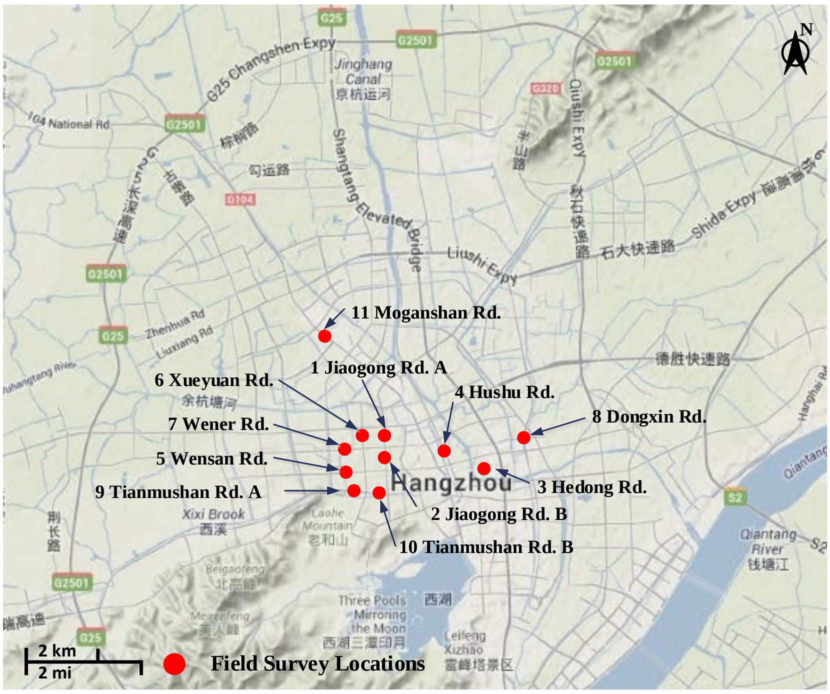


FIG. 1 Field survey locations

The survey days were sunny and nothing special happened. The bicycle data were collected in dry weather and at peak hours, from 7:00–9:00 a.m. and 4:30–6:30 p.m. on every weekday. The traffic volume is high during morning and evening peak hours on weekdays on the eleven sites. It is possible to continuously observe both over-saturated and under-saturated flows of the mixed non-motorized traffic during survey periods. One camera was set on the side of a bicycle path to take videos there. White lines were used to mark the detection area ("virtual detector"). The camera was set to capture details of bicycles' behaviors, especially their head positions and movements. Using the video processing technology, we can get the moment when a bicycle crossing the marked white lines. Then traffic flow parameters (such as volume, speed) can be calculated automatically. In order to get other variables, Table 1 shows the variables coded and their coding methods. The codes of every bicycle were carried out manually. In Table 1, gender and age are easy to understand. "Bicycle type" can be classified into three categories: conventional bicycle, bicycle-style e-bike (BSEB) and scooter-style e-bike (SSEB). BSEB and SSEB are two different electric bicycles. In this paper, we do not distinguish these two e-bikes because of the less percentage of BSEB. More detailed information about BSEB and SSEB can be seen in related references *(2)*. “Carry things” means that the cyclist carrying something (such as a person or some objects) which beyond the size of a bicycle and has influence on other bicycles. Though bicycles carrying things are illegal in China, there are about 10% cyclists carrying something from our survey data.

Table 1 Definitions of variables coded

Variables	How to code
Bicycle type	Bicycle: 1, bicycle-style e-bike(BSEB): 2, scooter-style e-bike(SSEB): 3
Gender	Male: 1, female: 0
Age	Teenage: <20, young: [20, 40], middle: [40, 60], elderly >60
Carry things	Person: 1, luggage: 2

Data Description

The sample statistical descriptions of these eleven sites are listed in table 2. From the table, it can be seen that eleven bicycle paths cover typical path widths with the different width from 2.27 to 4.60 meters. As the definition that 1-m or 1.2-m per bicycle lane in China or other countries, the widest bicycle path (Moganshan Road) includes about four lanes one way. This provides valid data for analyzing the effect of bicycle path width on capacity.

The percentages of e-bikes (including BSEB and SSEB) in all bicycle path except Xueyuan Road are more than a half and the average percentage is up to 66.75%, which shows that there is a large percentage of electric bicycle as an important travel mode of commuters in Hangzhou. Therefore, the capacity of bicycle path mixed with e-bikes and conventional bikes can be estimated and analyzed with different percentages of e-bikes.

From the field data, the percentages of male cyclists and young cyclists are also larger than the others. The average percentage of male cyclists and young cyclists are 63.08% and 67.14%, respectively. The survey found that the major use group of e-bikes is constituted by those who are low-middle degrees, low-middle income and middle age. This is due to that the purposes of e-bikes travel mode in peak time are for work and the income level of cyclists are lower. Because the low level of service of public transport in Hangzhou, and only a subway line in operation, more people tend to choose e-bikes or bikes, which are more convenient and inexpensive travel modes.

Another interesting result is that the percentages of carrying things are large, average up to 10.64%, although this is illegal in China and will rise in electric-bicycle-related accidents. Due to the strong power of e-bikes, a part of e-bikes will be used for freight and carrying people. This will have great lateral effect on other bicycles and lead to the decrease of bicycle path capacity.

Table 2 Statistical descriptions of filed bicycle survey data.

No.	Survey sites	Abbr.	Lane width (m)	Sample number	E-bikes percentage	Male percentage	Young percentage	Carry things percentage
1	Jiaogong Road A	JG-A	2.27	2943	68.60%	63.81%	80.29%	12.95%
2	Jiaogong Road B	JG-B	2.43	2944	67.53%	64.06%	66.20%	13.38%
3	Hedong Road	HD	2.76	2176	59.05%	58.32%	52.94%	11.31%
4	Hushu Road	HS	2.93	3604	70.26%	59.68%	62.21%	5.80%
5	Wensan Road	WS	3.01	3252	68.37%	65.85%	69.67%	18.05%
6	Xueyuan Road	XY	3.45	2571	49.01%	66.52%	79.33%	6.78%
7	Wener Road	WE	3.52	2885	71.56%	65.64%	42.28%	16.70%
8	Dongxin Road	DX	3.65	3364	63.26%	66.52%	69.54%	8.68%
9	Tianmushan Road A	TMS-A	3.97	2222	66.76%	67.77%	59.37%	7.39%
10	Tianmushan Road B	TMS-B	4.50	4704	53.88%	65.09%	78.41%	5.38%
11	Moganshan Road	MGS	4.60	9155	77.14%	58.80%	67.27%	11.50%
	Average		**3.37**	**3620**	**66.75%**	**63.08%**	**67.14%**	**10.64%**

ESTIMATION OF BICYCLE PATH CAPACITY

Methodology

Roadway capacity is a very important parameter that is used in highway planning, design, and operation evaluation. The capacity of a road section is referred to as the maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions *(4)*.

There were two main ways to estimate capacity. One way for estimating the roadway capacity is to collect the time headway of vehicles in saturated conditions, and the capacity is the reciprocal of saturated time headway. The other method is to calibrate a relationship (also known as the fundamental diagram of traffic flow) between the three traffic flow variables: speed, volume, and density (or occupancy).

Typically, speed-density relationship models were considered in the calibration process and only a single-regime function is developed for this calibration. Then, the density-volume relationship can be obtained by using the fundamental formula $q=kv$. In this approach, the maximum point of the density-volume relationship function is estimated as the capacity. Due to the staggered driving behavior of bikes traffic flow, it's almost impossibility to define the time headway between consecutive two bikes. Therefore, in this paper, we use the second method for estimating the capacity of bicycle facility.

The main process is to select an appropriate speed-density relationship model. There were lots of speed-density models proposed in the last eighty years beginning from Greenshields' linear model. Every model has its advantage and disadvantage, so that it's difficult to choose a very appropriate speed-density model for fitting bicycles traffic flow. In order to estimating capacity more accurately and comprehensively, four famous and familiar speed-density relationship models, Greenshields model (GS) *(15)*, Underwood model (UW) *(16)*, Newell model (NW) *(17)*, and Logistic model (LG) *(18)*, were introduced for capacity estimation as follows,

$$v = v_f (1 - k/k_j) \tag{1}$$

$$v = v_f \exp(-k/k_m) \tag{2}$$

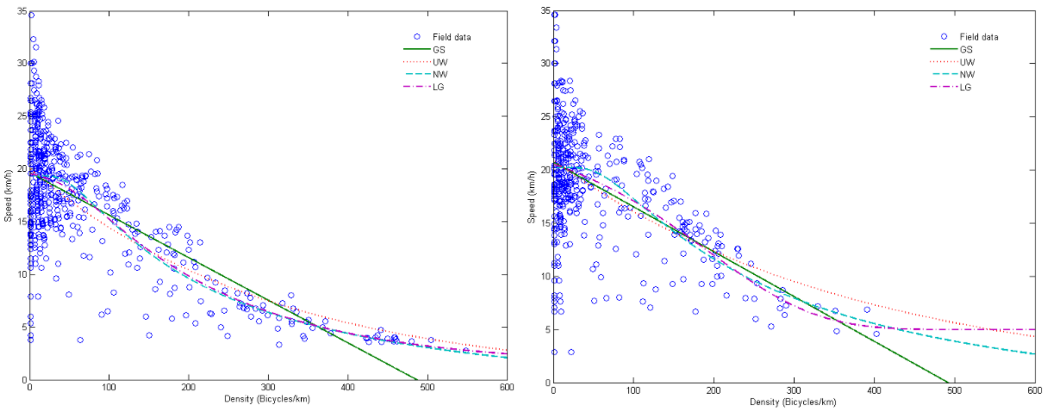
$$v = v_f \left\{ 1 - \exp\left[-\frac{\lambda}{v_f} \left(\frac{1}{k} - \frac{1}{k_j} \right) \right] \right\} \tag{3}$$

$$v = v_b + \frac{v_f - v_b}{\left\{ 1 + \exp\left[\left(k - k_m \right) / \theta_1 \right] \right\}^{\theta_2}} \tag{4}$$

Where, v and k are the speed and density of mixed bicycles in a time interval, v_f is free-flow speed, k_j is the jam density, k_m is the density-at-capacity, v_b is the average travel speed at stop and go condition, θ_1 is a scale parameter which describes how the curve is stretched out over the whole density range, and θ_2 is a parameter which controls the lopsidedness of the curve.

Results

Nonlinear least squares fitting method (Levenberg-Marquardt, LM) was proposed for bicycle density-speed relationship model parameters calibration. LM method is the most widely used non-linear least squares algorithm, which used gradient to seek the maximum (minimum) value. LM method has both the advantage of gradient and Newton's method. Figure 2 shows the fitting results of Greenshields model, Greenberg model, Newell model, and Logistic model, (a) and (b) express the field data of Jiaogong Road A and Tianmushan Road B, respectively. Blue dot indicates measured field data points, and four lines represent the model curves obtained by least-squares fitting algorithm. As can be seen from the figures, four different types of models can fit the measured field data very well.



(a) JG-A (b) TMS-B

FIG. 2 Fitting performance of density-speed relationship model.

The bicycle path capacity is estimated by the maximum point of the density-volume relationship function. Differently with motor vehicles, cycling behaviors are non-lane-based and very complicated. Therefore, the total width of the bicycle facility is far more important than the number of effective bicycle lanes. In order to overcome this shortcoming, in this paper we use bicycle/h per meter as a normal unit of bicycle path capacity. Figure 3 shows the estimated capacities of eleven sections with different path widths. It can be seen that estimated capacities vary from 1700 to 3100 bicycles/h per meter, average up to about 2500 bicycles/h/m. Different density-speed models have different estimated capacities, which will be difficult for us to choose an appropriate capacity estimating model.

Compared with the designed bicycle path capacity, 1500 bicycles/h/m in the United States and 1600~1800 bicycles/h/m in China *(4, 7)*, the estimated capacities are larger. We think the difference of capacity is due to some reasons: (a) the purpose in peak time is mainly for work commuter travel, the cyclists are urgent, (b) the larger percentage of e-bikes will lead to higher speed and larger capacity, and (c) the larger percentage of young cyclists which have better driving skills.

In order to analyze the relationship between bicycle path capacity and path width, Table 3 shows the mean and standard deviation of capacity from eleven field survey locations, linear regression model between bicycle path capacity (C_b) and path width (w), and the correlation coefficient (R^2). The results show that the correlation coefficients of all models are small, which presents that there is no significant correlation between path capacity per meter and path width. Therefore, bicycle path capacity can be defined as bicycles/h per meter, and the path capacity increases linearly with path width. In the following description, we use bicycles/h/m to define bicycle path capacity, which is easy to compare under different path width.

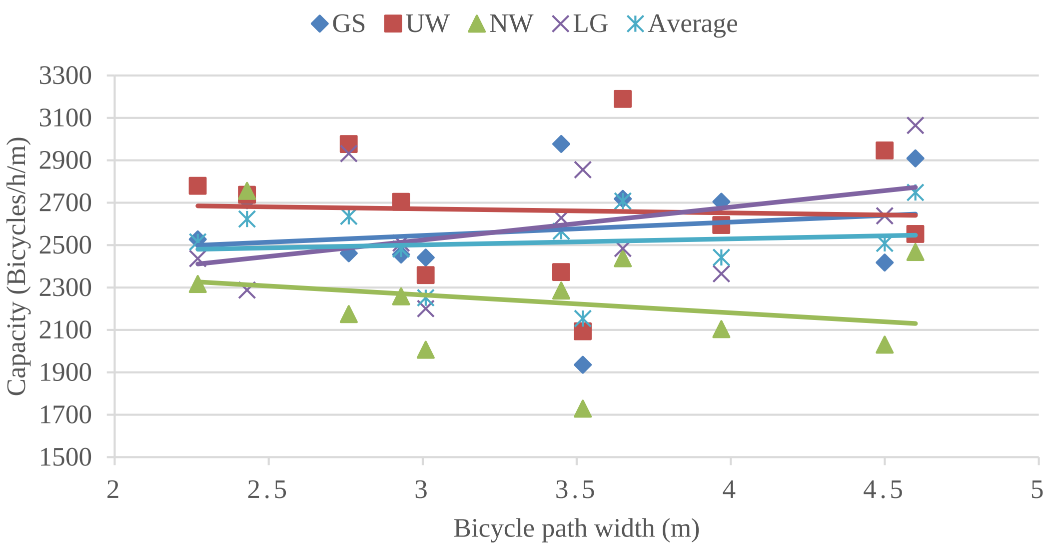


FIG. 3 Estimated capacity with different bicycle path width.

Table 3 Results of bicycle path capacity estimation.

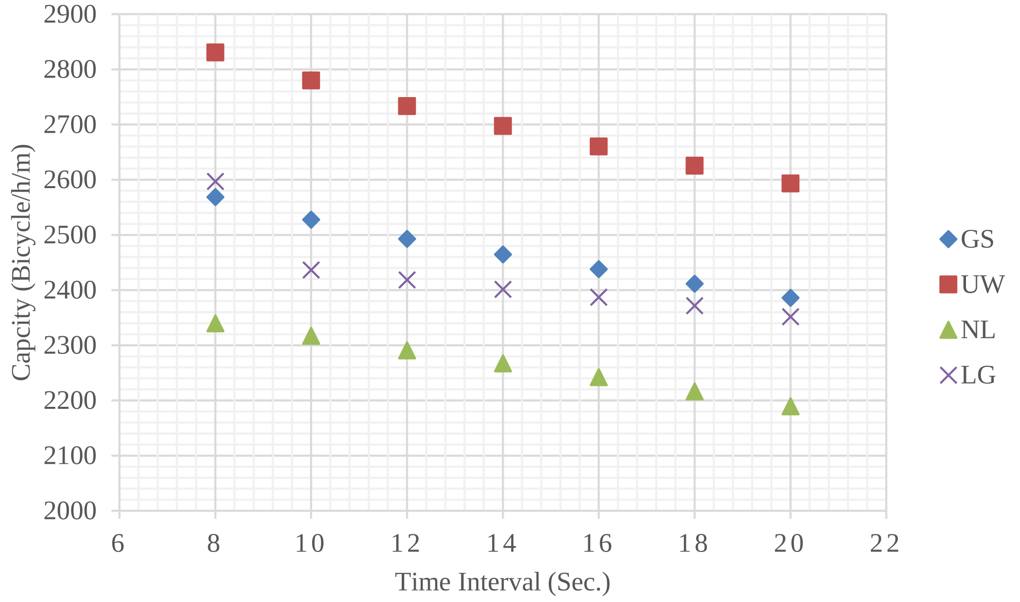
Model name	Capacity mean (Bicycles/h/m)	Capacity STD (Bicycles/h/m)	Path width-capacity relationship (Bicycles/h/m)	R^2
GS	2569	285	$C_b = 63.08w + 2356.5$	0.0297
UW	2664	315	$C_b = -19.218w + 2729$	0.0022
NW	2234	273	$C_b = -84.267w + 2517.8$	0.0574
LG	2582	274	$C_b = 154.91w + 2060$	0.1933
Average	2512	181	$C_b = 28.627w + 2415.8$	0.0152

DISCUSSIONS

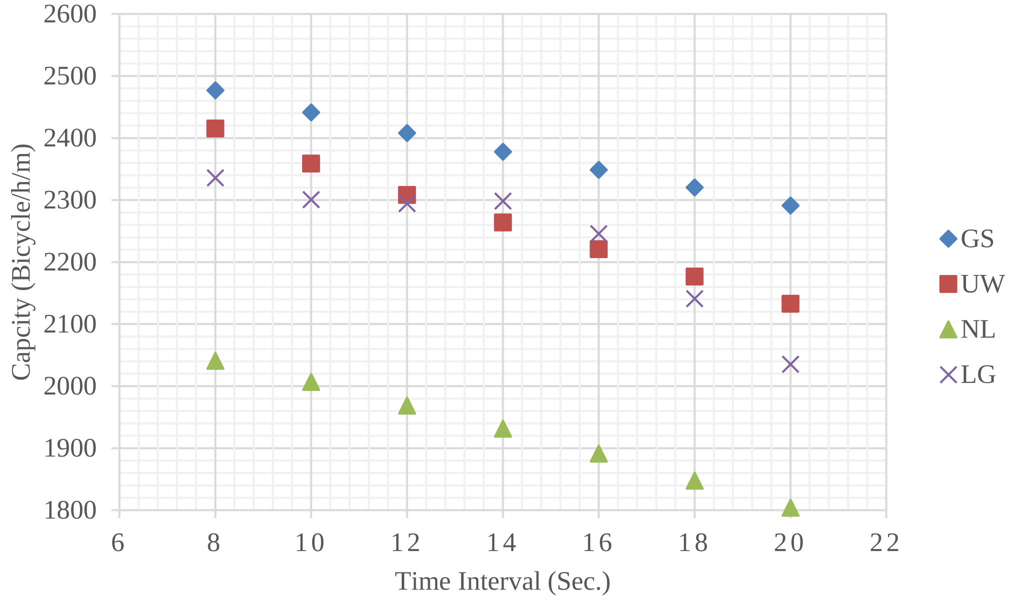
Sampling Time Interval

Time interval is one of significant parameters in capacity estimating. Different time interval would lead to different estimation results. HCM *(4)* suggests that the analysis period is typically 15 minutes for bicycles' planning and design procedures and policies, and agency resources, which is established in a way similar to the vehicular analysis period. But 15 minutes is too long for capacity estimation, and bicycle traffic flow cannot be observed under continuous saturated state in 15 minutes.

Figure 4 shows the estimated capacity under different sampling time intervals from 8 to 20 seconds, Figures 4(a) and 4(b) correspond to Jiaogong Road A and Hushu Road, respectively. From the figures, it is obtained that the estimated capacities used different density-speed models decrease nearly in linear with the increase of time interval. Therefore, the time interval of field survey data has a great effect on estimation of capacity. But unfortunately, there was little literature to discuss how to choose an appropriate time interval. Through the experiential observation of bicycle traffic from videos and variations of curve in Figure 4, we have found that the variations of estimated capacity values were small with time intervals from 10 to 16 seconds. In this paper, for the sake of simplicity, we used 10 seconds as the time interval for all capacity estimation. Further research will focus on how to determine the most optimal sampling time interval.



(a) Jiaogong Road A



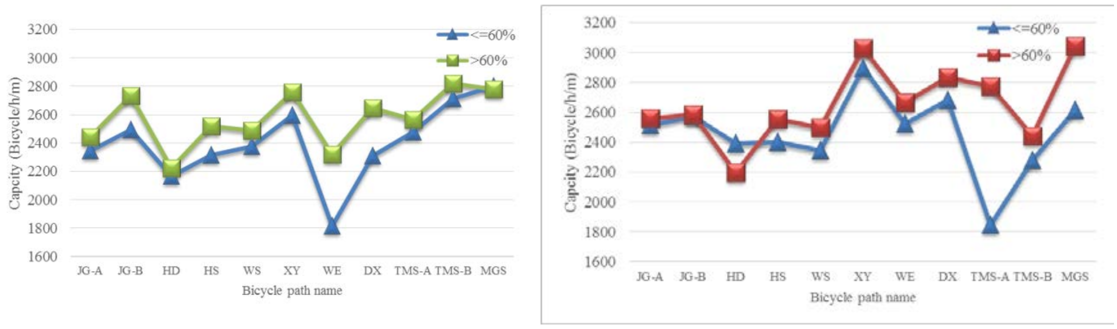
(b) Hushu Road

FIG. 4 Estimated capacity vs. time interval.

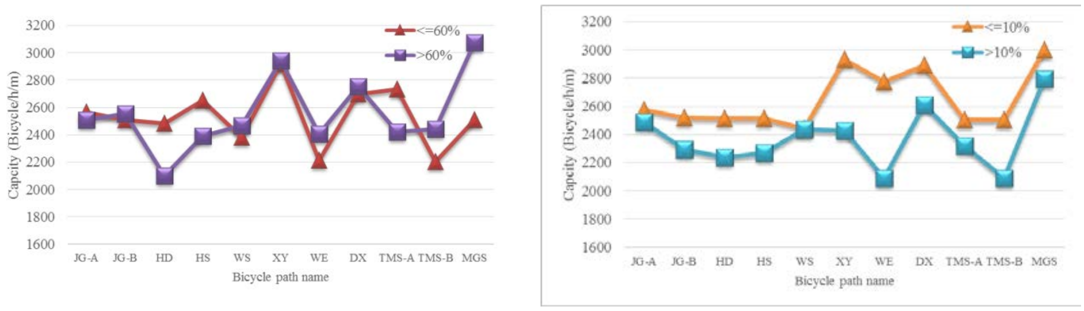
Capacity Factors

Bicycle path capacity may vary according to traffic conditions, driver characteristics (e.g., age, income, gender), or weather conditions. In order to validate the effects of e-bikes percentage, age, gender, and carrying things percentage on estimated bicycle path capacity, we divided each sampling interval data into two categories, one is the factor value more than the average percentage and the other is less than the average percentage. Based on the results of Table 2, the average percentages of e-bike, male, young rider and carrying things were set to 60%, 60%, 60%, and 10%, respectively. Therefore, the traffic flow data surveyed from one time interval have four kinds of classification methods, composed of more than 60% e-bikes or not, composed of more than 60% male or not, composed of more than 60% young rider or not, and composed of more than 10% carrying things rider or not, respectively. Using the methodology presented above, we can estimated the capacity under different traffic flow composition.

Figure 5 shows the results of estimated capacity under four different factors, where (a), (b), (c), and (d) represent the capacity difference under different percentage composition of e-bike, male, young rider, and carrying things rider, respectively. The results indicate that different compositions of bicycle traffic flow have great effect on estimating capacity.



(a) e-bikes percentage **(b) male percentage**



(c) youg cyclists percentage **(d) carrying things percentage**

FIG. 5 Estimated capacities under different factors.

T-test was proposed for studying the effect of traffic composition factors quantitatively. We assume that the estimated capacities from 11 bicycle path sections which composed of more than 60% e-bikes or not belong to two samples. Therefore, a paired T-test of the hypothesis that two matched samples come from distributions with equal means was proposed for hypothesis testing. The difference of two samples is assumed to come from a normal distribution with unknown variance. The significance level is set to 0.05. H=0 indicates that the null hypothesis ("mean is zero") cannot be rejected at the 5% significance level. H=1 indicates that the null hypothesis can be rejected at the 5% level. *P* is the probability of observing the given result, or one more extreme, by chance if the null hypothesis is true. Small values of *P* cast doubt on the validity of the null hypothesis.

Table 4 shows the T-test results of four factors. H values indicate that three factors, bicycle type, gender, and carry things will lead to significant differences of capacity in statistical. It also can be seen from *P* values (significantly less than 0.05) that the percentages of e-bike and carry things rider have great influence on bicycle path capacity. This is due to that two kinds of bicycles with significant differences in size and operation speed on the same facilities will inevitably lead to a complicated mixed traffic flow and variations in their static and dynamic characteristics, and ultimately affect the important traffic parameters (i.e. flow, density, and speed). These changes of bicycle traffic parameters will challenge the capacity of conventional bicycle path.

Table 4 Results of bicycle path capacity estimation.

Factor	Percentage	Capacity mean (Bicycles/hr/m)	Capacity STD (Bicycles/hr/m)	*P* Value	T-test H
Bicycle type	≤ 60%	2400	256	0.0028	1
	> 60%	2573	187		
Gender	≤ 60%	2461	255	0.0495	1
	> 60%	2653	241		
Age	≤ 60%	2533	207	0.8361	0
	> 60%	2551	263		
Carry things	≤ 10%	2651	196	6.0478e-04	1
	> 10%	2369	202		

CONCLUSIONS

Bicycle path capacity estimation is an important topic especially under heterogeneous traffic which composed with conventional bikes and e-bikes using conventional bicycle path. In this paper, we use field survey data of eleven bicycle path sections in Hangzhou, China for case study. The data covered congested and uncongested traffic conditions and four density-speed models were used to estimate capacity. There were several results found in this paper.

(1) For case study, 11 bicycle path sections were surveyed for capacity estimation. The average percentages of e-bikes, male riders, and young riders are more than 50%. There also has about 10% riders using bicycle to carry things which is illegal in China.

(2) The average estimated capacity per meter for different path width was about 2500 bicycles/h per meter. Results of T-test show that the path width has on effect on estimated capacity. The capacity values have great difference using different density-speed models for estimation.

(3) Time intervals have a certain influence on the results of capacity estimation. Using the same time interval for capacity estimation is important for capacity studies under different conditions.

(4) The percentages of E-bikes and carrying things riders have great influence on conventional bicycle path capacity. The planning, design and management of bicycle path should consider these two factors.

Consequently, the results of this study demonstrate the ability of density-speed models to estimate capacity, and determine the key influencing factors of bicycle path capacity. Further research is needed to develop new techniques to optimize time interval and model a relationship between bicycle path capacity and influencing factors (such as e-bikes percentages) quantitatively.

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