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RESEARCH ON THE EVALUATION MODEL OF NON-MOTORIZED TRAVEL ENVIRONMENT IN HISTORICAL DISTRICTS CONSIDERING RIDING SPEED

Hao Sun[1,2] and Yuhua Chen[3]

1. *Northwest University, College of Urban and Environmental Sciences, Xi'an, 710055, China; sunhao7572@nwu.edu.cn*
2. *Shaanxi Provincial Key Laboratory of Surface System and Environmental Carrying Capacity, Xi'an, 710055, China*
3. *Chang'an University, College of Highways, Xi'an, 710064, China; 787445886@qq.com*

ABSTRACT

Encouraging the use of non-motorized transportation is an effective strategy for alleviating traffic congestion in historic districts. This study utilizes data from a survey on 48 representative roads in Xi'an's historic districts. By considering the cycling environment, the non-motorized roadways in these districts are classified into three categories. The recommended average cycling speed that meets the psychological needs of cyclists at each category is chosen as the evaluation indicators. Based on OLS model, Poisson regression model and negative binomial regression model, an evaluation model for the non-motorized traffic environment in historic districts is established. By comparing the fitting performance of regression models, suitable evaluation models for the non-motorized traffic environment are determined. The results indicate that the Negative Binomial model performs well in fitting the results for class I and class III roads, with fitting coefficients of 0.8070 and 0.9199, respectively. On the other hand, the OLS regression model demonstrates a better fit for class II roads, with a fitting coefficient of 0.7003. The non-motorized travel environment on class III auxiliary roads in Xi'an's historic districts is poor, as most roads fail to meet the speed requirements of cyclists. Class I roads exhibit a favorable non-motorized travel environment, indicating the potential for further encouraging non-motorized travel. Most class II roads in the districts generally meet the requirements for non-motorized travel, but there is limited room for increased non-motorized traffic volumes in the future. The research findings provide a theoretical basis for enhancing the quality of cycling environment in historic districts.

KEYWORDS

Historic districts, Non-motorized travel, Regression analysis, Travel environment

INTRODUCTION

Historic districts with significant cultural value face various contradictions between traffic service levels and district preservation, as well as limitations in infrastructure renovation and high transportation demands [1]. In recent years, the transportation and travel issues within historic districts have drawn increasing attention from scholars both domestically and internationally. Scholars have proposed theories and methods related to transportation planning, traffic organization, and spatial optimization based on the preservation of historic districts [2,3]. Currently, China is actively promoting the development of non-motorized transportation. Many cities in China have introduced bike sharing projects, including bicycles and e-bikes [4,5]. These shared bicycles are like mushrooms after the rain, promoting the increase of non-motorized travel. Simultaneously,

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studies have found that non-motorized transportation, characterized by flexibility and convenience, is particularly favored by travelers within historic districts, with non-motorized vehicles accounting for a higher share of transportation compared to other urban areas [6]. In recent years, the concepts of "low-carbon" and "sustainable development" have been introduced in the renovation and protection of historical districts, and more and more historical districts are inclined to develop slow traffic systems [7]. Non-motorized transportation can better coincide with the development concept of the historical districts, and it is the transportation mode that the historical districts should focus on [8]. Encouraging healthy modes of transportation in terms of transportation strategies within historic districts can not only improve the physical and mental health of residents and increase their sense of happiness, but also adjust the transportation structure of historical blocks, reduce carbon emissions and contribute to the sustainable development of historical blocks. However, due to the varying road hierarchies within historic districts in China, there is a significant disparity in the non-motorized traffic environment. Some roads experience excessive non-motorized vehicle saturation, encroachment by motorized vehicles, and severe congestion, negatively impacting the experience quality of travelers. The travel behavior of residents is influenced by the traffic environment, and the higher the degree of environmental suitability, the higher the comfort of travel [9].

Behavior serves as a mediator between the environment and health characteristics. Therefore, scholars are increasingly interested in developing a healthy transportation system, so as to effectively promote the physical and mental health of residents. According to the research of Wu, Ma et al., the physical and mental health of residents is significantly correlated with their travel behavior and daily commuting pattern [10,11]. Walking, cycling, and other forms of active transportation are considered effective methods for preventing and treating physical illnesses [12]. For instance, Woodcock et al. conducted a health impact assessment on transportation policies in several cities in the UK and concluded that the health benefits from increased physical activity outweigh the health risks associated with increased air pollution exposure and traffic-related injuries [13,14]. Overall, as the daily durations of walking and cycling increase, residents tend to report higher levels of self-perceived health. This suggests a significant positive association between levels of physical activity related to commuting and self-perceived physical health [15]. Furthermore, a series of studies have indicated that physical activity behaviors have an impact on an individual's mental health [16]. Physical activity affects individuals' mental health in two main aspects. Firstly, at the cognitive level, engaging in physical activity stimulates individuals to pursue goals related to the activity. Secondly, at the emotional level, individuals experience positive or negative emotions during physical activity. Emotional experiences can be used to assess the aspect of "how one feels" in terms of mental health status. Typically, emotional experiences are manifested as short-term moods, which are considered important indicators of mental health. Prolonged exposure to negative emotions such as chronic stress can trigger psychological issues [17]. For instance, Bergstad found, through a survey of a sample of 1330 Swedish citizens, that residents' positive emotions about their daily trips would have a direct positive effect on subjective well-being or an indirect positive effect through the promotion of outdoor activities [18,19]. Steg et al. found that factors driving people to use small cars to travel included the positive emotions associated with driving a small car (happiness, freedom, etc.) [20]. Meanwhile, scholars have found that pedestrian perception of walking is influenced by factors such as walking environment, air quality, sidewalk type and surrounding crowd congestion [21]. It can be seen that the physiological and psychological state of non motor vehicle travelers will also be affected by cycling activities, environment and other factors. Cyclists experience the travel environment, resulting in psychological and physiological reactions, and then form a judgment on the quality of the travel environment. For example, when vehicles are overcrowded during peak periods, frequent shifts, changes of direction, and bumps of vehicles, travelers will experience severe psychological stress and fatigue, which greatly affects the travel experience [22]. Li et al. [23] based on a study of 80 sets of cycling data in Xi'an, found that most individual cyclists had higher levels of mood states after cycling compared to before, while a minority experienced a decrease. In the field of non-motorized transportation evaluation, scholars have done a lot of research. From the perspective of safety, road infrastructure and traveler satisfaction, scholars select appropriate evaluation indicators and methods to evaluate the non-motorized road environment [24-27]. Literature shows that the study of subjective perception is of great significance for bicycle traffic [26]. Therefore, some scholars evaluated the road environment from the perspective of traveler satisfaction. For instance, Zhu et al. [28] established a satisfaction model for bicycle travelers in urban road environments. They selected 23 indicators for commuting traffic, designed a questionnaire, and conducted a survey. Through structural equation modeling, they found that the main external factors influencing bicycle traveler satisfaction were smoothness and environmental comfort, with the most significant impacts coming from two measurement items: roadside parking and the influence of electric bicycles. Liu et al. [29] constructed an evaluation index system for cycling perception, ranked the importance and satisfaction of travelers' environmental perception, and proposed optimization suggestions for cycling environment. In addition, Biassoni et al. [30] found that safe, comfortable and attractive cycling infrastructure can achieve a high satisfaction cycling experience. It proves the importance of designing safer, more accessible, more comfortable and more attractive environments for cycling experience.

Transportation plays an important role in the daily life of residents, and a good transportation environment enables people to enjoy physical and mental well-being during the travel process. Meanwhile, a good traffic environment can promote active transportation, including walking and riding, so as to increase the amount of physical activity of residents and form a healthy lifestyl. However, there are few studies on the relationship between travel process state and traffic environment in China, but scholars generally agree that travel process state affects people's travel well-being and emotions [11]. On the other hand, as an important part of the urban transportation network and an important place for residents to carry out slow travel, it is necessary to pay attention to slow travel characteristics from the level of improving the travel experience of cyclists in historic districts. Xi'an is a typical historical and cultural city, the capital of Shaanxi Province, a national central city, and one of the best tourist destinations in China and one of the best cities in China in terms of international image. Xi'an is also a transportation-based city that provides ample mobility and accessibility for its residents. A greater proportion of trips are made by non-motorized vehicles in historic districts compared to other areas of the city [31]. Currently, most studies exploring cyclists' travel state have been conducted with a focus on the macro level of the city, which is dominated by private vehicle travel, while the meso level of the historical district is largely unknown. In view of this, this study uses field surveys to obtain relevant traffic data, takes 48 roads within three historic districts in Xi'an as examples, investigates the non-motorized traffic characteristics of historic districts, and constructs a non-motorized travel environment evaluation model for roads in historic districts from the perspective of cyclist travel state. This study can complement the literature in this area, and provide a theoretical reference for the high-quality development of the slow traffic system in historical districts.

METHODS

Study area and data collection

Xi'an, China, is a globally renowned historical and cultural city with numerous protected cultural heritage sites. According to the officially approved Xi'an Historical and Cultural City Conservation Plan (2020-2035), three designated historic districts have been identified: Bei Yuanmen, San Xuejie, and Qi Xianzhuang. Within the typical inner streets of Xi'an's historic districts, single-lane roads are the most common, while dual-lane and triple-lane roads are relatively rare, and dual-lane and triple-lane roads are predominantly for mixed traffic. Through our investigation of multiple historic districts' transportation, based on the functional and width characteristics of the roads within the historic districts and referring to the existing literature on road classification within historic districts, we have categorized the roads within the historic districts into three types [32,33], as shown in Table 1. As depicted in Figures 1-3, this study has selected typical roads from these three historic districts, resulting in a total of 48 road segments chosen as research sites.

Tab. 1 - Functional classification of roads in historic districts

Classification	Description	Road width characteristics
III	For internal transportation within the neighborhood, residents are allowed to travel by motor vehicles in one direction, while non-motorized modes of transportation are also present.	4-6 m
II	Connecting traffic on adjacent grade crossings with mixed motor/non-motor traffic for motorized and transit travel	6-20 m
I	Through traffic, generally machine and non-machine separation, to meet the motor vehicle two-way	>20 m

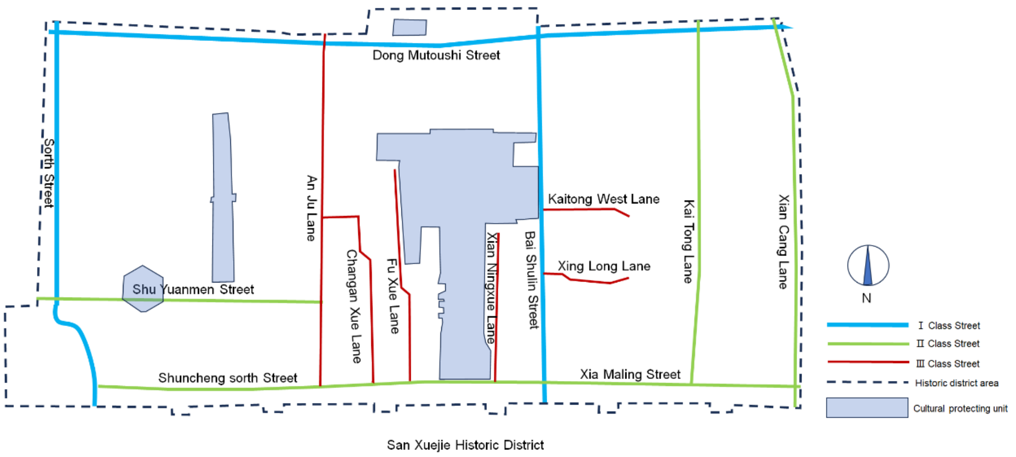

Fig. 1 – The research road segments within San Xuejie historic district

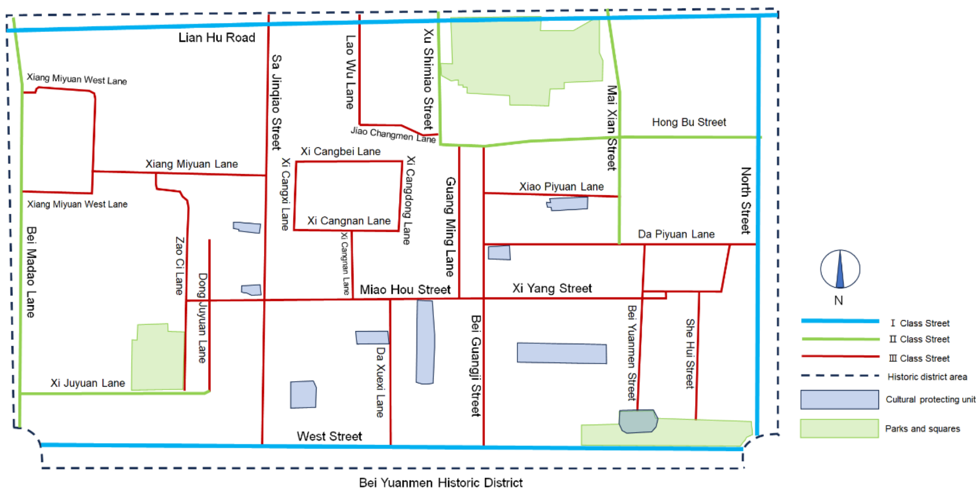

Fig. 2 – The research road segments within Bei Yuanmen historic district

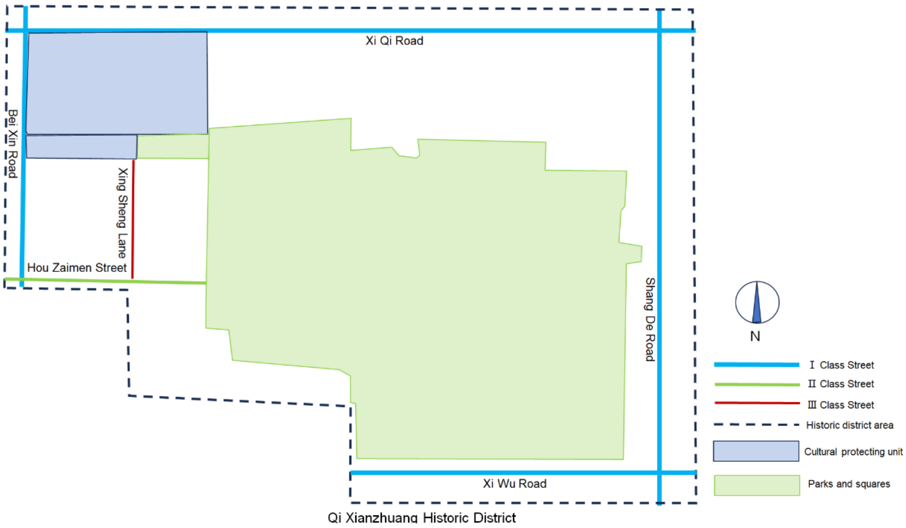

Fig. 3 – The research road segments within Qi Xianzhuang historic district

Taking into consideration the comprehensive impact of factors such as people, vehicles, the environment, and other elements on the travel experience of cyclists within historic districts, it is necessary to select and analyze the influencing factors based on different road types within each historical district. Research has shown that when the volume of non-motorized traffic and the number of pedestrians increase, it occupies the space for cyclists and may lead to feelings of tension and anxiety [34]. Therefore, the travel environment of non-motorized lanes is the primary influencing factor on the emotional state of cyclists. As the main influencing factors, travel environment conditions include the width of non-motorized vehicle lane, the quality of the road surface, slope and barrier free facilities, as well as non-motorized vehicle flow, pedestrian interference, motor vehicle interference and other factors. It should be noted that according to the actual survey, the barrier free facilities in historical districts in Xi'an are generally lacking. At the same time, the geographical locations of the three historical districts are adjacent, and their non-motorized lane pavement and slope are almost the same. Therefore, the variables such as slope and quality of the road surface are not considered in this study. Factors to consider include the volume of non-motorized traffic (*F*, *veh/h*), adjacent motor vehicle flow (*Cvol*, *veh/h*), average speed of adjacent motor vehicles (*Cv*, *veh/h*), width of the non-motorized lane (*meter, m*), number of bus stops along the road (*Bvol*, *veh/h*), and pedestrian flow on adjacent roads (*Pvol, person/h*). It is worth mentioning that during the survey period of this study, the historical districts in Xi'an were implementing the policy of “banning motorcycles “. Therefore, the non-motorized vehicles in the study only include bicycles and e-bikes.

Additionally, the survey data also includes characteristics of non-motorized traffic flow, namely the average speed of all non-motorized vehicles (*bV, km/h*), measured bicycle traffic volumes (F_b, *veh/h*), measured e-bike traffic volumes (F_m, *veh/h*), and non-motorized vehicle flow density (*K, veh/km*). The average speed of all non-motorized vehicles is calculated based on the measured data.

$$bV = P_b \cdot v_b + P_m \cdot v_m$$
$$P_b = \frac{F_b}{F_b+F_m};\ P_m = \frac{F_m}{F_b+F_m} \qquad (1)$$

In the equation, P_b represents the proportion of measured bicycle traffic volumes in hours, and P_m represents the proportion of measured e-bike traffic volumes in hours. v_b represents the measured average speed of bicycles, and v_m represents the measured average speed of e-bikes.

On the selected 48 road segments, we conducted video-based traffic surveys during weekdays and non-weekdays, including morning peak hours (7:00-9:00), evening peak hours (17:30-19:30), and non-peak hours. We collected at least 2 hours of traffic survey data for each period, resulting in a total of 570 sets of valid observations.

Regression model

Poisson regression model

Due to the high volume of non-motorized traffic and severe mixed traffic conditions within historic districts, it is challenging to accurately measure the headway of vehicles during peak hours. The number of vehicles distributed on certain road segments during a specific time is considered a random variable [35,36], and statistical distributions are commonly used to describe the patterns of such random variables. Poisson distribution and negative binomial distribution are widely used discrete distributions to describe these statistical patterns [37]. Currently, Poisson regression and negative binomial regression are commonly employed to predict the number of traffic accidents in a particular road section or area. For example, Ma Zhuanglin et al. analyzed the relationship between the occurrence of traffic accidents and factors such as road gradient using a negative binomial regression model [38,39]. Discrete distributions are also used to describe the statistical distribution of bicycle and pedestrian arrival volumes [40,41].

Within a given time, the number of non-motorized vehicles arriving at a road segment can be considered as count data. Let's assume the dependent variable is the non-motorized traffic volumes (F_i) on road segment i, and the observed values (y_i) follow a Poisson distribution with a parameter of λ_i. The probability equation can be written as follows:

$$P(F_i = f_i | x_i = \frac{e^{-\lambda_i} \lambda_i^{f_i}}{f_i!} \ (f_i = 0,1,2, \dots n) \tag{2}$$

$\lambda_i > 0$ represents the "Poisson arrival rate", which is determined by the explanatory variable x_i. The expectation and variance of the Poisson distribution are both equal to the Poisson arrival rate, λ_i can be understood as the average traffic volumes of non-motorized vehicles on the road segment. To ensure that λ_i is non-negative, the conditional expectation function of F_i is defined as follows:

$$E(F_i | \mathbf{x}_i = \lambda_i = exp(\mathbf{x}_i^{'}\boldsymbol{\beta}) \tag{3}$$

The i-th observation is $x_i = (x_{i1}, x_{i2}, \dots x_{ik})'$, $\boldsymbol{\beta} = (\beta_1, \beta_2, \dots \beta_k)$ is the unknown parameter vector, and thus we have $\ln\lambda_i = x_i'\boldsymbol{\beta}$, the Poisson distribution assumes that the samples are independently and identically distributed. The log-likelihood function of the sample can be expressed as follows:

$$lnL(\boldsymbol{\beta}) = \sum_{i=1}^{n}[-\lambda_i + f_i ln\lambda_i - \ln(f_i!)] = \sum_{i=1}^{n}\left[-\exp(\mathbf{x}_i^{'}\boldsymbol{\beta}) + f_i \mathbf{x}_i^{'}\boldsymbol{\beta} - ln(f_i!)\right] \tag{4}$$

The first-order condition for maximization is:

$$\sum_{i=1}^{n}\left[f_i - \exp(\mathbf{x}_i^{'}\boldsymbol{\beta})\right]\mathbf{x}_i = 0 \tag{5}$$

The numerical calculation leads to $\widehat{\beta}_{MLE}$,Since $\ln\lambda_i = x_i'\beta$, then $\frac{\partial \ln \lambda_i}{\partial x_{ik}} = \beta_k$, which leads to the Poisson regression model.

Negative binomial regression model

A negative binomial regression model can be considered if the expectation and variance of the explanatory variables are very different and the variance is significantly larger than the expectation, i.e., there are excessive dispersion characteristics. If the error term (μ_i) for the mean and variance of the non-motorized traffic volumes on the i -th road segment follows an $\boldsymbol{\Gamma}$-distribution, the mean of the non-motorized traffic volumes on the i-th road segment remains as λ_i. However, the arrival probability of each non-motorized vehicle is influenced by the values of the random variable μ_i. In this case, the non-motorized traffic volumes on the i-th road segment follows the following Poisson distribution [42]:

$$P(F_i = f_i|x_i, \mu) = \frac{\exp[-\lambda_i \exp(\mu_i)][\lambda_i \exp(\mu_i)]^{f_i}}{f_i!} \ (f_i = 0,1,2, \dots n) \tag{6}$$

Then the average value of non-motorized traffic on road i, λ_i, can be expressed as $\lambda_i = (x_i'\beta + \mu_i)$.

Its average value is: $E(F_i|x_i) = \lambda_i$;

Its variance is : $Var(F_i|x_i) = \lambda_i(1 + \frac{\mathbf{1}}{\boldsymbol{\theta}}\lambda_i)$.

OLS model

An OLS model was selected for regression analysis to analyze the linear relationship between the dependent variable and multiple independent variables. The dependent variable is the non-motorized traffic volumes F_i on road i. The independent variables are: adjacent motor vehicle flow $(Cvol, km/h)$, average speed of adjacent motor vehicles $(cV, km/h)$, average speed of non-motorized vehicles $(bV, km/h)$, non-motorized passable width $(meter, m)$, number of road bus stops $(Bvol, veh/h)$, pedestrian flow on adjacent roads $(Pvol, person/h)$, etc. The OLS model can be expressed as:

$$\mathbf{F_i} = \boldsymbol{\beta}\mathbf{x_i} + \boldsymbol{\varepsilon}; \quad (i = 0,1,2, \dots n) \tag{7}$$

Where, ε_i is the random error term conforming to the normal distribution.

Non-motorized traffic volumes calculation method

In the actual traffic organization, traffic organizers and cyclists generally pursue the smoothness of travel and are more satisfied with the road access environment where the cycling speed is undisturbed, and the average speed is guaranteed [43]. Therefore, the average speed of road non-motorized vehicles can be chosen as the evaluation index of non-motorized road access environment.

In the model mentioned above, the road non-motorized traffic volumes is taken as the explained variable and the factors affecting the road non-motorized traffic volumes are taken as the explanatory variables, and the relationship between the road non-motorized traffic volumes and its influencing factors is obtained, then the non-motorized traffic volumes can be described as：

$$F_i = f(Cvol, cV, bV, meter, Bvol, Pvol) \tag{8}$$

Similarly, the above equation can be expressed as:

$$bV = f(F_i, Cvol, cV, , meter, Bvol, Pvol) \tag{9}$$

Established studies have labeled that cyclists' perceived, emotional, and psychological changes in travel behavior vary at different riding speeds during travel. When the actual riding speed is lower than the cyclist's expectation, the cyclist's perceived travel time is longer than the actual travel time and the cyclist becomes irritable [28]. Therefore, we can use this as a basis to construct a non-motorized road traffic environment evaluation model within the historic district as in the above equation.

For different types of roads, to more reasonably judge whether the non-motorized road access environment meets the cyclists' requirements for road fluidity, the travel environment can be judged by whether the average speed (*V**) of road non-motorized vehicles meets the cycling speed threshold for good travel states of cyclists. When the other access environment conditions of the road remain unchanged, by bringing in the proposed average speed of road non-motorized vehicles (*V**), then the proposed flow of non-motorized vehicles can be inferred.

RESULTS

Descriptive statistics of of historical district survey data

To explore the relationship between cyclists' cycling speed and the non-motorized road traffic environment in the historic district, this study includes two types of independent variables: non-motorized travel-related characteristics and road traffic environment-related characteristics. The non-motorized travel-related characteristics as well as the road traffic environment-related characteristics variables were obtained from the field research. Among them, the non-motorized traffic volumes *F* is the sum of measured traffic volumes of bicycle and measured traffic volumes of electric vehicle. *bV* is the average speed of non-motorized vehicle, which is obtained by converting from the measured data. The statistical descriptions of the independent variables are shown in Table 2.

Tab. 2 - Variable description (No. obs. = 570)

Variable	Minimum value	Maximum value	Standard deviation	Average value
Road traffic environmental characteristics				
cV	11.1	40.7	8.65	25.46
meter	1.0	4.0	1.01	2.55
Cvol	93	1723	519.08	722.89
Pvol	1607	2556	125.69	378.25
Bvol	11	206	75.87	87.5
Non-motorized travel characteristics				
bV	9.3	23.16	3.99	14.37
F	107	977	279.04	477.3

The associations between riding speed and non-motorized travel environment on Class III Roads

Class III roads are neighbourhood level roads, mostly to meet the neighbourhood internal residents travel, mixed motor and non-motorized, and some roads are one-way, the road width is narrow. It was found that due to the narrow roads in this class, the roads are generally closed to buses, and the non-motorized traffic width, motor vehicle flow, the average speed of adjacent motor vehicles, the average speed of non-motorized vehicles, and pedestrian flow are the main factors affecting the non-motorized traffic. When model regressions were conducted, it was found that the non-motorized passable width and pedestrian flow had multicollinearity, so the explanatory variable of pedestrian flow was removed, and the parameter estimates of each model (Table 3), and the fitting results of each model (Table 4) were as follows:

Tab. 3(1) - OLS model parameter estimation for Class III Roads

	OLS model (1)				OLS model (2)			
Variables	Parameter estimation	Standard Error	t-value	P>|t|	Parameter estimation	Standard Error	t-value	P>|t|
cV	-11.1634	2.2599	-4.94	0.000	-11.5464	1.5405	-7.50	0.000
meter	-5.6078	24.1305	-0.23	0.817	—	—	—	—
Cvol	-0.3349	0.08487	-3.95	0.000	-0.3247	0.0723	-4.49	0.000
bV	40.4775	3.4751	11.65	0.000	40.0009	2.7944	14.31	0.000
Cons.	-111.2100	19.5741	-5.68	0.000	-111.5223	19.4521	-5.73	0.000

Tab. 3(2) - Negative binomial model parameter estimation for Class III Roads

	Negative binomial model (1)				Negative binomial model (2)			
Variables	Parameter estimation	Standard Error	Z-value	P>|Z|	Parameter estimation	Standard Error	Z-value	P>|Z|
cV	-0.0060	0.0054	-1.11	0.268	—	—	—	—
meter	-0.3978	0.0959	-4.15	0.000	-0.4458	0.0680	-6.55	0.000
Cvol	-0.0017	0.0004	-3.94	0.000	-0.0018	0.0004	-3.94	0.000
bV	0.1987	0.0125	15.84	0.000	0.1993	0.0128	15.56	0.000
Cons.	3.6581	0.0852	42.96	0.000	3.6637	0.0823	44.50	0.000

Tab. 3(3) - Estimated parameters of Poisson model for Class III Roads

	Poisson model			
Variables	Parameter estimation	Standard Error	t-value	P>|t|
cV	-0.0192	0.0042	-4.60	0.000
meter	-0.2835	0.0881	-3.22	0.001
Cvol	-0.0020	0.0004	-4.75	0.000
bV	0.2057	0.0124	16.63	0.000
Cons.	3.5941	0.1037	34.67	0.000

Tab. 4 - Comparison of the superiority of different models for Class III Roads

Models	Sample size	ll(model)	dif	AIC	BIC	R^2	Pseudo R^2
OLS(1)	292	-686.061	5	1382.123	1396.304	0.6832	—
OLS(2)	292	-686.090	4	1380.179	1391.524	0.6830	—
Negative binomial(1)	292	-677.543	6	1367.085	1384.103	—	0.8090
Negative binomial(2)	292	-677.644	5	1365.288	1379.469	—	0.8070
Poisson	292	-1431.772	5	2873.545	2887.726	—	0.6050

The OLS model scores better in terms of fit and goodness of fit, but the parameter test eliminates the variable "non-motorized width", which is not consistent with the fact that the actual non-motorized width significantly affects the non-motorized traffic flow, so the model is excluded. significant, but their AIC values and BIC values are too large to be optimal regression models. After the comparison of the superiority, the negative binomial regression model with one variable excluded is the best model. The variable excluded from the model is "average speed of adjacent motor vehicles", because the motor vehicle flow of this class of road is low and the average speed of traffic is low, the impact on non-motorized traffic is small, the exclusion of this variable is in line with the actual situation. The proposed non-motorized traffic model for Class III roads is as follows:

$$F^{*} = \exp(3.6637 - 0.4458merter - 0.0018Cvol + 0.19933bV) \quad (10)$$

The associations between riding speed and non-motorized travel environment on Class II Roads

Class II roads are neighborhood-level arterials that perform connectivity functions, generally with mixed motorized and non-motorized 4-lane roads, with non-motorized passable widths of about 2-3.5m, and bus stops in most road segments. During the survey, it was found that there was almost no pedestrian interference on the road, and the non-motorized traffic width, adjacent motor vehicle flow, average speed of non-motorized vehicles, and the number of bus stops were the main factors affecting the non-motorized traffic flow.

The results of running the three models in turn show that the negative binomial “LR test of alpha= 7.63e-11” alpha is extremely small, i.e., it does not pass the LR test and the model should not be used. The results of the OLS and Poisson models run with robust standard deviations are as Table 5:

Tab. 5(1) - OLS model parameter estimation for Class II Roads

Variables	OLS model (1)				OLS model (2)			
	Parameter estimation	Standard Error	t-value	P>|t|	Parameter estimation	Standard Error	t-value	P>|t|
cV	5.51061	0.7315	7.53	0.000	5.5660	0.7350	7.57	0.000
meter	124.1769	7.1320	17.41	0.000	123.6794	7.1669	17.26	0.000
Cvol	-0.0234	0.0148	-1.58	0.117	—	—	—	—
bV	-7.9927	1.8517	-4.32	0.000	-7.2656	1.8042	-4.03	0.000
Bvol	0.1909	0.0653	2.93	0.004	0.1504	.06035	2.49	0.014
Cons.	205.1829	40.7805	5.03	0.000	187.7517	39.4897	4.75	0.000

Tab. 5(2) - Estimated parameters of Poisson model for Class II Roads

Variables	Poisson model (1)				Poisson model (2)			
	Parameter estimation	Standard Error	t-value	P>|t|	Parameter estimation	Standard Error	t-value	P>|t|
cV	0.0095	0.0020	4.67	0.000	0.0095	0.0020	4.65	0.000
meter	0.1695	0.0185	9.16	0.000	0.1695	0.0185	9.17	0.000
Cvol	-0.00004	.00004	-0.99	0.324	—	—	—	—
bV	-0.0233	0.0051	-4.60	0.000	-0.0218	0.0048	-4.51	0.000
Bvol	0.0004	0.0002	2.21	0.027	0.0003	0.0002	1.98	0.048
Cons.	5.9575	0.1094	54.44	0.000	5.9251	0.1043	56.79	0.000

Tab. 6 - Comparison of the superiority of different models for Class II Roads

Models	Sample size	ll(model)	dif	AIC	BIC	R^2	Pseudo R^2
OLS(1)	176	-934.7436	6	1881.487	1901.739	0.9250	—
OLS(2)	176	-941.7247	5	1893.449	1910.326	0.9199	—
Poisson (1)	176	-942.5237	6	1897.047	1917.299	—	0.4512
Poisson (2)	176	-945.6927	5	1901.385	1918.262	—	0.4494

By comparing the performance of the two regression models, the variable “adjacent motor vehicle flow” was excluded from both models. The exclusion of this variable is realistic since each neighbourhood-level arterial road within the historic district has high motor vehicle volumes during the evening peak period. The OLS model was found to be a more accurate fit for the proposed non-motorized traffic on Class II roads:

$$F^* = 187.7517 + 5.56596cV + 123.6794merter - 0.150399Bvol - 7.265606bV \qquad (11)$$

The associations between riding speed and non-motorized travel environment on Class I Roads

The road width of Class I roads are relatively large, and non-motor vehicle lanes are set up. The road's non-motorized traffic only by bus interference. Through the survey, the factors that mainly affect the non-motorized traffic flow within the Class I roads are the average speed of non-motorized vehicles, the width of non-motorized lanes, and the number of bus stops. The data were analyzed and the results are shown in Tables 7 and 8:

Tab. 7 - Estimation of model parameters for Class I Roads

Variables	OLS Model			Poisson model			Negative binomial model		
	Parameter estimation	t	P>|t|	Parameter estimation	t	P>|t|	Parameter estimation	t	P>|t|
meter	267.147	10.92	0.000	0.3690	49.29	0.000	0.3452	12.28	0.000
bV	-233.3818	-8.52	0.000	-.3145	-38.97	0.000	-0.2979	-9.17	0.000
Bvol	-1.0222	-2.68	0.009	-0.0014	-12.24	0.000	-0.0016	-3.2	0.001
Cons.	3292.08	8.41	0.000	10.0007	86.75	0.000	9.8683	20.89	0.000

Tab. 8 - Comparison of the superiority of different models for Class I Roads

Models	Sample size	ll(model)	dif	AIC	BIC	R^2	Pseudo R^2
OLS	102	-615.6465	4	1239.293	1249.793	0.6882	—
Poisson	102	-982.7548	4	1973.51	1984.01		0.6109
Negative binomial	102	-596.565	5	1203.13	1216.255	—	0.7003

All three variables significantly affect non-motorized traffic. The model superiority was compared and the negative binomial model was the optimal model:

$$F^* = \exp(9.868253 + 0.345242merter - 0.001554Bvol - 0.297912bV) \quad (12)$$

DISCUSSION

Recommended non-motorized riding speed thresholds for historic districts

The recommended speeds for non-motorized vehicles should be determined based on the different road grades within historic districts. Through our questionnaire surveys conducted in historic districts in cities such as Xi'an, Luoyang, Zunyi, and Zhangye, we found that the psychological tolerance threshold for the minimum riding speed of non-motorized vehicles among cyclists in historic districts is generally around 8-10 km/h. Taking the most unfavorable scenario into account, we can consider the lower critical value of 8 km/h. When the riding speed is below 8 km/h, it indicates a poorer cycling environment in the district, where the riding speed is significantly affected, resulting in decreased enjoyment and potential feelings of tension and frustration for cyclists. Conversely, if the riding speed is above 8 km/h, it indicates a well-improved slow traffic infrastructure in the district, with less influence from external factors on the riding speed and higher cycling quality [42]. Therefore, the recommended speeds for non-motorized vehicles on different levels of roads within historic districts can be determined as shown in Table 10.

Tab. 10 - Recommended minimum riding speed for non-motorized vehicles on roads within historic districts

Projects	Class I roads	Class II roads	Class III roads
Recommended minimum riding speed for electric vehicles (V^*_m)	18 km/h	15 km/h	12 km/h
Recommended minimum cycling speed for bicycles (V^*_b)	12 km/h	10 km/h	8 km/h

Environmental assessment of non-motorized travel in historic districts

Based on the recommended non-motorized riding speed of roads at all levels and the measured bicycle and electric bicycle traffic volumes of each road, the recommended average non-motorized riding speed of each road (***V****) was calculated according to equation (1). With the suggested average riding speed as the control index, typical roads were selected, and the average of the survey data of each variable was calculated and brought into the regression model respectively, and the suggested non-motorized traffic volume of each road considering the travel state of cyclists was calculated, and the specific data and model calculation results are as follows:

Tab. 11 - Recommended non-motorized traffic volume on typical roads

Road grade	Road name	*meter*	*bV*	*Bvol*	*cV*	*Cvol*	F_i	F_i'	*V**	F_i^*
Class III Road	Xiao Piyuan Lane	1	11.33	—	—	263	135	149	11.3	148
	Miao Hou Street	1.5	11.65	—	—	93	162	172	11.0	151
	An Ju Lane	1	9.80	—	—	218	124	119	10.1	126
Class II Road	Hong Bu Street	2	19.08	60	28.12	—	450	444	15.3	471
	Shu Yuanmen Street	3	12.02	37	20.56	—	577	580	12.5	578
	Kai Tong Lane	2.5	14.16	26	18.89	—	487	495	13.0	504
Class I Road	West Street	4	15.38	145	—	—	613	628	15.0	703
	North Street	4	13.68	206	—	—	977	947	13.5	1000
	South Street	4	14.42	194	—	—	761	774	14.5	756

Note: F_i is the average value of survey data of non-motorized travel, and F_i' is the calculated value of non-motorized travel influence factor model.

By comparing the measured data with the model calculation results, the model calculated value of non-motorized traffic volumes F_i' for all levels of roads does not differ significantly from the actual value F_i, and this result marks the model accuracy as credible. The non-motorized traffic volumes F_i^* at the recommended riding speed can be obtained by adjusting the recommended riding speed (V^*) of non-motorized vehicles when other conditions of the non-motorized roadway access environment remain unchanged. If $F_i^* < F_i$, then the current non-motorized road traffic environment is poor and needs to be improved.

Suggestions

The validation results are consistent with the actual situation: the non-motorized traffic environment of Class II roads in the historic district is good, and the actual non-motorized traffic volumes of most roads ≈ the recommended non-motorized traffic volumes, i.e., it can basically ensure the cyclists' continuous passage. However, there is little room for non-motorized traffic volumes to rise on Class II roads. According to the calculation results, considering the comfort and safe passage of cyclists, it is suggested to reasonably manage the speed of non-motorized vehicles on Class II roads, especially to reduce the speed of e-bikes. At the same time, managers should consider improving the level of traffic organization to ensure the sustainability of non-motorized roads' environment.

Due to the narrow space of class III roads, which are mostly connected with residential areas, the traffic of non-motorized vehicles is greatly affected by the operation of pedestrians and motor vehicles. Therefore, the non-motorized traffic environment on class III roads is poor. According to the calculation results, the actual non-motorized traffic volumes on many roads > proposed non-motorized traffic volumes. Due to the difficulty in widening the roads in historical districts, in order to improve the traffic environment of non-motorized roads, measures can be taken to reduce the traffic volumes of non-motorized vehicles or the traffic volumes of motor vehicles. Therefore, on the one hand, according to the scale and current situation of the historic district, we should scientifically arrange and organize the motor vehicles that must enter the district, so as to reduce the motor traffic volumes. On the other hand, the traffic microcirculation of non-motorized vehicles can be dredged to reduce the non-motorized traffic volumes on class III roads.

The average speed of non-motorized vehicles measured on class I roads basically meets the needs of cyclists. It has the best travel environment, and there is still room for an increase in non-motorized travel on the road, so non-motorized vehicle travel should be encouraged.

Limitations

Several limitations of this study deserve attention. First, the case validation of this study is only carried out in 3 historical districts of Xi'an, and the sample size is limited. and the sample size is limited, so the validation objects can be further increased in the future. In the future research, the number of respondents should be further increased, and the verification in other representative historical districts should be considered.

Secondly, although necessary influencing factors were considered as much as possible in this study, part of the variability of non-motorized traffic volumes in the historical district still cannot be explained. Therefore, in the future investigation, more influencing factors can be considered, such as further considering the regional heterogeneity, road shade rate, etc. Third, our results cannot be extended to historical districts that are very different from Xi'an historical districts in terms of physical environment, liquidity culture and transportation policy.

CONCLUSIONS

In order to judge the road non-motorized traffic environment more scientifically and consider the travel experience of non-motorized cyclists, the non-motorized roads in the historical district are divided into three categories, the proposed average riding speed that satisfies the psychology of cyclists in non-motorized roads at all levels is selected as the judgment threshold, and the evaluation model of non-motorized traffic environment in the historical district is established based on OLS model, Poisson model and negative binomial model theory. The evaluation model established in this study can reflect the relationship between non-motorized traffic volumes and explanatory variables such as average non-motorized vehicle speed, non-motorized vehicle lane width, adjacent lane motor vehicle speed, etc. The calculated results of the model can be referenced when evaluating the non-motorized travel environment in historic districts. The main conclusions are listed below:

(1) The negative binomial model provides a good fit for the non-motorized traffic volumes and its influencing factors on class III roads. The external factors that have the greatest degree of explanation for the non-motorized traffic volumes of class III roads are the non-motorized passable width, the average speed of non-motorized vehicles and the adjacent motor vehicle flow. Due to the narrow road space, the traffic environment of most class III roads cannot meet the speed requirements of riders. In the pursuit of a better travel experience, the focus of improving the traffic environment of non-motorized vehicle road in the future should be on road segments where the measured non-motorized vehicle volume exceeds the recommended volume.

(2) The OLS regression model performs better in fitting class II roads. The non-motorized passable width, the average speed of non-motorized vehicles and the average speed of adjacent motor vehicles can better explain the dependent variable. At present, the non-motorized traffic environment of class II roads in the historical district is relatively good, but the non-motorized traffic volumes have little room to rise. In order to ensure the riding experience of riders, we should consider improving the level of traffic organization to ensure the sustainability of the travel environment on non-motorized road.

(3) The negative binomial model provides a good fit for the non-motorized traffic volumes and other influencing factors on class I roads. The factors that have the greatest degree of explanation for non-motorized traffic volumes on class I roads are the average speed of non-motorized vehicles, the non-motorized passable width and number of road bus stops. The measured average speed of non-motorized vehicles on class I roads can meet the needs of cyclists. Class I roads have the best travel environment, and there is still room for an increase in non-motorized traffic volumes on the road, so non-motorized travel can still be encouraged in the future.

(4) In practical application, if the calculated F_i^* is high, it indicates that the non-motorized travel environment is more abundant. In the road's cross-section design, the width of non-motorized vehicle lane can be appropriately reduced to optimize the allocation of road space resources. When the calculated F_i^* is low, the non-motorized lane can be widened appropriately if the conditions allow,

and the measures such as facilities optimization and traffic organization management can also be taken to improve the travel comfort and safety of travelers.

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