Transportation Research Part D 17 (2012) 256–261

Contents lists available at SciVerse ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Physical environments influencing bicyclists' perception of comfort on separated and on-street bicycle facilities

Zhibin Li [a,*], Wei Wang [b], Pan Liu [b], David R. Ragland [c]

[a] School of Transportation, Southeast University and Safe Transportation Research & Education Center, Institute of Transportation Studies, University of California, Berkeley, 2614 Dwight Way #7374, Berkeley, CA 94720-7374, USA
[b] School of Transportation, Southeast University, Si Pai Lou #2, Nanjing 210096, China
[c] Safe Transportation Research & Education Center, Institute of Transportation Studies, University of California, Berkeley, 2614 Dwight Way #7374, Berkeley, CA 94720-7374, USA

ARTICLE INFO

Keywords:
Physical environment
Influences on bicycling
Cycling comfort
Separated bicycle paths
On-street cycle lanes

ABSTRACT

This study investigates the impacts of physical environments on bicyclists' perceptions of comfort on separated and on-street bicycle facilities. Based on a field investigation conducted in Nanjing, China, we find that physical environmental factors significantly influencing bicyclists' perception of comfort on the two types of facility. Cyclists' comfort is mainly influenced by the road geometry and surrounding conditions on physically separated paths while they pay attention to the effective riding space and traffic situations on on-street bicycle lanes.

1. Introduction

Bicycling has become widely recognized as an environmentally friendly mode of transport. Bicycles occupy less road space and produce fewer emissions as compared to motorized transport modes, and thus their use in urban areas is generally seen as beneficial to environment and air quality in cities. Bicycle facilities were designed to increase the use of bicycle for both recreational and commuting travel.

Previous work has largely evaluated the relationships between physical environments and cycling "comfort"[1] by measuring the level of service (LOS) of bicycle facilities. Several indexes, such as bicycle level of service (BLOS), have been developed to evaluate the compatibility of on-street bicycle facilities for cycling (Landis et al., 1997; Harkey et al., 1998). For example, the *2010 Highway Capacity Manual* recommended using the width of outside through lane, proportion of parking occupied, mid-segment vehicle volume, number of through lanes, vehicle running speed, percentage of heavy vehicles, and pavement condition rating to evaluate the bicycle LOS for urban streets. Highway Capacity Manual, 2010.

Some studies used the hindrances encountered during traveling to evaluate bicyclists' comfort. Botma (1995) measuring the number of passings and meetings as functions of pedestrian and bicycle volume, bicycle speeds and path width to develop bicycle LOS in Netherlands. Hummer et al. (2006) developed the LOS scales for shared-use paths in United States by measuring the number of passing events, path width, and presence of centerline. Most has been conducted for on-street bicycle facilities and shared-use bicycle paths. In China, two types of bicycle facility, the physically separated bicycle paths and on-street bicycle lanes, are commonly adopted in urban areas. On separated facilities, bicycles are physically separated from motor vehicles by barriers and operate between vehicle and pedestrian traffic with the right-of-way. In contrast on-street

* Corresponding author.
E-mail address: lizhibin@seu.edu.cn (Z. Li).

[1] We use the word "comfort" as a generic term reflecting level of satisfaction a cyclist gets from using a facility.

1361-9209/$ - see front matter
doi:10.1016/j.trd.2011.12.001

facilities involve bicycles traveling in the same road cross-section with motor vehicles but separated by lane markings. Winters and Teschke (2010), Lusk et al. (2011) and others have found that separated bicycle roadways can encourage bicycling and reduce accidents compared to on-street bicycle facilities, but they did not investigate cycling comfort on different facilities.

2. Data and methods

Data were collected from filed studies in the metropolitan area of Nanjing, one of the biggest cities in China, to obtain bicyclists' perception of comfort and various physical environmental conditions. Twenty-nine segments of separated facilities and 14 of on-street bicycle facilities covering a wide range of path width and diverse environmental condition were used. A questionnaire was designed to provide an identical description of "comfort" with the cycling comfort being treated in terms of bicyclists can ride as easily and freely as they wish. A five-point scale from "it is terrible" to "it is excellent" was used to describe their perceptions.

Investigations were carried out on fine-weather weekdays including morning peak and non-peak periods to allow for various traffic conditions. Interviewers were placed in the vicinity of intersection entrances at selected segments. Cyclists waiting for green signals were asked to give their perceptions towards the links that they had just used. Assuming the arrival of bicycle follows a random process, the sampling of respondents was taken as random.

One thousand one hundred and seventy-seven people participated in the survey, although several did not complete the questionnaire and were excluded from the database providing a usable sample of 1074; 730 in the separated facility group and 344 in the on-street facility group. Traffic information was collected in middle of each section. The bicycle type (i.e., electric or conventional bicycle) was recorded because electric bicycles run faster than conventional ones they may impact on cyclists' comfort. Road geometry and environmental surroundings on selected sites were also investigated. The explanatory variables are outlined in Table 1.

The dependent variable, the perception of comfort, is defined as a typical ordinal variable scaled form 1-terrible to 5-excellent. An ordered probit (OP) model is used to explore the relationships between perception of comfort and environmental variables. A latent variable Y representing the comfort value is introduced as:

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

where $\mathbf{X}$ is a vector of explanatory variables, $\boldsymbol{\beta}$ a vector of coefficients, and $\boldsymbol{\epsilon}$ a normally distributed random error term. The probability of dependent variable Y taking on each of the comfort values, $j = 1,\ldots,J$ is:

Table 1
Variables used for model development.

Variable	Description	Separated path group			On-street lane group		
		Mean	Std.	Frequency	Mean	Std.	Frequency
Response variable							
Comfort	Bicyclists' perception of comfort	2.85	1.05	730	2.62	0.98	344
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	0.38	0.49	131
	0 (Horizontal)			660			213
SepaType	1 (Separated from vehicle by strip)	0.60	0.49	435	/	/	/
	0 (Separated from vehicle by barrier)			295	/	/	/
SepaPede	1 (Physically separated from pedestrian)	0.15	0.36	108	/	/	/
	0 (No physical separation)			622	/	/	/
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	0.27	0.44	93
	0 (No bus station)			430			251
ParkOccu1	1 (Parking occupancy over 50%)	/	/	/	0.47	0.50	162
ParkOccu2	1 (Parking occupancy less than 50%)	/	/	/	0.39	0.49	135
	0 (No side parking)	/	/	/			47
LandResi	1 (Residential land type)	0.08	0.26	55	/	/	/
LandComm	1 (Commercial land type)	0.53	0.50	388	0.60	0.49	207
LandOffi	1 (Official land type)	0.23	0.42	170	0.27	0.44	92
	0 (Green area or enclosing wall)			117			45
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

$$
\begin{aligned}
&P(Y=1) = \Phi(\tau_1 - \mathbf{X\beta}) \\
&P(Y=j) = \Phi(\tau_j - \mathbf{X\beta}) - \Phi(\tau_{j-1} - \mathbf{X\beta}) \\
&P(Y=J) = 1 - \Phi(\tau_{J-1} - \mathbf{X\beta})
\end{aligned}
\tag{2}
$$

where $P(Y = j)$ is the probability of comfort taking a specific level j, J the number of levels (in this case, $J = 5$), $\Phi(\cdot)$ the standard normal cumulative distribution function, and τ_j is the threshold parameter (cut-off points) to be estimated for each level.

In the ordered probit model, the coefficient associated with each explanatory variable indicates the impact of the variable on the comfort value. They do not quantify the impacts of variables, and cannot be intuitively interpreted, especially for intermediate comfort levels. The marginal effect is calculated for each variable to quantify its impact on each comfort level.

For a continuous variable, the marginal coefficient illustrates the change of probability of a comfort level by one unit increase in the variable, while keeping other variables at mean values. For a dummy variable, the marginal effect for a comfort level is computed by comparing the outcome when the variable takes value 'one' with it when the variable takes value 'zero', keeping all other variables at their means.

3. Analysis

Two ordered probit models are estimated separately for the two facilities. All candidate variables are initially considered, but then in significant variables are excluded step by step. The variable selection processes were repeated to determine the contributing factors in the final model (Table 2).

In the separated facility group, nine variables are identified as significantly related to bicyclists' cycling comfort, including the presence of slope, physical separation from pedestrian, path width, presence of bus stop, residential, commercial and office land uses, and bicycle flow rate. In the on-street facility group, the contributing factors include the presence of slope, width of bicycle lane, width of curb lane, presence of bus stop, side parking with occupancy less than 50%, bicycle flow rate, electric bicycle rate, and motor vehicle flow rate.

Marginal effects of contributing factors are estimated in the OP models (Table 3). A positive marginal coefficient indicates the increase of probability of a comfort level for a one unit increase in an input variable, e.g., a meter increase in separated path width could decrease the probability of levels 1 and 2 by 3.1% and 5.3%, while increasing the probabilities of levels 3–5 by 1.5%, 5.4% and 1.6%.

When comparing the cycling comfort of the separated and of on-street facility groups, Fig. 1, the proportions of "excellent" and "good" perceptions of comfort in the separated facility group are higher than for the on-street group. More cyclists complained of "terrible" or "bad" conditions when cycling on on-street bicycle lanes than on separated paths.

Responses are classified into light and heavy traffic conditions on each facility and three measurements used to compare the perceptions of cyclist's comfort between the facilities; these measures beings; the mean comfort value, comfort with

Table 2
Results of the two OP models.

Variable	Coefficient estimate	
	Separated path group	On-street lane group
Grade	−0.538***	−0.486***
SepPede	0.294**	/
Width	0.231***	1.490***
CurbWidth	/[a]	1.528**
BusStop	−0.181**	1.265**
ParkOccu2	/	0.415**
LandResi	−1.409***	/
LandComm	−0.242*	
LandOffi	−0.246*	
BicyFlow	−0.688***	−0.952***
EbikRate		−1.918***
VehiFlow	/	−0.137***
Threshold τ_1	−2.060***	4.633***
Threshold τ_2	−1.006***	5.953***
Threshold τ_3	0.150*	7.277***
Threshold τ_4	1.278***	8.081***
Summary statistics		
L(c)	−716.749	−374.259
L(β)	−640.297	−316.678
−2(L(c) − L(β))	152.904	115.161
P-value	$P < 0.001$	$P < 0.001$

[a] "/" Indicates the variable was not observed in the survey.
* 0.1 Level.
** 0.05 Level.
*** 0.01 Level.

Table 3
Marginal effects of variables in the OP models.

Variable	Level 1	Level 2	Level 3	Level 4	Level 5	X
Physically separated bicycle path						
Grade[a]	0.099	0.109	−0.073	−0.110	−0.025	0.096
SepPede[a]	−0.034	−0.068	0.007	0.070	0.025	0.148
Width	−0.031	−0.053	0.015	0.054	0.016	3.167
BusStop[a]	0.025	0.041	−0.013	−0.042	−0.012	0.411
LandResi[a]	0.377	0.134	−0.270	−0.203	−0.038	0.075
LandComm[a]	0.033	0.055	−0.015	−0.056	−0.017	0.532
LandOffi[a]	0.037	0.055	−0.022	−0.056	−0.015	0.233
BicyFlow	0.094	0.158	−0.044	−0.160	−0.048	1.204
On-street bicycle lane						
Grade[a]	0.074	0.118	−0.102	−0.065	−0.024	0.381
Width	−0.207	−0.382	0.297	0.211	0.081	1.711
CurbWidth	−0.212	−0.392	0.304	0.216	0.083	3.611
BusStop[a]	−0.125	−0.313	0.106	0.199	0.132	0.270
ParkOccu2[a]	−0.054	−0.107	0.076	0.061	0.025	0.392
BicyFlow	0.013	0.024	−0.019	−0.014	−0.005	8.727
EbikRate	0.266	0.492	−0.382	−0.272	−0.105	0.567
VehiFlow	0.019	0.035	−0.027	−0.019	−0.007	1.342

[a] Discrete change of dummy variable from zero to one.

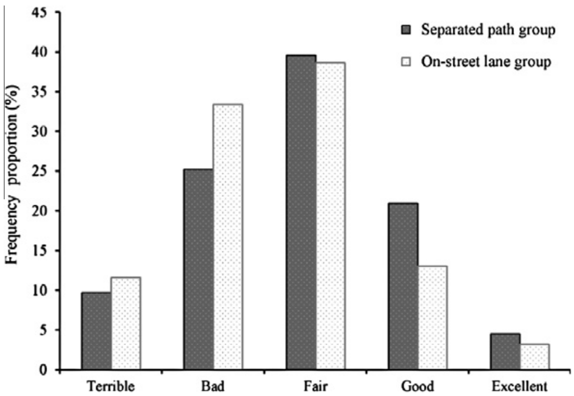

Fig. 1. Comfort perception on bicycle facilities.

exposure (comfort value multiply bicycle flow rate), and comfort with exposure per width (comfort with exposure divided by path/lane width) – Table 4.

The mean comfort value for the separated facility group is higher than for the on-street group under both traffic conditions. When considering the bicycle traffic exposure, the comfort in the separated facility group is 2.62 times that of the on-street facility group under light traffic conditions, it is only 1.26 under heavy traffic condition. When considering both traffic exposure and path/lane width, the cycling comfort with low traffic volumes for the separated facility group is greater than the on-street group, but the comfort in the on-street facility group is greater with more traffic.

Table 4
Comparison of comfort perception between bicycle facilities.

Measurement	S_{mean}[a]	O_{mean}[b]	S_{mean}/O_{mean}	t-test[c]
Light bicycle traffic (<400 bicycles/h/m)				
Comfort	3.07	2.86	1.07	Yes
Comfort with exposure	2.83	1.08	2.62	Yes
Comfort with exposure per width	0.85	0.53	1.59	Yes
Heavy bicycle traffic (>400 bicycles/h/m)				
Comfort	2.65	2.46	1.08	Yes
Comfort with exposure	3.88	3.08	1.26	Yes
Comfort with exposure per width	1.31	1.97	0.67	Yes

[a] Mean value on separated path group.
[b] Mean value on on-street lane group.
[c] Significant at a 95% confidence level.

The results show that under light traffic conditions, the physically separated bicycle paths can provide bicycle travelers more comfortable environment for cycling, while the on-street bicycle lanes are more efficient in providing spaces for comfortable cycling when bicycle traffic is large. Possible reasons would be that when bicycle traffic is small, exclusive environment for cycling can reduce the hindrances from vehicle and the collision risks between bicycles and vehicles and then increase the perception of cycling comfort. When bicycle traffic is large, the physically separated bicycle paths limit the effective space for cycling and then remarkably increase the interactions between bicycles which result in the low perception of comfort.

4. Discussion

The impacts of several of our variables on cycling comfort are consistent for both separated and on-street cycling facilities. The presence of slope is, for example, negatively associated with cyclists' perceptions of comfort on the two facilities probably because cycling up steeper slopes consumes more energy. Slope was not considered as a contributing factor for bicycle LOS by Landis et al. (1997) but was found important here the width of bicycle path/lane is normally assumed to be positively related to the comfort, wider lanes offering potentially more space for cycling. The width of curb lane can provide potential space for cycling and is positively related to the comfort on on-street bicycle facilities. These findings are consistent with previous studies for on-street bicycle facilities, off-street bicycle facilities, and shared-use bicycle facilities (Landis et al., 1997; Harkey et al., 1998; Hummer et al., 2006; Highway Capacity Manual, 2010).

The bicycle traffic flow is negatively related to cyclists' perceptions of comfort. Peoples do not like riding in heavy bicycle traffic because of congestion (Li et al., 2010), and this is supported by or findings. Additionally, heavy high motor vehicle volumes decrease cyclists' comfort for on-street bicycle facilities, probably because of the increased risks of collision.

Some variables differ in their impacts with respect to separated and on-street facilities. Regarding the former, the presence of bus stops has a negative impact on comfort; presumably buses block bicycle traffic and cause cyclists to feel uncomfortable. On the contrary, bus stops have a positive impact on comfort for the on-street facility group. It is unclear why this is so but perhaps it is because there are no parking vehicles in the vicinity of a bus stop providing more space for cycling. Further, bicyclists enjoy more comfort when street side parking is less than 50% adjacent to on-street bicycle facilities allowing unoccupied parking space to be used by bicycles when traffic is heavy.

The data also show that the residential, commercial and office land use around the physically separated pathways decrease bicyclists' comfort. In China, there are many human activities in residential, commercial and office areas that may make bicyclists feel tense or nervous during the trip, or even disturb their ridings. Thus, the physical separation from pedestrians shows to increase the cycling comfort. But the surrounding land use variables are not significant in the on-street facility group. Bicyclists may not pay much attention to surroundings when riding on on-street bicycle lanes with large bicycle and vehicle traffic. Besides, the rate of use of electric bicycles show to impact bicyclists' comfort on on-street bicycle lanes, but not on physically separated bicycle paths.

A comparison of contributing factors between the two facilities indicates some findings. In the separated facility group, most of environmental factors influencing the cycling comfort are the surrounding conditions. Bicyclists do not want to be disturbed by slope, bus stop, pedestrians and other bicyclists, and prefer enjoyable and quiet surroundings. It could suggest that bicyclists care about the smoothness and enjoyment of the trip. While in the on-street facility group, most of contributing factors are associated with effective riding space and traffic situation. Variables that could potentially provide more riding space (lane width, curb lane width, presence of bus stop, and low occupied side parking) are found to be positively related with cycling comfort. Large bicycle traffic and vehicle traffic, as well as high percentage of electric bicycle (which indicates more fast traveling bicycles) are reported to decrease bicyclists' perception of comfort. It could suggest that bicyclists want more riding space in the street and pay much attention to avoiding potential collisions with other bicycles or vehicles.

Our findings provide information for understanding how physical environments influence bicyclists' perception of comfort and help design comfortable environments for cycling on bicycle facilities. Moreover, the comparison of cycling comfort and contributing factors between the two bicycle facilities can help determine the facility type according to the actual environmental surroundings and traffic conditions. Physically separated bicycle facility reduces the interferences from vehicles and provides a safe cycling environment for bicyclists. Thus, this facility type is recommended for heavy vehicle traffic and light bicycle volumes. However, when bicycle traffic becomes large, the limited space for cycling on this facility remarkably increases the interferences between bicycles and reduces their perception of comfort. In this situation, the on-street bicycle facility is more efficient in improving the cycling comfort and is recommended for large bicycle traffic. Furthermore, we can estimate the comfort level on the two facilities according to the current environment and traffic conditions in the OP models and select the facility type with a higher comfort level.

5. Conclusions

Based on data from field China study investigated the relationships between physical environments and bicyclists' perception of comfort on separated and on-street bicycle facilities. The results show that for the former facilities, the main factors influencing cyclist's comfort include the width of path, presence of slope, presence of bus stop, physical separation from pedestrians, surrounding land use, and bicycle flow rate. For on-street bicycle facilities, the contributing factors include the width of the bicycle lane, width of the curb lane, presence of slope, presence of a bus stop, amount of occupied car parking spaces, bicycle flow rate, motor vehicle flow rate, and rate of use of electric bicycles. Bicyclists' perception of comfort is mainly influenced by the road geometry and surrounding conditions on physically separated paths, while they pay more attention to the available riding space and traffic conditions when it comes to on-street lanes. Physically separated paths provide greater comfort when there is light bicycle traffic, and when there is traffic congestion on the street, while on-street bicycle lanes are preferred when bicycle volume is heavy.

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 data collection and reduction.

References

Botma, H., 1995. Method to determine level of service for bicycle paths and pedestrian-bicycle paths. Transportation Research Record 1502, 38–44.

Harkey, D., Reinfurt, D., Sorton, A., Knuiman, M., Stewart, J., 1998. The bicycle compatibility index: a level-of-service concept, Report No. FHWA-RD-98-095, FHWA, McLean.

Highway Capacity Manual, 2010. Transportation Research Board. Washington DC.

Hummer, J.E., Rouphail, N.M., Toole, J.L., Patten, R.S., Schneider, R.J., Green, J.S., Hughes, R.G., Fain, S.J., 2006. Evaluation of safety, design, and operation of shared-use paths – final report. US Department of Transportation.

Landis, B.W., Vattikuti, V.R., Brannick, M.T., 1997. Real-time human perceptions: toward a bicycle level of service. Transportation Research Record 1578, 119–126.

Li, Z.B., Wang, W., Shan, X.F., Jin, J., Lu, J., Yang, C., 2010. Analysis of bicycle passing events for LOS evaluation on physically separated bicycle roadways in China. In: Presented at 89rd Annual Meeting of the Transportation Research Board. Washington, DC.

Lusk, A.C., Furth, P.G., Morency, P., Miranda-Moreno, L.F., Willett, W.C., Dennerlein, J.T., 2011. Risk of injury for bicycling on cycle tracks versus in the street. Injury Prevention 17, 131–135.

Winters, M., Teschke, K., 2010. Route preferences among adults in the near market for bicycling: findings of the cycling in cities Study. American Journal of Health Promotion 25, 40–47.