Exploring Factors Influencing Bicyclists' Perception of Comfort on Bicycle Facilities

Submitted by

Zhibin Li (Corresponding author)
Ph.D. Candidate, School of Transportation, Southeast University
Visiting Scholar, Safe Transportation Research & Education Center, Institute of Transportation Studies, University of California, Berkeley
2614 Dwight Way #7374, Berkeley, CA 94720-7374
Tel: 412 296 1353
E-mail: lizhibin@seu.edu.cn

Wei Wang
Ph.D., Professor, School of Transportation, Southeast University
Si Pai Lou #2, Nanjing, China, 210096
Email: wangwei@seu.edu.cn

Yuanyuan Zhang
Ph.D. Candidate, School of Transportation Engineering, Tongji University
Visiting Scholar, Safe Transportation Research & Education Center, Institute of Transportation Studies, University of California, Berkeley
2614 Dwight Way #7374, Berkeley, CA 94720-7374
Email: yuanyuanzhang@berkeley.edu

Jie Lu
Student Research Assistant, School of Biological Science and Medical Engineering, Southeast University
Si Pai Lou #2, Nanjing, China, 210096
Email: keshuilu@163.com

AND

David R. Ragland
Ph.D., Professor, Safe Transportation Research & Education Center, Institute of Transportation Studies, University of California, Berkeley
2614 Dwight Way #7374, Berkeley, CA 94720-7374
Email: davidr@berkeley.edu

Total number of words = 4956 + 250×6 = 6456

November 15, 2011

Paper for Presentation at the 91st Annual Meeting of the Transportation Research Board

Exploring Factors Influencing Bicyclists' Perception of Comfort on Bicycle Facilities

By Zhibin Li, Wei Wang, Yuanyuan Zhang, Jie Lu and David R. Ragland

Abstract

The primary objective of this study is to investigate the physical environmental factors influencing bicyclists' perception of comfort on physically separated bicycle paths and on-street bicycle lanes. We also look extensively at comparing the perception of comfort and the contributing factors between the two facility types. Field investigations were conducted at 43 segments on bicycle facilities in the metropolitan area of Nanjing, China. Bicyclists' perception of comfort and various environmental conditions were collected. We used an ordered probit (OP) model to analyze the data. Data analysis results showed that for physically separated bicycle paths, the environmental factors significantly influencing bicyclists' perception of comfort included the width of path, presence of grade, presence of bus station, physical separation from pedestrians, surrounding land use, and bicycle flow rate. For on-street bicycle lanes, the contributing factors associated with perception of comfort included the width of bicycle lane, width of curb lane, presence of grade, presence of bus station, amount of occupied car parking spaces, bicycle flow rate, motor vehicle flow rate, and rate of use of electric bicycles. The results suggested that bicyclists perceived a higher average comfort on physically separated bicycle paths as compared to on-street bicycle lanes. On physically separated bicycle paths, bicyclists' perception of comfort was mainly influenced by road geometry and surrounding physical conditions. In the case of on-street bicycle lanes, bicyclists paid attention to the effective riding space and traffic conditions. The findings of this study can help inform design and planning of these bicycle facilities.

INTRODUCTION

In recent years, the bicycle has been widely recognized as an environmentally friendly mode of transport. The bicycle has drawn an increasing amount of attention from transportation researchers. Studies have been conducted to explore how to increase bicycle use for both commuting trips and recreational trips in the United States (*1*, *2*), Canada (*3*), and some European countries (*4-6*). In China, bicycle use has significantly decreased during the past several decades due to rapid motorization (*7*). However, in recent years, as urban roads have become increasingly congested in most large cities in China, several researchers started to realize the potential benefits of bicycle use for short distance trips (*8*, *9*). Providing bicyclists favorable riding environments is an important objective for transportation planners and designers around the world.

Investigating the factors related to bicyclists' perception of the comfort of the physical environment can assist in the planning and design of bicycle facilities. This study focused on two types of bicycle facilities, physically separated bicycle paths (or "cycle track") and on-street bicycle lanes. These two bicycle facilities are commonly implemented on most streets in the urban cities of China, as illustrated in Figure 1. Both of them are built on each direction of streets and traffic is unidirectional on them. On physically separated bicycle paths, bicycles are physically separated from motor vehicles by a barrier or a planting strip. On on-street bicycle lanes, bicycles travel in the same road cross-section with vehicles, separated by a lane marking.

On-street bicycle lane is one traditional bicycle facility that is commonly used in most countries (*2*,*5*,*7*,*10*,*11*). In recent years, the physically separated bicycle paths have received increasing attentions from researchers. Wardman et al. forecasted that a completely segregated bicycle roadway would result in a 55% increase in bicycling (*12*). A survey conducted in Canada corroborated that physically separated pathways were preferred by bicyclists and encouraged more bicycling (*13*). Another study in Canada reported that the injury risk of bicycling on cycle tracks is less than bicycling in streets (*14*). But these studies did not focused on bicyclists' perception of comfort when riding on the two facilities.

Previously, bicyclists' perception of comfort was considered by evaluating the level of service (LOS) of bicycle facilities. For on-street bicycle facilities, several researchers proposed some indexes, such as BLOS (bicycle level of service) and BCI (bicycle compatibility index), to evaluate the compatibility of bicycle facilities for bicycling (*15-18*). The Highway Capacity Manual (HCM 2010) recommended the bicycle LOS for a link of urban street (bicycle travels in the street, possibly in a bicycle lane) is determined by the effective width of outside through lane, proportion of on-street parking occupied, midsegment vehicle flow rate, number of through lanes in subject travel direction, vehicle running speed, percent heavy vehicles in midsegment, and pavement condition rating (*11*).

For off-street bicycle facilities, studies evaluated the bicyclists' perception of comfort by measuring the hindrances encountered by bicyclists during bicycling. Botma proposed a procedure for determining the bicycle LOS by measuring the number of passing and meeting events as a function of pedestrian and bicycle volume, path width and bicycle speeds (*19*). Hummer et al. developed LOS scales for shared-use paths (*20*). The number of events (including active passings, meetings and delayed passings), path width and presence of a centerline were identified as contributing factors. The Highway Capacity Manual (HCM 2010) recommended using the procedure in (*19*) for determining bicycle LOS on off-street facilities (*11*).

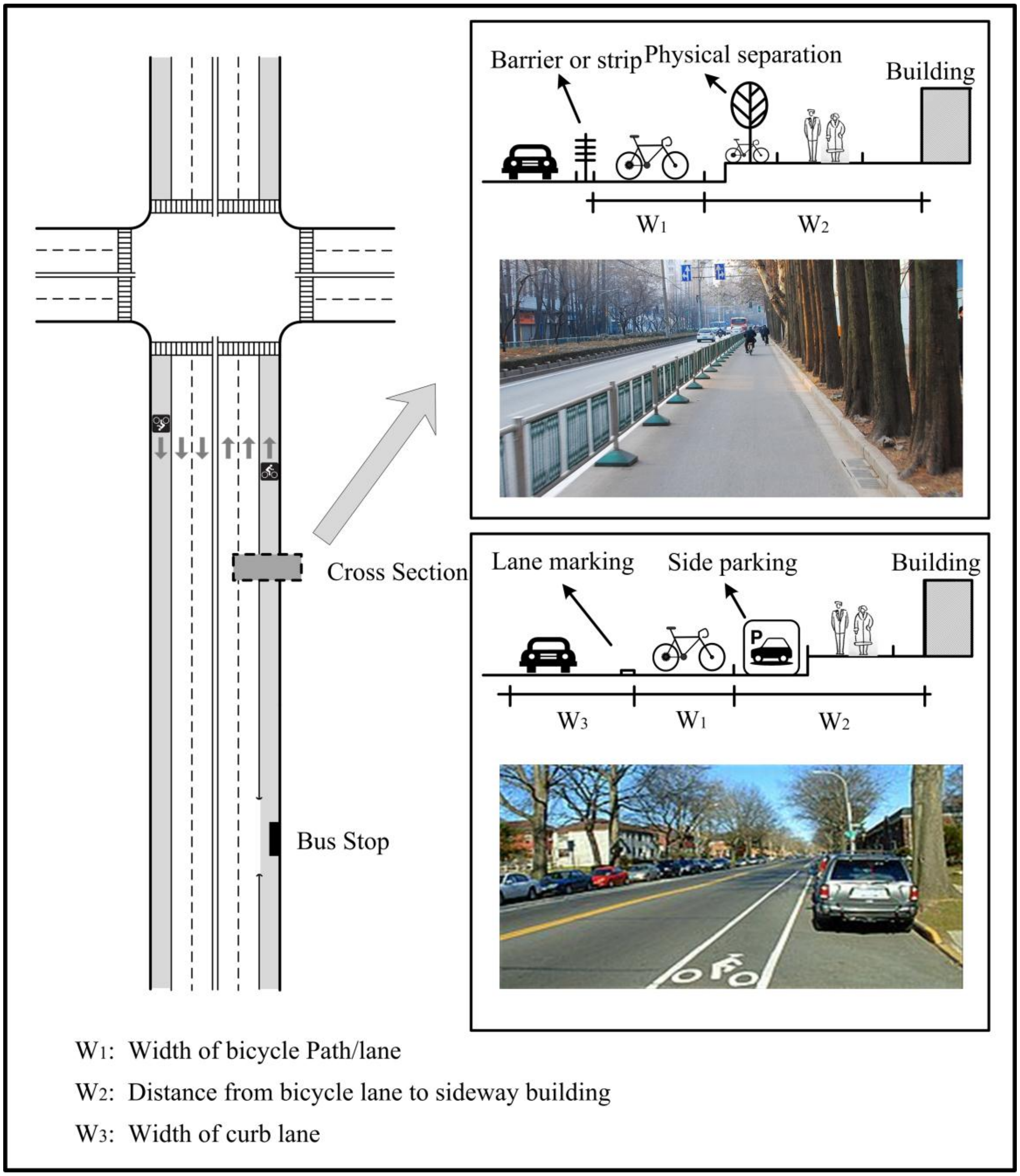

FIGURE 1 Typical layout of physically separated bicycle path and on-street bicycle lane.

In these studies, participants were asked to provide perceptions of riding comfort towards road segments. However, most of those studies were conducted on on-street bicycle facilities. The bicyclists' perception of comfort on physically separated bicycle paths when riding between motor vehicle and pedestrian traffic with the right-of-way has not been investigated. Moreover, previous studies did not compare the bicyclists' perception of comfort and the contributing factors between physically separated bicycle paths and on-street bicycle lanes.

A review of the literatures regarding bicycle LOS on bicycle facilities in China found a few studies. One used bicycle speed and density to evaluate bicycle LOS (*21*). High speed and low density of bicycle traffic were regarded as the most comfort bicycling condition. However, Shan et al. reported that mean bicycle speeds do not vary intensively with bicycle density under uncongested bicycle traffic (*22*). Other studies recommended using the number of bicycle passing events for evaluating LOS of bicycle traffic on urban streets in China (*7*, *23*). Li et al. further classified the passing events based on bicycle traffic and road conditions in China, and proposed a method to estimate the probability of each passing event (*24*). But these studies did not conduct field surveys on bicyclists' perception of comfort and quantitatively relate the bicycle LOS measurements to the perception of comfort.

This study investigates the physical environmental factors influencing bicyclists' perception of comfort on bicycle facilities, using survey techniques, combined with modeling to analyze the results. More specifically, this study includes the following tasks: (1) to quantify the impacts of contributing factors on the bicyclists' perception of comfort on physically separated bicycle paths and on-street bicycle lanes; and (2) to compare bicyclists' perception of comfort and their contributing factors between the two bicycle facilities.

DATA AND METHODS

Data Collection

Field surveys were designed to get bicyclists' perception of comfort and various explanatory variables including road geometric designs, environmental conditions and bicycle traffic factors. Surveys were conducted in the metropolitan area of Nanjing, China. Nanjing is one of the biggest cities in China by the year of 2010 with a population of 7.2 million and an area of 4,700 square kilometers. Our research team selected 29 segments of separated bicycle paths and 14 segments of on-street bicycle lanes. The total sites include 43 segments. These segments cover a wide range of path width and diverse environmental conditions.

Bicyclists' perception of comfort was investigated using a questionnaire method. In this study, the surveyors described comfort as whether bicyclists can ride easily and freely as they wish and how favorably they viewed bicycling on the target segment. A five-point scale from "it is terrible" to "it is excellent" was used for responders to describe their perceptions.

Surveys were conducted on two weekdays in June 2010. The time period covered morning peak period and non-peak period in order to get various bicycle traffic conditions. We selected fine weather days to exclude the impacts of severe weather on bicyclists' perception of comfort. During the survey, questionnaire investigators were placed at selected segments in the vicinity of intersection entrance areas, as shown in Figure 2. Bicyclists waiting for green signals were asked to give their perceptions towards the links that they had just passed by. Our investigators distributed the questionnaire to bicyclists near them. Since bicycle traffic are large on those sites, the probability that the same people participated in multiple survey points is quite small.

Bicycle and vehicle flow rate was investigated in the middle area of each link by keeping a sufficient distance from the upstream and downstream intersections, as Figure 2 shows. The impacts of intersection signals on traffic flow were excluded. During the investigation on bicycle traffic, the type of bicycle (electric bicycle or conventional bicycle) was recorded for the consideration that electric bicycles run much faster than conventional ones (*25*). The road geometrical and environmental conditions on selected sites were also recorded during the survey.

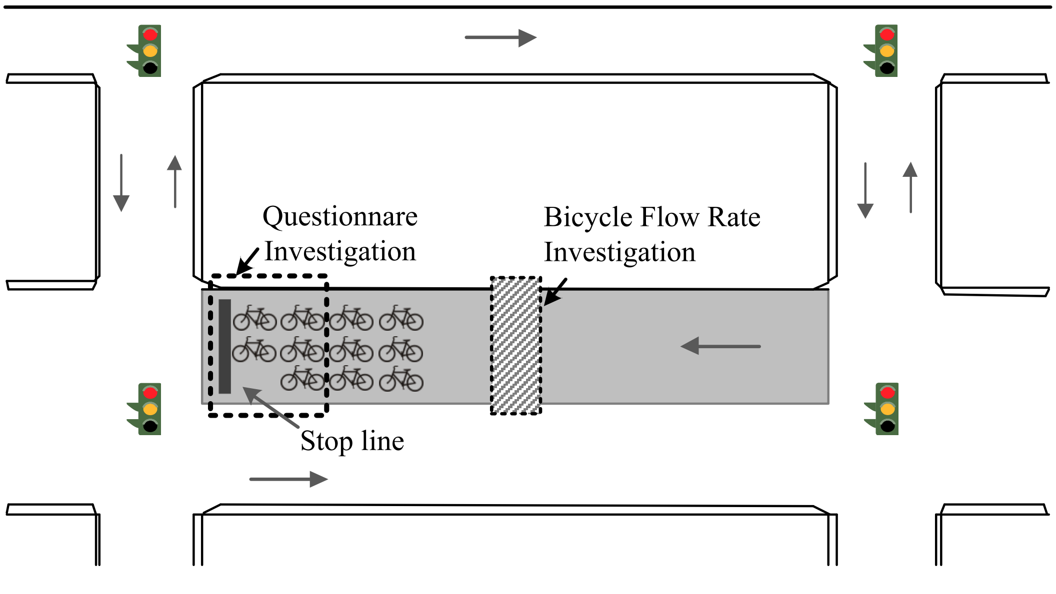

FIGURE 2 Description of field investigation on segments.

Statistical Methods

The dependent variable of this study, the perception of comfort, was defined as a typical ordinal variable that was scaled in to five levels (scores): 1-Terrible; 2-Poor; 3- Fair; 4-Good; and 5-Excellent. Ordinal regression models have been widely used for fitting the data structure of an ordinal response. The ordered probit (OP) model was used in this study to explore the relationships between perception of comfort and explanatory variables.

OP Model

The bicyclists' perception of comfort includes five ordinal levels. Assuming that **Y** represents the comfort level, then a latent variable $\mathbf{Y}^*$ is introduced as:

$$\mathbf{Y}^* = \mathbf{X\beta} + \boldsymbol{\varepsilon} \tag{1}$$

where **X** is the vector containing the full set values of explanatory variables, **β** is the vector of coefficients associated with explanatory variables, and **ε** is a random error term following the standard normal distribution. The value of the dependent variable **Y** is determined as (C.f. (*26*))::

$$Y = \begin{cases} 1 & if\ Y^* < \tau_1 \\ j & if\ \tau_{j-1} < Y^* < \tau_j \\ J & if\ \tau_{J-1} < Y^* \end{cases} \tag{2}$$

where J is the number of comfort levels (in this case, J=5), and τ_j is the threshold parameter (cut-off points) to be estimated for each level. From the above, it can be determined that the probabilities of **Y** taking on each of the values j=1, . . . , J are equal to:

$$\begin{aligned} P(Y=1) &= \Phi(\tau_1 - \mathbf{X\beta}) \\ P(Y=j) &= \Phi(\tau_j - \mathbf{X\beta}) - \Phi(\tau_{j-1} - \mathbf{X\beta}) \\ P(Y=J) &= 1 - \Phi(\tau_{J-1} - \mathbf{X\beta}) \end{aligned} \tag{3}$$

where $P(Y=j)$ is the probability of response variable taking a specific comfort level j, $\Phi(\cdot)$ is the standard normal cumulative distribution function, and the threshold parameter τ_j satisfies the restriction $\tau_1<\tau_2< \ldots<\tau_{J-1}$.

For the OP model, the values of **β** and ***τ*** can be determined by the Maximum Likelihood Estimate method (MLE). Then, the likelihood function, L, can be formulated as:

$$L = L(Y \mid \tau_1, \tau_2, \tau_3, \tau_4, \beta_0, \beta_1, \cdots, \beta_n) = \prod_{m=1}^{N}\prod_{j=1}^{J}\{\Phi(\tau_j - \beta' X_n) - \Phi(\tau_{j-1} - \beta' X_n)\}^{Y,n+5} \quad (4)$$

$$\ln L = \sum_{m=1}^{N}\sum_{j=1}^{J} Y \cdot \ln(\Phi(\tau_j - \beta' X_n) - \Phi(\tau_{j-1} - \beta' X_n)) \quad (5)$$

By maximizing the log-likelihood function, ln$L$, the coefficient of each variable and threshold parameters can be estimated. Since the full estimation procedure is outside of our research scope, details are not described in this paper.

In the OP model, the coefficient associated with each explanatory variable indicates the positive or negative impact of the variable on perception of comfort. These coefficients do not quantify these impacts of variables, and cannot be intuitively interpreted, especially for intermediate comfort levels. The marginal effect of each variable was calculated in the OP model to quantitatively get the impact on each category of outcome. The marginal coefficient of a variable illustrates the change of probability of each comfort level caused by one unit increase in the input variable, while keeping other variables at their mean value.

For continuous explanatory variables, the marginal effect of a variable i for comfort level j, $\Delta P(Y=j \mid x_i)$, is given by:

$$\Delta P(Y = j \mid x_i) = P(Y = j) / \partial x_i = [\Phi(\tau_{j-1} - \mathbf{\beta X}) - \Phi(\tau_j - \mathbf{\beta X})]\beta_i \quad (6)$$

For binary (dummy) variables, the marginal effect of a variable i for comfort level j is computed by comparing the outcome when the variable takes value ‘one’ with that when the variable takes value ‘zero’, while all other variables remain constant, which is:

$$\Delta(Y = j \mid x_i) = P(Y = j \mid x_i = 1) - P(Y = j \mid x_i = 0) \quad (7)$$

DATA ANALYSIS RESULTS

Data Description

A total of 1,177 respondents participated in the questionnaire survey and reported their perception of comfort toward the actual traffic and roadway conditions. Several samples did not complete the survey due to the limitations of the traffic signal cycle, and were excluded from the database. Successive research was carried out based on 1,074 effective answers including 730 samples on physically separated paths and 344 on on-street lanes. The mean value of perceived comfort for the separated path group is 2.85 while for the on-street lane group is 2.62. The descriptions of bicyclists’ perception of comfort are shown in Table 1.

Road geometric designs, environmental variables and traffic conditions were measured in the field during the survey. The summarized descriptions for explanatory variables are given in Table 2. The width of physically separated bicycle paths ranges from 1.9m to 5.5m, and the width of on-street bicycle lanes ranges from 1.1m to 2.5m. During the survey period, the mean bicycle flow rate on separated paths was 1,200 bicycles/h, while the mean bicycle flow rate on on-street lanes was 870 bicycles/h.

TABLE 1 Summarized Comfort Perceptions of Respondents

Level	Score	Description	Separated Path		On-street Lane	
			Frequency	Percent %	Frequency	Percent %
Level 1	1	Terrible	71	9.72	40	11.63
Level 2	2	Bad	184	25.21	115	33.43
Level 3	3	Fair	289	39.59	133	38.66
Level 4	4	Good	153	20.96	45	13.08
Level 5	5	Excellent	33	4.52	11	3.20
Total sample			730		344	
Mean comfort score			2.85		2.62	
Standard deviation of score			1.05		0.98	

Comfort Comparison between Facilities

Our research team compared bicyclists' perception of comfort between physically separated bicycle paths and on-street bicycle lanes. Table 1 shows that the comfort level 3 (fair) is the most common selection for bicyclists, while the comfort level 5 (excellent) is the least selection. The proportions of comfort level 5 (excellent) and level 4 (good) on separated bicycle paths are higher than that of on-street bicycle lanes. More bicyclists choose the comfort level 1 (terrible) and level 2 (bad) on on-street lanes than on separated paths.

On average, bicyclists felt more comfortable when riding on physically separated bicycle paths than on-street bicycle lanes. As compared to on-street lanes, more bicyclists on separated paths reported an excellent comfort (level 5) and a good comfort (level 4), while less bicyclists selected the terrible (level 1) and bad (level 2) option. The mean comfort score for separated path group, which is 2.85, is also higher than that for on-street lane group, which is 2.62. The *t*-test was conducted to compare if the difference of mean comfort score between the two bicycle facilities was statistically significant. The *t*-test result showed that with a 95% level of confidence, the difference between separated path group and on-street lane group is statistically significant. The results suggested that bicyclists perceived a significant higher average comfort on physically separated bicycle paths as compared to on-street bicycle lanes.

OP Model Estimates

Two OP models were separately proposed for physically separated bicycle paths and on-street bicycle lanes to identify the impacts of explanatory variables on bicyclists' perception of comfort. All explanatory variables were initially considered in the models. Variables not significantly related to the outcome were excluded from the model specification step by step. The contributing factors were kept in the model specification. The variable selection processes were repeated to carefully determine the contributing factors in the final model. The estimation results of the two OP models are shown in Table 3.

TABLE 2 Descriptions of Explanatory Variables for Model Development

Variable	Description	Separated Path			On-street Lane		
		Mean	Std.	Frequency	Mean	Std.	Frequency
Road geometric design							
Length	Length of target bicycle path (km)	0.35	0.22	730	0.30	0.11	344
Width	Width of bicycle path (m)	3.17	0.92	730	1.71	0.44	344
CurbWidth	Width of curb lane (m)	/	/	/	3.61	0.42	344
Grade	1 (presence of up slope)	0.10	0.29	70 (9.6%)	0.38	0.49	131 (38.1%)
	0 (Horizontal)			660 (90.4%)			213 (61.9%)
SepaType	1 (Separated from vehicle by strip)	0.60	0.49	435 (59.5%)	/	/	/
	0 (Separated from vehicle by barrier)			295 (40.5%)	/	/	/
SepaPede	1 (Physically separated from pedestrian)	0.15	0.36	108 (14.8%)	/	/	/
	0 (No physical separation)			622 (85.2%)	/	/	/
Environmental condition							
BuilDist	Distance from bicycle to side building (m)	5.49	4.28	730	4.00	2.69	344
BusStop	1 (Presence of bus station)	0.41	0.49	300 (41.1%)	0.27	0.44	93 (27.0%)
	0 (No bus station)			430 (58.9%)			251 (73.0%)
ParkOccu1	1 (Parking occupancy over 50 percent)	/	/	/	0.47	0.50	162 (47.1%)
ParkOccu2	1 (Parking occupancy less than 50 percent)	/	/	/	0.39	0.49	135 (39.2%)
	0 (No side parking)	/	/	/			47 (13.7%)
LandResi	1 (Residential land type)	0.08	0.26	55 (7.6%)	/	/	/
LandComm	1 (Commercial land type)	0.53	0.50	388 (53.2%)	0.60	0.49	207 (60.2%)
LandOffi	1 (Official land type)	0.23	0.42	170 (23.3%)	0.27	0.44	92 (26.7%)
	0 (Green area or enclosing wall)			117 (16.0%)			45 (13.1%)
Traffic condition							
BicyFlow	Bicycle flow rate (thousand bicycles/h)	1.20	0.39	730	0.87	0.77	344
EbikRate	Proportion of electric bicycle	0.54	0.20	730	0.57	0.12	344
VehiFlow	Vehicle flow rate (hundred vehicles/h)	/	/	/	1.34	1.56	344

TABLE 3 Estimation Results of Two OP Models

Variables	Separated Path				On-street Lane			
	Estimate	SE	Wald	Sig.	Estimate	SE	Wald	Sig.
Grade	-0.538	0.155	12.106	0.001	-0.486	0.157	9.538	0.002
SepPede	0.294	0.129	5.167	0.023	/	/	/	/
Width	0.231	0.047	23.675	<0.001	1.490	0.219	46.180	<0.001
CurbWidth	/[*]	/	/	/	1.528	0.199	58.774	0.016
BusStop	-0.181	0.091	3.950	0.047	1.265	0.212	35.759	0.020
ParkOccu2	/	/	/	/	0.415	0.179	5.365	0.021
LandResi	-1.409	0.195	52.033	<0.001	/	/	/	/
LandComm	-0.242	0.130	3.462	0.063	-	-	-	-
LandOffi	-0.246	0.131	3.521	0.061	-	-	-	-
BicyFlow	-0.688	0.108	40.227	<0.001	-0.952	0.141	46.297	<0.001
EbikRate	-[**]	-	-	-	-1.918	0.605	10.046	0.002
VehiFlow	/	/	/	/	-0.137	0.053	6.603	0.010
Thresholdτ_1	-2.060	0.258	63.690	<0.001	4.633	0.862	28.911	<0.001
Thresholdτ_2	-1.006	0.250	16.204	<0.001	5.953	0.875	46.333	<0.001
Thresholdτ_3	0.150	0.248	0.366	0.545	7.277	0.895	66.166	<0.001
Thresholdτ_4	1.278	0.258	24.621	<0.001	8.081	0.911	78.723	<0.001
Summary statistics:								
L(c)			-716.749			-374.259		
L(β)			-640.297			-316.678		
$-2(\mathrm{L}(c) - \mathrm{L}(\beta))$			152.904			115.161		
P-value			P<0.001			P<0.001		

[*] “/” indicates that this variable was not observed in the survey;
[**] “-” indicates that this variable was not significant at the 90% confidence level

For separated bicycle paths, nine variables were identified as significantly related to bicyclists’ riding comfort in the OP model. These variables include the presence of grade, physical separation from pedestrian, width of path, presence of bus station, residential, commercial and office land uses, and bicycle flow rate. For on-street bicycle lanes, the contributing factors to bicyclists’ perception of comfort include the presence of grade, width of bicycle lane, width of curb lane, presence of bus station, side parking with occupancy less than 50%, bicycle flow rate, electric bicycle rate, and motor vehicle flow rate.

The marginal effects of contributing factors on each comfort level were estimated in the OP models, to quantitatively show their impacts. The estimation results are given in Table 4. A positive marginal coefficient of a variable for a particular comfort level means that the proportion of this comfort level will increase as one unite increase of the input variable. For example, one meter increase of width of separated bicycle path could decrease the proportions of ‘terrible’ and ‘bad’ perceptions (level 1 and level 2) by 3.1% and 5.3%, while increase the proportions of comfort level 3, level 4 and level 5 by 1.5%, 5.4% and 1.6% respectively. Since the quantitative impact of each contributing factor on each comfort level can be found in Table 4, the interpretation of each marginal coefficient is not presented here.

TABLE 4 Marginal Effects of the Ordered Probit Models

Variable	Level 1		Level 2		Level 3		Level 4		Level 5		X
	dy/dx	SE	dy/dx	SE	dy/dx	SE	dy/dx	SE	dy/dx	SE	
Physically Separated Bicycle Path											
Grade*	0.099	0.037	0.109	0.026	-0.073	0.031	-0.110	0.027	-0.025	0.006	0.096
SepPede*	-0.034	0.013	-0.068	0.030	0.007	0.005	0.070	0.032	0.025	0.013	0.148
Width	-0.031	0.007	-0.053	0.012	0.015	0.005	0.054	0.012	0.016	0.004	3.167
BusStop*	0.025	0.013	0.041	0.021	-0.013	0.008	-0.042	0.021	-0.012	0.006	0.411
LandResi*	0.377	0.073	0.134	0.027	-0.270	0.044	-0.203	0.018	-0.038	0.007	0.075
LandComm*	0.033	0.018	0.055	0.030	-0.015	0.008	-0.056	0.030	-0.017	0.010	0.532
LandOffi*	0.037	0.022	0.055	0.029	-0.022	0.015	-0.056	0.029	-0.015	0.008	0.233
BicyFlow	0.094	0.017	0.158	0.028	-0.044	0.013	-0.160	0.027	-0.048	0.010	1.204
On-street Bicycle Lane											
Grade*	0.074	0.028	0.118	0.037	-0.102	0.036	-0.065	0.022	-0.024	0.009	0.381
Width	-0.207	0.039	-0.382	0.069	0.297	0.060	0.211	0.040	0.081	0.023	1.711
CurbWidth	-0.212	0.037	-0.392	0.066	0.304	0.058	0.216	0.039	0.083	0.023	3.611
BusStop*	-0.125	0.023	-0.313	0.050	0.106	0.030	0.199	0.039	0.132	0.043	0.270
ParkOccu2*	-0.054	0.023	-0.107	0.048	0.076	0.032	0.061	0.028	0.025	0.014	0.392
BicyFlow	0.013	0.003	0.024	0.004	-0.019	0.004	-0.014	0.003	-0.005	0.001	8.727
EbikRate	0.266	0.090	0.492	0.164	-0.382	0.132	-0.272	0.092	-0.105	0.041	0.567
VehiFlow	0.019	0.008	0.035	0.014	-0.027	0.011	-0.019	0.008	-0.007	0.004	1.342

* *dy*/*dx* is for discrete change of dummy variable from 0 to 1

DISCUSSION

The physical environmental characteristics influencing bicyclists' perception of comfort on physically separated bicycle paths and on-street bicycle lanes were investigated in this study. Bicyclists' perception of comfort in this study was similar to previous indexes for bicycle LOS evaluation such as *BLOS* or *BCI*. This study made an effort to investigate bicyclists' preferences towards the riding environment. Based on the survey data in China, the contributing factors to bicyclists' perception of comfort were identified in the OP model for each facility type.

For several variables, their impacts on bicyclists' riding comfort are quite similar for separated bicycle paths and on-street bicycle lanes. This study shows that the presence of incline is negatively associated with bicyclists' perception of comfort on the two bicycle facilities. The interpretation is straightforward since incline consumes more physical energy of bicyclists. The presence of incline was not considered as a contributing factor for bicycle LOS evaluation in previous studies (*11*, *15*, *16*). The findings of this study suggest that the presence of incline should be considered when evaluating the LOS of bicycle facilities.

The width of bicycle path/lane is positively related to bicyclists' perception of comfort. This result is quite intuitive since wider path/lane provides more potential space for bicycling. The curb lane width is positively related to riding comfort on on-street bicycle lanes because the curb lane also provides space for bicycling. These findings are consistent with previous studies for bicycle LOS evaluation on on-street bicycle facilities (*11*, *15*, *16*), off-street bicycle facilities (*11*), and shared-use bicycle facilities (*20*).

The bicycle flow rate is found to be negatively related to bicyclists' perception of comfort on the two bicycle facilities. This finding is reasonable because the bicycle flow rate is quite large on urban streets in China. Bicyclists do not like to ride in heavy amounts of bicycle traffic because high bicycle flow rate increases disturbances among bicycles (*11*, *24*). The bicycle flow rate was not considered as a contributing factor for bicycle LOS evaluation of on-street bicycle facilities in previous studies (*11*, *15*, *16*). The possible reason would be that there are not many bicycle traffic on that kind of bicycle facility. The finding of this study suggests that the bicycle flow rate may be considered when evaluating bicycle LOS for on-street bicycle facilities, if bicycle traffic becomes large. The data also show that high level of motor vehicle traffic decreases the bicyclists' riding comfort on on-street bicycle lanes. This finding is intuitive because collision risk rises as motor vehicle traffic increases. Consistent findings were also found in previous studies (*11*, *15*, *16*).

For some variables, their impacts on riding comfort show some differences between separated bicycle paths and on-street bicycle lanes. For separated path group, the presence of bus station is shown to have a negative impact on riding comfort. The arrival of the bus would block bicycle traffic and make bicyclists feel uncomfortable. On the contrary, the presence of bus station is estimated in OP model to increase the riding comfort on on-street bicycle lanes which is counter-intuitive. One possible reason would be that the presence of a bus station provides some space for bicycling since there are no parking vehicles in vicinity of a bus station. Bicyclists may not like riding on vehicle lanes, but the bicycle lane cannot accommodate large volumes of bicycle traffic. Thus, the potential riding space of bus station increases the bicyclists' perception of comfort. That would also explain the estimate that bicyclists perceive more comfort when side parking occupancy is less than 50% on on-street facilities.

The survey data in this study shows that residential, commercial and office land use around physically separated bicycle pathways decrease the bicyclists' perception of comfort. In China, there are many human activities at residential, commercial and office areas that may make bicyclists feel tense or nervous during the trip, or even disturb bicyclists' riding. Thus, the result that physical separation from pedestrians increased bicyclists' comfort is reasonable. But the surrounding land use variables are found to be insignificant factors in the OP model for on-street bicycle lanes. It suggests that bicyclists may not pay much attention to surroundings when riding on on-street bicycle lanes with large volumes of bicycle traffic and motor vehicles. Moreover, the rate of use of electric bicycles show to impact bicyclists' comfort when riding on on-street bicycle lanes, but not on physically separated bicycle paths.

The data analysis results show that the contributing factors to bicyclists' perception of comfort are different between physically separated bicycle paths and on-street bicycle lanes. For separated paths, most of factors influencing bicyclists' riding comfort are the physical surrounding conditions. It may suggest that bicyclists care about the enjoyment and smoothness of the trip. They do not want to be disturbed by grade, bus stations, pedestrians and other bicyclists, and prefer enjoyable and quiet surroundings. For on-street bicycle lanes, most of contributing factors are associated with riding space and traffic conditions. The variables that may potentially provide more riding space (lane width, curb lane width, presence of bus station, and low occupied side parking) are found to be positively related with riding comfort. Higher bicycle traffic and vehicle traffic, as well as more fast travelling bicycles (which indicates a higher rate of electric bicycle) are reported to decrease bicyclists' perception of comfort. It may suggest that bicyclists pay much attention to avoiding potential collisions with other road users and want more bicycling space when riding in the street.

The findings of this study may provide useful information for understanding how characteristics of the physical environment influence bicyclists' perception of comfort on physically separated bicycle paths and on-street bicycle lanes. These findings can help design a comfortable riding environment for bicycling. Based on the coefficient estimates of OP models, the model specifications calibrated in this study can also be used to predict bicyclists' perception of comfort on bicycle facilities including both separated pathways and on-street lanes. Those comfort estimates can be used to develop the LOS criteria for bicycle facilities and evaluate the service level of existing facilities.

By comparing the bicyclists' perception of comfort and the contributing factors of the two bicycle facilities, the results may help transportation engineers determine facility types according to the actual surroundings and traffic conditions. In this study, the results shows that bicyclists' perception of comfort on on-street bicycle lanes are more severely impacted by traffic conditions including bicycle flow rates and motor vehicle flow rates. The reason would be that the lack of physical separation between bicycles and vehicles makes bicyclists feel unsafe when traveling in large traffic. Thus, the separated facility type is recommended for large bicycle and vehicle traffic, to improve the comfort perception of bicycle travelers during their traveling on roads. Furthermore, we developed two models separately for separated paths and on-street lanes. We can estimate the comfort perception level of the two facility types according to the current environment and traffic conditions and select the facility type with a higher comfort level.

There are several limitations in the present study. The survey was conducted only on 43 segments of bicycle facilities in one Chinese city. Similar studies should be done in other cities in China and other parts of the world. It might be important to include other factors in the analysis in the future, such as crime safety (*27*), path maintenance (*11*, *28*), width of separation from motor vehicle (for separated bicycle paths), auto traffic volume and speed(for separated bicycle paths), and pedestrian volume. These factors may potentially be related to bicyclists' perception of comfort. Furthermore, other bicycle facility types such as shared-use paths could be investigated and the results could be compared to this study. The authors recommend that future studies could focus on these issues.

ACKNOWLEDGMENTS

This research is supported by the key project of the National Natural Science Foundation of China (No. 50738001). The authors would like to thank the senior students from Transportation School of Southeast University for their assistance in field data collection and data reduction.

REFERENCES

1. Xing, Y., S.L. Handy, and P.L. Mokhtarian. Factors associated with proportions and miles of bicycling for transportation and recreation in six small US cities. *Transportation Research Part D*, Vol. 15, No. 2, 2010, pp. 73-81.
2. Pucher, J., and R. Buehler. Analysis of Bicycling Trends and Policies in Large North American Cities: Lessons for New York. University transportation research center, Finial report, 2011.
3. Su, J.G., M. Winters, M. Nunes, and M. Brauer. Designing a route planner to facilitate and promote cycling in Metro Vancouver, Canada. *Transportation Research Part A*, Vol. 44, No. 7, 2010, pp. 495-505.
4. Martens, K. The bicycle as a feedering mode: experiences from three European countries. *Transportation Research Part D*, Vol. 9, No. 4, 2004, pp. 281-294.
5. Pucher, J. and R. Buehler, Making cycling irresistible: Lessons from the Netherlands, Denmark and Germany. *Transport Reviews,* Vol. 28, No. 4, 2008, pp. 495-528.
6. Meeusen, R., B. de Geus, I. De Bourdeaudhuij, and C. Jannes. Psychosocial and environmental factors associated with cycling for transport among a working population. *Health Education Research*, Vol. 23, No. 4, 2008, pp. 697-708.
7. Shan, X. A Research on Urban Bicycle Transportation Rational Ridership and Road Resource Allocation. Doctoral dissertation, Southeast University: Nanjing, China, 2007.
8. Chen, X.H., W. Xiong, Z.Y. Huang, and H. Yang. Planning Bicycle Corridor for Shanghai Central City. Presented at 86rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2007.
9. Yang, C., W. Wang, X. Shan, J. Jin, J. Lu, and Z. Li. The Effects of Personal Factors on Bicycle Commuting in Developing Countries: A Case Study of Nanjing, China. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2193, TRB, National Research Council, Washington, D.C., 2010, pp. 96-104.
10. American Association of State Highway and Transportation Officials. Guide for the development of bicycle facilities. Washington, DC: AASHTO, 1999.
11. Highway Capacity Manual. Transportation Research Board, N.C., Washington D.C., 2010.
12. Wardman, M., M. Tight, and M. Page. Factors influencing the propensity to cycle to work. *Transportation Research Part A,* Vol. 41, No. 4, 2007, pp. 339-350.
13. Winters, M. and K. Teschke. Route Preferences Among Adults in the Near Market for Bicycling: Findings of the Cycling in Cities Study. *American Journal of Health Promotion*, Vol. 25, No. 1, 2010, pp. 40-47.
14. Lusk, A. C., P.G. Furth, P. Morency, L.F. Miranda-Moreno, W.C. Willett, and J.T. Dennerlein. Risk of injury for bicycling on cycle tracks versus in the street. *Injury Prevention*, Vol. 17, No. 2, 2011, pp. 131-135.

15. Landis, B.W., V. R. Vattikuti, and M. T. Brannick. Real-Time Human Perceptions: Toward a Bicycle Level of Service. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1578, Transportation Research Board of the National Academies, Washington, D.C., 1997, pp. 119-126.

16. Harkey, D., D. Reinfurt, A. Sorton, M. Knuiman, and J. Stewart. The Bicycle Compatibility Index: A Level-of-Service Concept, Report No. FHWA-RD-98-095, FHWA, McLean, VA, 1998.

17. Sorton, A., and W. Thomas. Bicycle Stress Level as a Tool to Evaluate Urban and Suburban Bicycle Compatibility. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1438, Transportation Research Board of the National Academies, Washington, D.C., 1994, pp. 17–24.

18. Epperson, B., 1994. Evaluating Suitability of Roadways for Bicycle Use: Toward a Cycling Level-of-Service Standard. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1438, Transportation Research Board of the National Academies, Washington, D.C., 1994, pp. 9–16.

19. Botma, H., 1995. Method to Determine Level of Service for Bicycle Paths and Pedestrian-Bicycle Paths. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1502, Transportation Research Board of the National Academies, Washington, D.C., 1995, pp. 38–44.

20. Hummer, J. E., N. M. Rouphail, J. L. Toole, R. S. Patten, R. J. Schneider, J. S. Green, R. G. Hughes, and S. J. Fain. Evaluation of Saftey, Design, and Operation of Shared-Use Paths - Final Report. U.S. Department of Transportation, 2006.

21. Li, F. The capacity and level of service of bicycle traffic on bicycle facility in China. *China Municipal Engineering*, Vol. 3, 1995, pp.11-14.

22. Shan, X., W. Wang, H. Wang, and S. Xu. Properties of Bicycle Flow in Non-congested Road. *Computer and Communications*, Vol. 24, No. 6, 2006, pp. 41-43.

23. Chen, J., and Z. Xie. Cycle traffic conflict model on urban pedestrian-bicycle paths. Journal of Jilin University, Vol. 39, No. 2, 2009, pp. 121-125.

24. Li, Z., W. Wang, X. Shan, J. Jin, J. Lu, and C. Yang. Analysis of Bicycle Passing Events for LOS Evaluation on Physically Separated Bicycle Roadways in China. Presented at 89rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.

25. Lin, S., M. He, Y. Tan, and M. He. Comparison Study on Operating Speeds of Electric Bicycles and Bicycles: Experience from Field Investigation in Kunming, China. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2048, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 52-59.

26. Washington, S., M. Karlaftis, and F. Mannering. Statistical and Econometric Methods for Transportation Data Analysis. Chapman & Hall/CRC, Boca Raton, FL, 2003.

27. Cerin, E., B.E. Saelens, J.F. Sallis, and L.D. Frank. Neighborhood environment walkability scale: Validity and development of a short form. *Medicine and Science in Sports and Exercise*, Vol. 38, No. 9, 2006, pp. 1682-1691.
28. Pikora, T., B. Giles-Corti, F. Bull, K. Jamrozik, and R. Donovan. Developing a framework for assessment of the environmental determinants of walking and cycling. *Social Science & Medicine*, Vol. 56, No. 8, 2003, pp. 1693-1703.