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Recommended Widths for Separated Bicycle Lanes Considering Abreast Riding and Overtaking

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Abstract: The paper aimed to develop width recommendations for separated bicycle lanes considering abreast riding and overtaking behaviors. We investigated eight segments of separated bicycle lanes in Nanjing with cameras, analyzed the major types of abreast riding and overtaking, and then explored the volume threshold for two-abreast riding as well as the suitable clearances in a comfortable overtaking, using a binomial logistic model for both. The main results and conclusions are as follows: (1) two-abreast riding and an electric bicycle passing a conventional bicycle were the main categories of abreast riding and overtaking, respectively. (2) The volume threshold at which two-abreast riding occurred was 1075 bicycles/h/m. (3) Distances of 0.48 m, 1.48 m, and 0.56 m were the suitable clearances for the distance from the center of the passed rider to the nearest curb, the distance center to the center of riders while overtaking, and the distance from the center of the passing rider to the nearest curb, respectively. (4) Below 1075 bicycles/h/m, a bicycle lane 2 m in width was acceptable; above that, 2.5 m was suggested as the minimum width of the bicycle lane.

Keywords: bicycle facility design; lane width; logistic regression; abreast riding; overtaking

1. Introduction

In recent years, urban transportation congestion and air pollution have been growing concerns for the public. As a green mode of transportation and a mode able to achieve door-to-door connectivity, bicycles are now attracting the attention of policy-makers, urban planners, and commuters. In Europe, the USA, and Asian areas, bicycles are increasingly popular alternatives. The emergence of electric bicycles has helped extend the travelling distance [1], notably lower the physical strengths required and, thus, attract more categories of bicycling groups, especially the physically disabled and elderly [2]. In addition, the spread of bicycle sharing systems in the world has made the use of this mode of travel more flexible and has been cited as an effective way to alleviate the "last mile problem". These two new developments have noticeably promoted the use of bicycles and have led to the recovery of this transportation mode.

To encourage the development of cycling, a growing number of bicycle facilities are being built on city roads. In this process, various design guidelines for bicycle facilities play an important role by specifying the requirements and details, especially in terms of the bicycle lane width. Although the design documents of many countries [3–9] regulate the widths of a variety of bicycle lanes, few of them have empirical study bases. The determination of the bicycle lane width needs to consider multiple factors, such as the capacity and operational space of the rider's maneuvers. The two maneuvers that require more lateral space are riding abreast and overtaking which, thus, should be focused on when determining the width of a bicycle lane. Furthermore, the use of these two maneuvers increases with an increase in biker volume [10]. However, few studies were found on bicycle lane widths related to the two maneuvers.

This study proposes suitable widths for bicycle lanes taking bicycle abreast riding and passing into consideration. To determine their characteristics, we conducted an observational study on traffic flows running on separated bicycle lanes. The reasons for choosing separated bicycle lanes are that they provide better comfort and safety on arterials or roads with high volume of automobiles. This type of facilities are increasingly preferred by city authorities to attract more cycling. Figure 1a shows the typical features of the bicycle flow we investigated. For simplicity, in the description below, EB refers to bicycles powered only by electricity, while CB refers to conventional bicycles propelled by human strength.

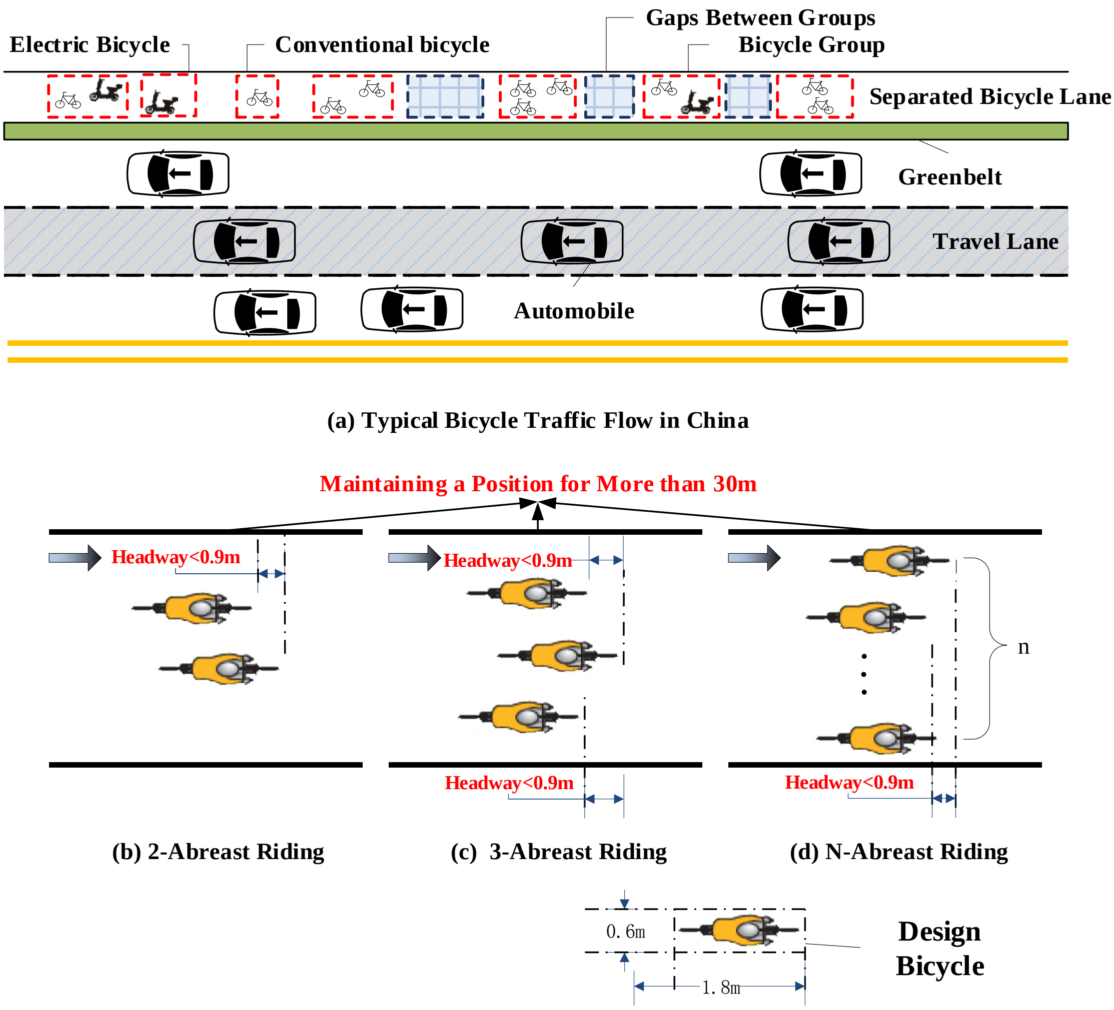


Figure 1. (**a**) Typical bicycle flow on a separated bicycle lane; and (**b**–**d**) definitions of abreast riding.

The rest of the paper is organized as follows: Section 2 performs a literature review on bicycle lane widths, riding abreast, and overtaking as well as summarizes the defects in previous studies. Section 3 indicates the data collection and extraction methods for this study as well as the necessary details of the binomial logistic model used in the data analysis. In Section 4, we discuss the main types of abreast riding and overtaking, the volume threshold of abreast riding, the lateral clearances that a comfortable overtaking requires and, on the basis of these discussions, develop the recommendations for separated bicycle lane widths. Finally, the results and conclusions drawn in this paper are summarized.

2. Literature Review

Lane width is an important parameter for a bicycle facility design, which directly affects lane capacity and safety. The bicycle facility design guides and standards of many countries have proposed specific settings and recommendations regarding bicycle lane widths for various roadway characteristics. Table 1 summarizes these bicycle lane specifications (most are physically separated) for widths in North America, Western Europe, Australia, and China. In general, most western agencies specify 1.2 m or 1.5 m as the minimum width for a bike lane and 1.5–2.5 m as the recommended width. The maximum bicycle lane width in western guidelines is 2.5 m. Differentiating from the western guidelines, the documents in China permit a minimum width of 2.5 m with the recommended width between 2.5 and 6 m. Both in national or representative cities' (Beijing, Shanghai) guidance documents, bicycle width settings are greater than their counterparts in the West. This is because the bicycle is mainly utilized as an important transport mode for commuting in China rather than for recreation and sport as it is in the West. Higher bicycle ridership in China requires much wider bicycle lanes.

Table 1. Minimums and recommendations for bicycle lane width from previous standards and guidelines.

Number	Guide	City/State/Country	Year	Minimum		Recommended		Country or Region
				British Unit (ft)	Metric (m)	British Unit (ft)	Metric (m)	
1	Bicycle facility manual [11]	Minneapolis	2009	5.0	1.5	5.0–6.0	1.5–1.8	
2	Wisconsin Bicycle Facility Design Handbook [12]	Wisconsin	2009	5.0	1.5	5.0	1.5	
3	Bikeway Facility Design Manual [13]	Portland	2010	6.5	2.0	6.5–8.2	2.0–2.5	
4	Urban Bikeway Design Guide [14]	US	2011	5.0	1.5	5.0–7.0	1.5–2.1	
5	Guide for the Development of Bicycle Facilities [3]	US	2012	4.0	1.2	5.0	1.5	North America
6	Recommended Bicycle Lane Widths for Various Roadway Characteristics [15]	US	2014	4.0	1.2	5.0	1.5	
7	Separated Bike Lane Planning and Design Guide [16]	US	2015	5.0	1.5	7.0	2.1	
8	Geometric Design Guide for Canadian Roads [4]	Canada	1999	4.5	1.4	4.5–9.0	1.4–2.7	
9	Haliburton County Cycling Master Plan Final Report [17]	Haliburton	2008	3.0	0.9	3.0–5.25	0.9–1.6	
10	Design Manual for Bicycle Traffic [5]	The Netherlands	2007	5.0	1.5	5.0–8.2	1.5–2.5	
11	London Cycling Design Standards [6]	London	2010	4.0	1.2	4.0–5.0	1.2–1.8	Western Europe
12	Collection of Cycle Concepts 2012 [7]	Denmark	2012	6.6	2.0	7.2	2.2	
13	Cycling Aspects of Austroads Guides [8]	Australia	2014	4.9	1.5	4.9–8.2	1.5–2.5	Australia
14	Code for Design of Urban Road Engineering [18]	China	2012	11.5	3.5	-	-	
15	Guide for Planning and Design of Walking and Bicycle Traffic System [9]	China	2013	8.2	2.5	8.2–19.7	2.5–6.0	China
16	Code for Planning & Design on Urban Road Space [19]	Beijing	2014	9.8	3.0	11.5	3.5	
17	Shanghai Street Design Guidelines [20]	Shanghai	2016	8.2	2.5	11.5	3.5	

Although most of the guidelines in Table 1 give the widths for bike lanes, only a limited number of widths reported in them are explicitly supported by experimental results or field data. Some scholars noticed this research gap and conducted some studies. Lee et al. used precise GPS instruments to measure bicycle trajectories on a bicycle lane without curbs. Based on the results of their study, a bike lane width should be at least 2.0 m to allow for rider stability on roadways with no curb or gutters [21]. Fees et al. tested the impacts of a buffer, bicycle lane width, vehicle mix, and on-street parking on bicycle operation. They recommended lane widths for urban and suburban two-lane undivided roadways with on-street parking and constrained roadway widths [22].

With respect to rider's maneuvers within bicycle lanes, more research was found on bicycle passing than that of riding abreast. Botma and Papendrecht analyzed bicycle passing based on the assumptions that the speeds of the passing and passed bicycles equal the speed measured at one cross-section and remain constant during passing, and the passing maneuvers occur within 50 m of the survey site. They reported that the average lengths of the passing maneuvers were 57 m and 24 m for cycle paths 2.40 m and 1.8 m wide, respectively [23]. By video analysis, Khan and Raksuntorn found passing and passed bicycles maintain a constant speed difference. Additionally, they reported the lateral spacing during passing, average passing lengths, and the shape of passing [24]. More recently, Lin et al. conducted a similar study in Shanghai, China. Characteristics of moped-passing-bicycle on shared lanes were analyzed in detail. They studied speed of passing and passed vehicles, lateral distance from closer curb, lateral spacing, longitudinal distance during, direction of passing, and average accelerations [25]. Li et al. classified bicycle passing events into free passing events, adjacent passing events and delayed passing events according to the attributes of spaces of bicycles during the passing [26]. When it comes to abreast riding, Botma and Papendrecht first observed that paired riders maintained a lower lateral spacing than passing bicycles. They reported the paired riding threshold as a speed difference less than 1.8 km/h and a headway less than 0.125 s [23]. By video and statistical analysis, Khan and Raksuntorn concluded that the average lateral spacing on a bicycle path 3 m wide for paired riding is 1.05 m and the average distance headway maintained during paired riding is 0.6 m [24]. Yan et al. conducted a study on the relationships among bicycle abreast riding, lateral space and volume. They found abreast riding kept a positive correlation with volume while lateral space presented negative with it [27].

As mentioned in the previous paragraphs, little research has been conducted on design guidelines for bicycle lane widths. However, the studies that do exist have their shortcomings. Lee et al. performed their experiments under an ideal condition without considering real volumes and riding behaviors, such as abreast riding or overtaking. Moreover, their experimental results only proved the minimum operational width of a bicycle. The observational study of Fees et al. was based on bicycle lanes installed on a mixed traffic road. This type of facility cannot improve the attractions of cycling like a separated lane does by promoting improved safety. Characteristics of bicycle passing and abreast riding were studied extensively and many results on lateral clearances were reported. However, the two maneuvers were not related to the selection of lane width. Due to the shortcomings above, we conducted observational research on abreast riding and overtaking on separated bicycle lanes, then proposed some recommendations for the widths of separated bicycle lanes.

3. Methodology

This section first indicates the procedures of data collection and the data extraction method for our investigation and tabulates the results of data collection. Second, some necessary details of the binomial logistic model used in the study are briefly described.

3.1. Data Collection, Extraction, Summary, and Splitting

3.1.1. Data Collection

We investigated bicycle flow operations using a dual-camera recording method during the workdays in Nanjing. Field observations were performed in commuting intervals, from 7:00 to 9:00 for the morning peak and from 17:00 to 19:00 for the evening peak. The following are the selection criteria for the survey sites:

1. differences in bicycle lane width;
2. paved level terrain, good sight;
3. far from intersections, block accesses and bus stations; and
4. suitable space for installing cameras.

The diversity of lane width can assure that data collection is under various conditions and circumstances. Based on the collected data, the models established below will be more general. The minimum length to complete a passing maneuver is 30.48 m (100 ft) [28]. Integrating with references [23–25] and according to our preliminary observation, we chose 50 m as the length of a survey segment.

The instruments used in our field work included a tape measure of 50 m, two wide-angle cameras, two tripods (maximum height of 4 m), 12 red traffic cones, and six marking tapes. The setting details for the observation are described in Figure 2a,b.

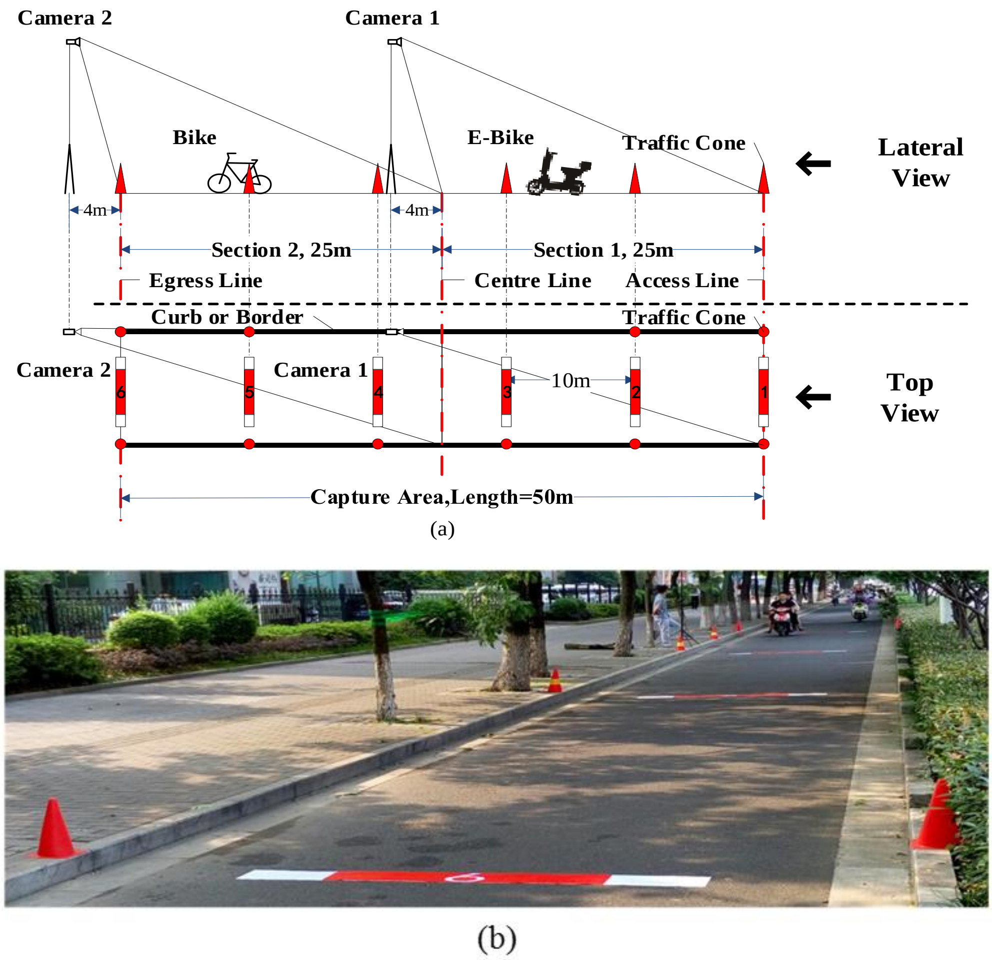
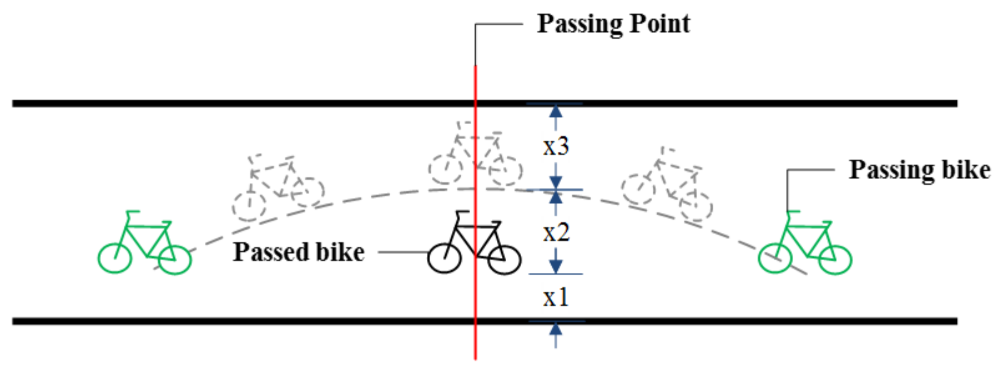


Figure 2. *Cont.*



(c)

Figure 2. (**a**) Setting details for field observation; (**b**) field photo; and (**c**) passing process description.

3.1.2. Data Extraction

The overall data observation process is described as follows: when a bicycle accessed the observing area, a video recorder identified the gender, age (estimated) of each bicyclist, and his (her) bicycle type.

Abreast Riding: The data extraction was conducted based on groups because bicycle flow comes in terms of groups. When a bicycle group entered the observing area, an investigator counted the number of bicycles in it. When each bicycle reached a marking tape, its type and the moment in time were recorded. The speed of a bicycle is computed by Equation (1), and the space headway between any two bicycles in a group is calculated by Equation (2). Based on the definitions in Figure 1b–d, abreast ridings were identified from space headway data.

$$v_n^{ij} = \frac{10}{t_j - t_i} \tag{1}$$

$$sh_{mn} = th_{mn} \bullet v_n \tag{2}$$

where v_n^{ij} speed of bicycle n between tape i and tape j; t_i, t_j moments that bicycle n reached tape i and tape j; sh_{mn} space headway between bicycle m and bicycle n, bicycle m riding ahead; th_{mn} time headway between bicycle m and bicycle n; v_n speed of bicycle n.

Passing Events: passing events on a bicycle lane include EB-passing-EB (EPE), EB-passing-CB (EPC), CB-passing-CB (CPC), and CB-passing-EB (CPE). When observing a passing event, the main goal is to closely watch the maneuver of a cyclist and classify as 'Yes' if there is no change in riding in any direction. If the passing rider on any occasion has to slow down the bicycle, changes direction to avoid a passed rider, applies brakes, or stops the bicycle completely to avoid a crash, it will be classified as 'No'. The counting starts after the passing maneuver occurs. The sample will be classified 'Yes' if found to be comfortable and 'No' if not comfortable. Table 2 indicates the methods that were employed for the dichotomous variables as classified in this study, while Figure 2c shows the definitions of the variables.

Table 2. Explanatory variables for modeling a comfortable distance.

Variables	Description	Coding
X1	Distance from center of passed rider to nearest curb	0—Not Comfortable 1–Comfortable
X2	Distance center to center of riders while overtaking	0—Not Comfortable 1–Comfortable
X3	Distance from center of passing rider to nearest curb	0—Not Comfortable 1–Comfortable

3.1.3. Data Summary

According to the data collection and extraction methods above, we counted 8060 bicycles, 3163 bicycle groups, 464 abreast ridings, and 1571 passing events on separated bicycle lanes from eight road segments. The road information and data are summarized in Table 3.

Table 3. Information description and data summary for eight road segments.

Number	Road Name	Lane Width (m)	Cycle Counts	Group Counts	Abreast Riding Counts	Passing Events
1	Hunan Rd.	2	528	345	18	33
2	Longpan Rd. (Blood Center)	3	582	239	30	156
3	Zhongshan Rd.	3.4	1990	474	108	541
4	Zhongshan South Rd.	3.5	799	282	70	190
5	Taiping North Rd.	3.85	593	446	20	52
6	Longpan Rd. (Baima Park)	4	1091	591	64	103
7	Zhongshan East Rd.	5	891	246	38	162
8	Zhongshan North Rd.	5	1586	540	116	334
Overall	-	-	8060	3163	464	1571

3.1.4. Data Splitting

In order to validate the fitted models in the present study, holdout method of cross-validation was employed, assigning data points to model-building set and validation set. Typically, the size of the validation set is smaller than that of the model-building set. Based on the principle above, 60% of abreast riding and passing data points, 278 and 942, respectively, were randomly chosen for the model building below. The rest of data was used to test the fitted models' validity in new realities.

3.2. Binomial Logistic Model

The logistic regression model is commonly used in economics, and it has been widely adopted in many other fields. Thus, we only indicate the response variables, independent variables in our models, and measurement of the fit of the model. Additionally, the methods of determining a cut-off volume at which an abreast riding event occurs and selecting suitable comfortable clearances will be described in the following text.

The binomial logistic model is adopted because all the responses in this study are binary, and the predicted probability is expressed by the formula below:

$$P(y = 1|x) = \frac{\exp(\beta_i x_i)}{1 + \exp(\beta_i x_i)} \tag{3}$$

where $P(y = 1|x)$ is the estimated ratio at which abreast riding occurs in determining the volume threshold or the estimated probability that the passing cyclist is comfortable in the overtaking analysis. Volume is the independent variable for determining a cut-off volume, while X1, X2, and X3 in Table 2 are for selecting suitable comfortable clearances. β_i represents the coefficients of the model. A Pearson chi-square statistical test is used to evaluate the goodness-of-fit of the models in the study.

To determine the volume threshold that an abreast riding happens at, a classification table is applied, employing the overall error rate instead of the hit rate as an assessment of the prediction accuracy. The best cut-off point of an event occurring is obtained when the overall error rate reaches the lowest level. To test the model's validity in new data, we applied the model and the best cut-off to a validation set containing 186 data points and then compared the prediction error rates in model-building set and validation set. The process described above is indicated in Figure 3a.

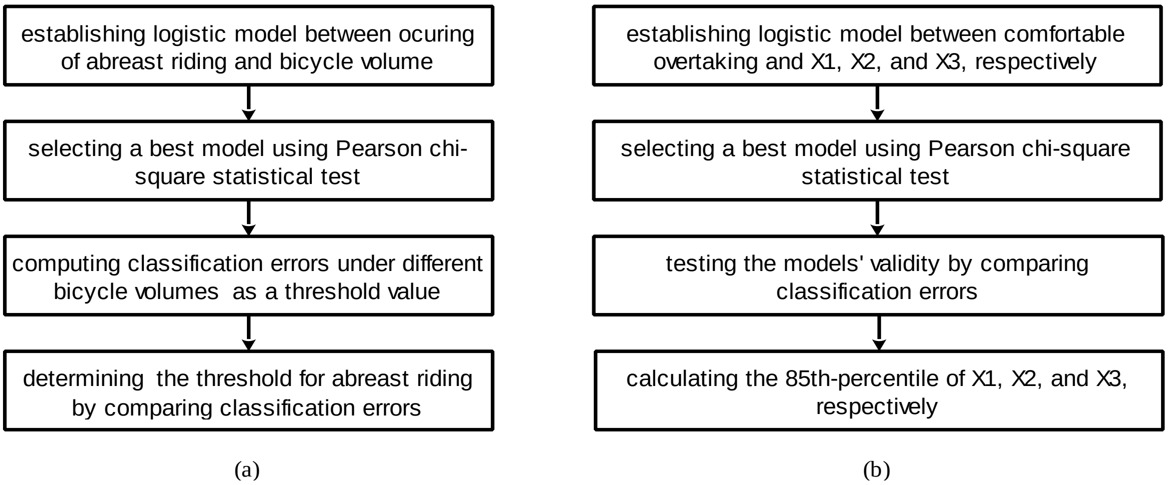


Figure 3. (**a**) Steps to determine the threshold for abreast riding; and (**b**) steps to calculate the 85th-percentile of X1, X2, and X3.

To find the suitable clearances in a comfortable overtaking, the 85th-percentile is used rather than a threshold in the passing analysis. When three clearances exist at passing point, there will be three thresholds. It cannot verified if the conditions for the three thresholds are the same. Namely, it is hard to determine that three suitable clearances will present at a same instant. Then, it is arbitrary to propose width recommendations with these clearances. The 85th-percentiles of clearances provide an alternative solution. Although it is not also determined if the 85th-percentiles will present simultaneously, the values are suitable for most of the cases. Thus, it is more reasonable to specify bicycle lane widths using an 85th-percentile instead of a threshold. The steps to determine the suitable clearances in a comfortable overtaking are shown in Figure 3b. In the third step, a model validating similar with abreast riding analysis was performed.

4. Results and Discussion

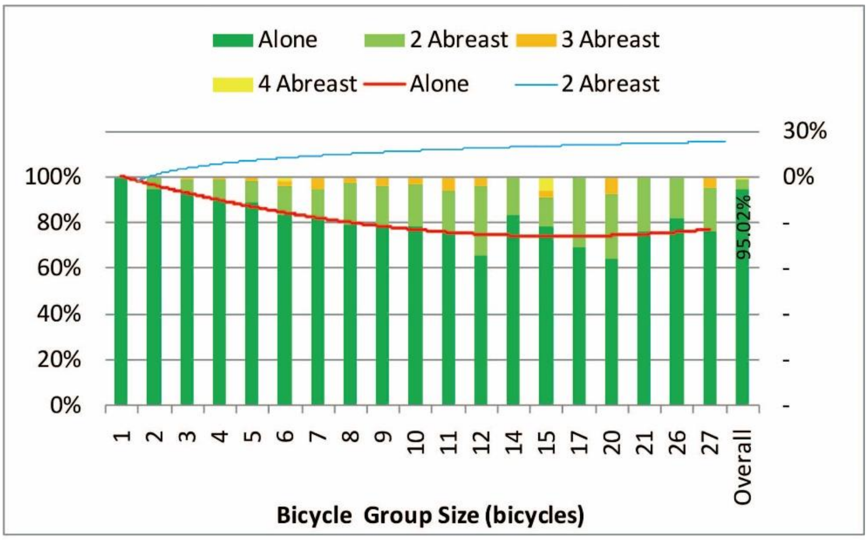
In this section, we present the statistical results regarding the types of bicycle abreast riding and overtaking to determine the main factors, which are later taken into consideration in the bicycle lane width design. Then, a logistic model is used to determine the volume threshold where abreast riding occurs. After that, the relationships between the probability of a cyclist comfortably overtaking and three lateral gaps existing in an EPC are investigated by logistic regression. Based on the results and conclusions gained in the three discussions above, we propose suitable widths for separate bicycle lanes.

4.1. Main Types of Abreast Riding and Overtaking

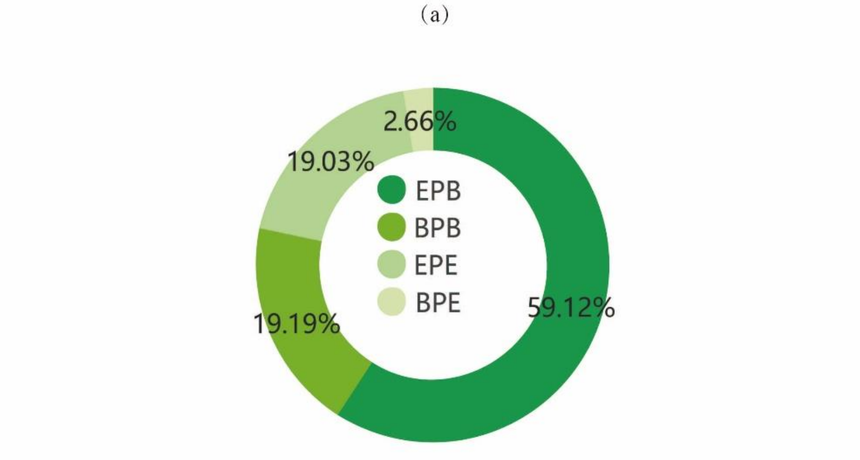
Since cyclists' abreast riding and overtaking behaviors are significant phenomena in lane width computation, the first problem is to find the two maneuvers' major categories or types in real riding.

As shown in Figure 4a, it presents the categories of abreast riding in bicycle groups and their variations with the increasing group size. We find the following:

(a) there are mainly four categories of abreast riding, including riding alone and riding two-, three-, and four-abreast;
(b) riding alone covers the biggest proportion (more than 60%) in each group, 95.02% in all with the ratio declining as group size increases;
(c) meanwhile, two-cycle abreast is increasing, and the type approaches 30% in groups with bigger sizes; and
(d) other types of abreast riding may be out of consideration because of their negligible amounts.



(a)



(b)

Figure 4. (**a**) Ratios of various types of abreast riding under different group sizes; and (**b**) types of bicycle overtaking.

In real riding, a cyclist usually prefers to ride single-file, which has been proven by the corresponding data. However, this condition will change as traffic surroundings deteriorate due to an increase in volume or riding in a group. The statistical results indicate two-abreast riding becomes a considerable type in the process.

Figure 4b shows that EPB occurs most often out of all four types with a value of 59.12%. EB's better kinetic properties in comparison to CB may perfectly explain this result. With higher speeds and better acceleration, an EB can easily pass a CB.

4.2. Volume Conditions when Abreast Riding Occurs

As discussed above, two-abreast riding in a bicycle flow becomes a noticeable event as bicycle volume grows. It is interesting and meaningful to find the critical point at which two-abreast riding begins to appear. In the following, we establish a logistic regression between the proportion of two-abreast riding and the bicycle volume to determine the critical point.

Table 4 gives the parameters of our logistic model. The p-values of coefficients and the χ^2 test both prove that this model is valid and can be accepted. Figure 5a shows the result of fitting the model to the real data, which also presents a good fit.

Table 4. Parameters of bicycle volume in the logistic regression.

Variables	Coefficient	*p*-Value	Prob > Chi^2
Intercept	−4.21	1.57×10^{-146}	0.0000
Volume (bics/h/m)	0.0023	4.30×10^{-32}	

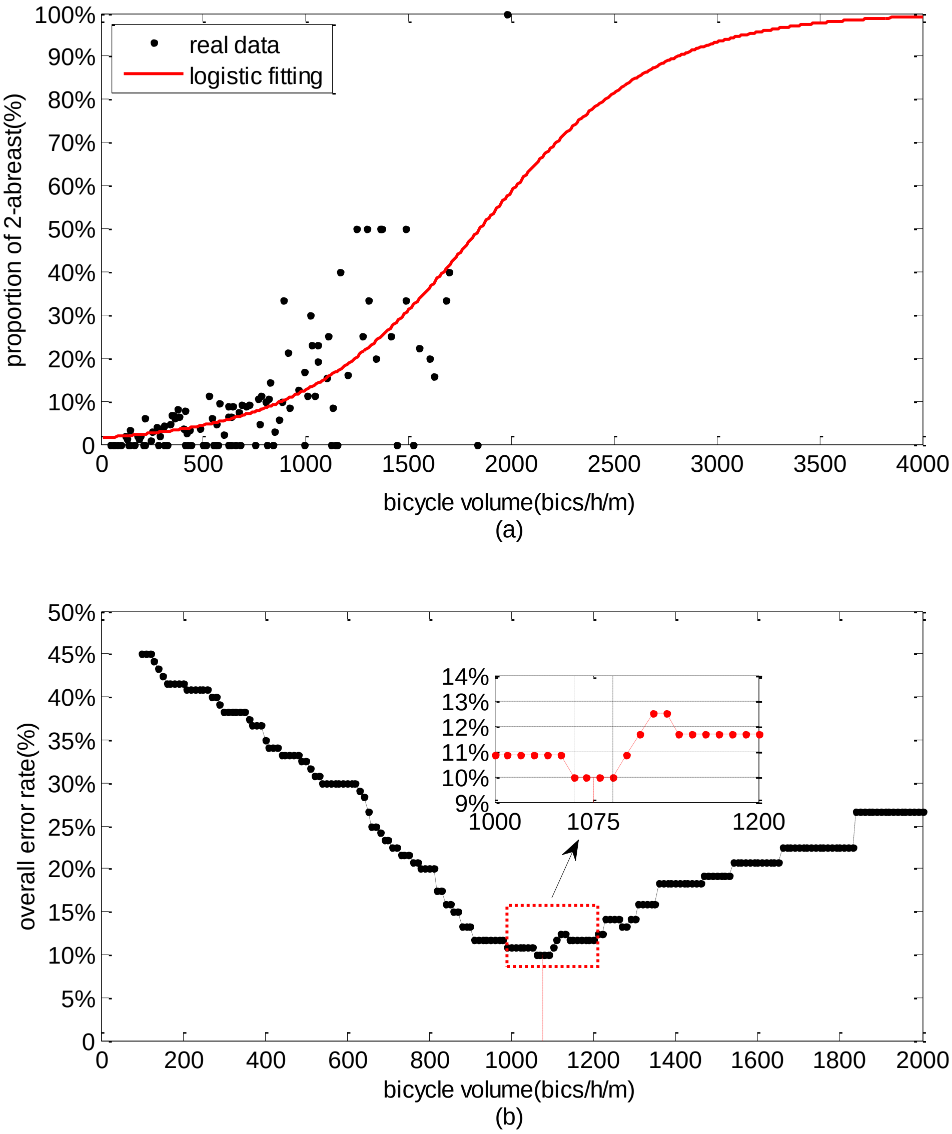


Figure 5. (**a**) Fitting curve for real data of the proportion of two-abreast; and (**b**) the relationship between the overall error rate and volume cut-off point.

By adjusting the cut-off value of the volume and calculating the corresponding overall error rate for the prediction of two-abreast riding, a threshold distribution, [1060, 1090] bics/h/m, was found in Figure 5b. We selected the median (1075 bics/h/m) as the final cut-off point. At 1075 bics/h/m, a classification table is used to assess the prediction accuracy and model validity in Table 5. The overall error rate of 9.7% in the model-building data set is good enough to support 1075 bics/h/m as the threshold for 2-abreast riding to occur. The prediction error rate (12.8%) observed in the validation data set is slightly higher than that in the model-building data set. This gives a reliable indication of the predictive ability of the fitted logistic regression in new independent data set.

Table 5. Predicted classification table base on model-building dataset and validation set taking 1075 bics/h/m as the cutoff.

Model-Building Dataset				Validation Dataset			
	Predicted				Predicted		
Observed	Yes	No	Error rate	Observed	Yes	No	Error rate
Yes	269	9	3.2%	Yes	175	11	5.9%
No	52	751	6.5%	No	38	510	6.9%
Overall Error Rate			**9.7%**	**Overall Error Rate**			**12.8%**

4.3. Lateral Clearances That a Comfortable Overtaking Requires

Statistical results have shown that EPC is the major type of passing. Thus, it is necessary to explore the lateral space characteristics of the passing type to provide a solid base in computing the bicycle lane width. Three logistic regression models were established to measure the influences of the three clearances (X1, X2, and X3) defined before on the overtaking comfort. Table 6 shows the respective parameters of these models and chi-square test results.

Table 6. Respective parameters of X1, X2, and X3 of the logistic regression.

Comfortable Distance	Coefficient	*p*-Value	Prob > Chi^2
Intercept 1	3.15	9.06×10^{-60}	0.0000
X1	−2.94	1.27×10^{-32}	
Intercept 2	−2.53	9.13×10^{-53}	0.0000
X2	2.98	6.32×10^{-100}	
Intercept 3	3.09	9.75×10^{-11}	0.0000
X3	−2.43	2.79×10^{-5}	

In order to validate the models established above, the classification table was used to compare the prediction error rates in the model-building dataset and validation dataset. Table 7 shows the comparison results taking 0.85 as cut-off. We can see that the overall error rates in the validation data set are not considerably higher. Thus, it indicates that the fitted binary logistic regression models can be used to predict the new data.

Table 7. Predicted classification table base on model-building dataset and validation set taking 0.85 as cutoff.

Comfortable Distance	Model-Building Dataset				Validation Dataset			
X1		Predicted				Predicted		
	Observed	Yes	No	Error rate	Observed	Yes	No	Error rate
	Yes	385	29	6.9%	Yes	272	17	6.0%
	No	43	485	8.2%	No	42	298	12.5%
	Overall Error Rate			**15.1%**	**Overall Error Rate**			**18.5%**
X2		Predicted				Predicted		
	Observed	Yes	No	Error rate	Observed	Yes	No	Error rate
	Yes	380	34	8.3%	Yes	258	31	10.8%
	No	32	496	6.0%	No	23	317	6.6%
	Overall Error Rate			**14.3%**	**Overall Error Rate**			**17.4%**
X3		Predicted				Predicted		
	Observed	Yes	No	Error rate	Observed	Yes	No	Error rate
	Yes	387	27	6.5%	Yes	265	24	8.2%
	No	38	490	7.2%	No	34	306	10.0%
	Overall Error Rate			**13.7%**	**Overall Error Rate**			**18.2%**

Figure 6 plots the curves of the three models. We can see the three lateral gaps' impacts on the probability of a comfortable overtaking (PCO) from the varying trends of the curves. The following is clear:

(a) The growth of X1 and X3 imposes a negative influence on the PCO;

X1 and X3 represent the passed bicycle and the passing bicycle's distances to the nearest curb, respectively. A larger X1 means less space left for the passing bicycle to use in its overtaking, which causes difficulties in passing smoothly and comfortably. X3 is the gap between the passing cyclist and the closer curb. A smaller X3 gives the passing bicycle a higher chance of scraping with the curb.

(b) An increase in X2 contributes to a comfortable passing.

X2 is the lateral space between the passing and the passed bicycles. In contrast to those static restrictions or obstacles such as curbs, a moving bicycle draws more attention from the cyclist in overtaking. This is confirmed by comparing the coefficient of X2 with those of the other two. Therefore, a larger clearance relative to the passed bicycle allows the passing bicyclist greater freedom and makes him/her feel safer.

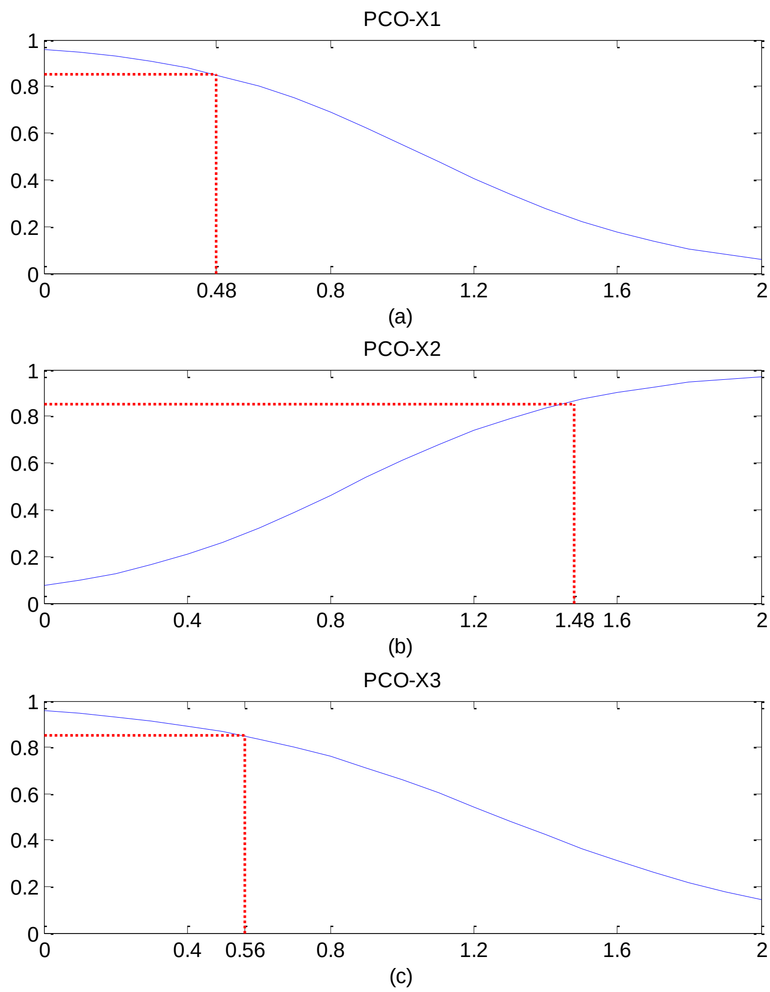


Figure 6. (**a**) Relationship between the probability of comfortable overtaking (PCO, y-axis) and X1 (x-axis). (**b**) Relationship between the probability of comfortable overtaking (PCO, y-axis) and X2 (x-axis). (**c**) Relationship between the probability of comfortable overtaking (PCO, y-axis) and X3 (x-axis).

After discussing the three lateral clearances' impacts on comfortable overtaking, it is useful to find the suitable levels of the three for most cases. The respective values of X1, X2, and X3 were calculated when the PCO equaled 0.85 as shown by the red lines in Figure 6. Values of 0.48, 1.48, and 0.56 m for X1, X2, and X3 were obtained, respectively. From another point of view, the three values are the 85th-percentile values of X1, X2, and X3 for a comfortable EPC overtaking. By comparing the 85th-percentile value of X2 with the corresponding results in [25], it can be seen that 1.48 m is between the mean and the maximum in [25]. This proves the result in the present study is valid to some extent. As reported in [25], the lateral clearances of an EPC are greater than those of the other types (EPE and CPC). Therefore, it is acceptable that the three values suit most passing events.

4.4. Recommended Widths for a Separated Bicycle Lane

As described in the introduction, abreast riding and overtaking are the important phenomena that create a desire for more operational space than usual riding on a bicycle lane. Therefore, the previous two sections discussed the volume condition at which an abreast riding event occurs and the suitable lateral clearances for a comfortable overtaking. Some widths for a separated bicycle lane are now suggested based on these results and conclusions.

According to the results in Section 4.1, single riding, two-abreast riding, and EPC are the most commonly observed situations in bicycle traffic flow, while the others are rare or negligible. EPC constitutes the largest proportion of the four passing types, but it is uncertain whether this type of passing occupies the most space accordingly. The bicycle flow in the present study involves two types of bicycles including EB and CB. Bicycle type is an indispensable factor influencing the lateral space of passing types [25]. Thus, [25] performed a statistical analysis on the lateral spacing of bicycle passing types. Herein, lateral spacing refers to the distances between the central lines of passing and passed vehicles. It was reported that the values of lateral spacing at the passing point obey the rule: EPC > EPE > CPC. Due to this, we only need to consider EPC in discussing bicycle lane widths.

For a single ride, it is enough to provide a minimum width. By the experimental results in [21], the required lane width was approximately 2.0 m when the speed of a bicycle varied from 10 km/h to 30 km/h, and it was concluded that 3.0 m exceeded the required width. The results recommended 2.0 m as the minimum safe width for a bike lane with no curb or gutter. It is reasonable to predict that the corresponding width of a lane with curbs or gutters is within 2.0 m because one would better maintain his or her riding direction due to a fear of scraping with a curb or a gutter.

In [3], 1.2 m and 1.5 m were reported as the minimum operating width and the preferred width, respectively. Hence, when 2-abreast riding occurs, at least 2.4 m of lane is required. Another method for obtaining the operating width for 2-abreast riding is measuring the lateral space size from a field investigation. However, this approach cannot capture the outer lateral space of the two bicycles riding abreast. At the end of Section 4.3, three 85th-percentile values of X1 (0.48 m), X2 (1.48 m), and X3 (0.56 m) were obtained. Thus, we calculated a width of 2.52 m as a comfortable overtaking by accumulating them. The width is slightly wider than the minimum required width for two-abreast riding. By combining the two levels of width, it is more general to recommend 2.52 m as a width allowing both two-abreast riding and overtaking.

In Section 4.2, a volume threshold of 1075 bics/h/m for two-abreast riding had been concluded. Based on this, single riding occurs more frequently under 1075 bics/h/m, and 2.0 m for a separate bicycle lane is suitable. Above the threshold, 2.52 m for a bicycle lane, which can accommodate two-abreast riding or passing, is recommended. To facilitate the practical application, the value is set to at least 2.5 m.

5. Conclusions

The paper investigated eight segments of physically separated bicycle lanes, analyzed the major types of abreast riding and overtaking, and then explored the volume threshold for the most common type of abreast riding as well as the suitable clearances in a comfortable overtaking, using the binomial logistic model for both. Integrating and considering the analysis above, we proposed recommendations for the widths of separated bicycle lanes. Accordingly, the present study draws the following conclusions based on the results:

A. Two-abreast riding and EPC were the main categories of abreast riding and overtaking, respectively.
B. The volume threshold at which 2-abreast riding occurs was 1075 bics/h/m.
C. Distances of 0.48 m, 1.48 m, and 0.56 m were the suitable clearances for the distance from the center of passed rider to the nearest curb, the distance center to the center of riders while overtaking, and the distance from the center of passing rider to nearest curb, respectively.
D. Below 1075 bics/h/m, a 2-m-wide bicycle lane was matched; above that, 2.5 m was suggested as the minimum width of the bicycle lane.

The empirical findings in this study enhance our understanding of the characteristics of bicycle abreast riding and overtaking and serve as a basis for designing bicycling infrastructure. Additionally, the width recommendations considering abreast riding and overtaking are direct and useful references for determining bicycle lane widths.

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References

1. Cherry, C.; Cervero, R. Use characteristics and mode choice behavior of electric bike users in China. *Transp. Policy* **2007**, *14*, 247–257. [CrossRef]
2. Fishman, E.; Cherry, C. E-bikes in the Mainstream: Reviewing a Decade of Research. *Transp. Rev.* **2015**, *36*, 72–91. [CrossRef]
3. American Association of State Highway and Transportation Officials. *Guide for the Development of Bicycle Facilities*; American Association of State Highway and Transportation Officials: Washington, DC, USA, 2012.
4. Transportation Association of Canada. *Geometric Design Guide for Canadian Roads*; Transportation Association of Canada: Ottawa, ON, Canada, 1999.
5. CROW. *Design Manual for Cycle Traffic*; CROW: Horaplantsoen, The Netherlands, 2007.
6. Transport for London. *London Cycling Design Standards*; Transport for London: London, UK, 2010.
7. Cycling Embassy of Denmark. *Collection of Cycle Concepts 2012*; Cycling Embassy of Denmark: Copenhagen, Denmark, 2012.
8. Austroads. *Cycling Aspects of Austroads Guide*; Austroads: Sydney, Australia, 2014.
9. Ministry of Housing and Urban-Rural Development of the People's Republic of China. *Guide for Planning and Design of Walking and Bicycle Traffic System*; Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2013.
10. Yan, X.; He, P.; Chen, J.; Ye, X.; Liu, Q. Relationship between number of passing events and operating parameters in mixed bicycle traffic. *J. Southeast Univ. (Engl. Ed.)* **2015**, *31*, 418–423.
11. Minnesota Department of Transportation. *Bicycle Facility Manual*; Minnesota Department of Transportation: Minneapolis, MN, USA, 2009.
12. Wisconsin Department of Transportation. *Wisconsin Bicycle Facility Design Handbook*; Wisconsin Department of Transportation: Madison, WI, USA, 2009.

13. Bureau of Transportation. *Bikeway Facility Design Manual*; Bureau of Transportation: Portland, OR, USA, 2010.
14. National Association of City Transportation Officials. *Urban Bikeway Design Guide*; National Association of City Transportation Officials: New York, NY, USA, 2011.
15. Torbic, D.J.; Bauer, K.M.; Fees, C.A.; Harwood, D.W.; Van Houten, R.; LaPlante, J.; Roseberry, N. *Recommended Bicycle Lane Widths for Various Roadway Characteristics*; 0309284163; Transportation Research Board (TRB): Washington, DC, USA, 2014.
16. Federal Highway Administration. *Separated Bike Lane Planning and Design Guide*; Federal Highway Administration: Washington, DC, USA, 2015.
17. Haliburton Highlands Cycling Coalition. *Haliburton County Cycling Master Plan Final Report*; Haliburton Highlands Cycling Coalition: Haliburton, ON, Canada, 2008.
18. He, K.; Zhu, Z.F. *Code for Design of Urban Road Engineering*; China Architecture & Building Press: Beijing, China, 2012.
19. Standardization Office of Urban-Rual Planning of Beijing. *Code for Planning&Design on Urban Road Space*; Standardization Office of Urban-Rual Planning of Beijing: Beijing, China, 2014.
20. Planning and Land Resources Administration of Shanghai. *Shanghai Street Design Guidelines*; Planning and Land Resources Administration of Shanghai: Shanghai, China, 2016.
21. Lee, C.; Shin, H.C.; Kang, S.; Lee, J.-B. Measurement of desirable minimum one-way bike lane width. *KSCE J. Civ. Eng.* **2015**, *20*, 881–889. [CrossRef]
22. Fees, C.A.; Torbic, D.J.; Bauer, K.M.; Van Houten, R.; Roseberry, N.; LaPlante, J. Design Guidance for Bicycle Lane Widths. *Transp. Res. Rec. J. Transp. Res. Board* **2015**, *2520*, 78–89. [CrossRef]
23. Botma, H.; Papendrecht, H. Traffic Operation of Bicycle Traffic. *Transp. Res. Rec. J. Transp. Res. Board* **1991**, *1320*, 65–72.
24. Khan, S.I.; Raksuntorn, W. Characteristics of Passing and Meeting Maneuvers on Exclusive Bicycle Paths. *Transp. Res. Rec. J. Transp. Res. Board* **2001**, *1776*, 220–228. [CrossRef]
25. Lin, D.; Chen, X.; Lin, B.; Li, L. Phenomena and Characteristics of Moped-Passing-Bicycle on Shared Lanes. In Proceedings of the 93th Transportation Research Board (TRB) Annual Meeting, Washington, DC, USA, 12–16 January 2014.
26. Li, Z.H.; Wang, W.; Shan, X.; Jin, J.; Lu, J.; Yang, C. Analysis of Bicycle Passing Events for LOS Evaluation on Physically Separated Bicycle Roadways in China. In Proceedings of the 89th Transportation Research Board (TRB) Annual Meeting, Washington, DC, USA, 10–14 January 2010.
27. Yan, X.; Zhu, L.; Chen, C.; Wang, T.; Ye, X. Features of Bicycle Abreast Riding and its Application in Bicycle Facility Operating Evaluation and Design Optimization. *Adv. Mech. Eng.* **2017**, *9*, 1–8. [CrossRef]
28. Hummer, J.E.; Rouphail, N.; Toole, J.; Patten, R.; Schneider, R.; Green, J.; Hughes, R.; Fain, S. *Evaluation of Safety, Design, and Operation of Shared-Use Paths—Final Report*; Federal Highway Administration: Washington, DC, USA, 2006.