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Article

# Research on Vibration Comfort of Non-motorized Lane Riding Based on Three Axis Acceleration

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**Abstract:** In order to enhance the comfort of cycling, it is imperative to investigate the effects of vibration on non-motorized bicycle riding from the perspectives of road characteristics and traffic features. Through an analysis of the mechanisms by which road and traffic conditions influence cycling vibrations, 13 influencing factors were identified. Subsequently, the non-motorized bicycle lanes in Wuhan city were selected as the subject of empirical research, where three-axis accelerometers attached to the rider's torso were employed to measure and categorize vibration comfort levels. The experimental road segments were found to exhibit comfort levels falling between slightly uncomfortable and relatively uncomfortable. Further analysis of the influencing factors was conducted using the Random Forest algorithm and Logistic Regression. The results revealed that six factors significantly impact the comfort of cycling: the presence of dedicated non-motorized bicycle lanes, the absence of physical separation between non-motorized and motorized traffic, cycling speed, the number of road surface irregularities, the presence of parking areas within the non-motorized bicycle lane, and the type of non-motorized bicycle. This study provides valuable insights into the factors affecting non-motorized bicycle lane usage and contributes to the refined design of urban non-motorized bicycle infrastructure, thereby facilitating better support for sustainable urban transportation.

**Keywords:** non-motorized lane; riding vibration comfort; triaxial acceleration; random forest; logistic regression

## 1. Introduction

Walking and bicycling transportation system and public transportation are interdependent, is an indispensable link in the whole green low-carbon travel chain, walking and bicycling transportation system will directly affect the residents' travel choices. The enhancement of public transportation cannot be separated from the support of a perfect walking and cycling transportation system, and the construction of a high-quality system is a prerequisite for guiding the residents to change their travel mode and create a green, low-carbon and sustainable travel mode, which must be given sufficient attention [1–4].

The quality and service level of urban non-motorized paths are not only for safety considerations, but also become more important for non-motorized riding comfort. Currently, the research results of non-motorized paths mainly focus on guaranteeing continuous space for non-motorized vehicles, safety issues and service level, while less research has been done to analyze the issue of comfort during non-motorized riding [5–8]. Achieving non-motorized comfort on urban roads encourages people to use non-motorized vehicles more frequently, which has social and environmental benefits such as improving air quality, relieving traffic congestion and reducing carbon emissions. Vibration is considered by non-motorized riders as one of the most important indicators of bicycle comfort, and it greatly influences the choice of non-motorized vehicles. Non-motorized lane comfort is a broad

concept, and Salvator et al. [9] use smartphone sensors to collect data to evaluate road conditions and define key performance indicators for bicycles and electric scooters, achieving comprehensive evaluation of urban non-motorized vehicles. Nathan et al. [10] studied the differences between buffer zone types and how they affect people's sense of safety and comfort when riding bicycles. The results showed that striped or painted buffer pads increased comfort to a certain extent. Marta et al [11] found that the comfort level of different cycling infrastructure can have a significant impact on comfort, leading to different route choices for cyclists. Giubilato and Petrone [12] explored the impact of road surface on bicycle comfort reflected in the perceived vibration intensity of bicycle users. B í l et al. [13] designed an effective and novel indicator, the Dynamic Comfort Index (DCI), which describes the vibration characteristics of bicycle lanes based on acceleration signals collected from bicycles. Gao Jie [14] et al. developed an innovative dynamic bicycle comfort measurement system with quantitative characterization of bicycle vibration for 46 road segments, and volunteers' perceptions of each segment were summarized through a questionnaire to obtain thresholds for acceptable rate, comfort, and vibration perception levels. Ni Ying [15] proposed a non-motorized cycling quality assessment model for urban roads containing evaluation indexes such as facility attributes and cycling behavior characteristic parameters based on natural cycling experiments. Mi Mingxuan [16] designed a situational simulation questionnaire based on the narrative preference method, and for the survey data, a discrete choice model was used to analyze the riding preferences of commuters and to analyze and evaluate the riding environment and improve the proposal.

In summary, non-motorized riding acceleration is closely related to road environment factors and traffic factors, but the relationship between them has not been elaborated in existing studies, which makes it difficult to guide the practical operation to improve the riding comfort on non-motorized roads [17–23]. In this study, we evaluated and analyzed the vibration comfort of non-motorized road riding by collecting the triaxial acceleration data of the human torso in the riding condition, and verified the role of road and traffic factors in influencing the vibration comfort.

## **2. Analysis of factors affecting riding vibration comfort**

Slow walking space mainly includes sidewalks, non-motorized roads, intersections and green facilities belt. Elements in the space mainly include roads (road surface, slope, etc.), ancillary facilities (sign marking, crossing facilities, bus stops, street lights, manhole covers, etc.), greening (green belts, tree pools, etc.) and natural environment. The main aspects affecting the comfort of non-motorized riding are: non-motorized paths are easy to break and collapse due to the strength of the material and other reasons, and lead to the accumulation of water and splashing in rainy days; the concrete mass brick paving slabs are smaller, with large gaps, and the sudden change in height difference of the sidewalks at the entrances and exits of the plots of land and at the street-crossing places at the crossroads, which leads to serious bumps for users of wheelchair bikes, carts, and pull-tabs, etc.; the well covers of all kinds of municipal pipes on the sidewalks do not match the paving, and intersect with the paved areas Riding, implementation of poor comfort; local non-motorized road plane or longitudinal by obstacles, entrances and exits, low linear standards, poor riding comfort. Previous studies have shown that the factors affecting the comfort of non-motorized road riding vibration can be broadly divided into the following two aspects.

### *2.1. Road characteristics*

#### **2.1.1. Impact of route alignment on riding vibration comfort**

Non-motorized roadway routes include bus stops, intersections, neighboring side access points and continuous driving sections. After passing through the bus station and bus on and off passenger flow conflict, signal intersection red light stall, resulting in riding braking and starting, riding acceleration to produce corresponding changes. When the non-motorized roadway has vehicles or pedestrians converging and intertwining, it will cause interference to the non-motorized riding, resulting in fluctuations in acceleration. In the continuous driving section, if the road line is straight and there is no sudden situation, it can be considered that the non-motorized vehicle is in a stable

driving state, and the acceleration change is small. If the road line is curved, the centrifugal force will make riding uncomfortable; curved road sections usually account for a very small proportion of the entire route, which can be reflected by the number of right turns and left turns. Therefore, this paper selects bus stops, intersections, the number of entrances between districts, and the number of turns as potential factors affecting riding vibration comfort.

#### 2.1.2. Influence of roadway cross-section on cycling vibration comfort

The non-motorized roadway cross-section generally includes non-motorized lanes, sidewalks, and medians. Whether or not there is a non-motorized lane will have an impact on the smoothness of non-motorized riding; in the dedicated lane, non-motorized vehicles can travel in a more stable state to avoid acceleration fluctuations. At the same time, on-street parking will also affect the non-motorized vehicle riding status, non-motorized vehicles are generally traveling on the right side of the motor vehicle road, the left side of the sidewalk, with or without non-segregation or non-segregation of people on the operation of its state will have a greater impact. The combined use of the two segregation facilities produces four roadway cross-section forms: A. No sidewalks, no non-motorized lanes, motorized and non-motorized vehicles and pedestrians share the same lane. B. No sidewalks, non-motorized lanes, separation of motorized and non-motorized traffic, and non-motorized and pedestrians mixing in the non-motorized lanes. C. With sidewalks, no non-motorized lanes, and the use of elevation differences to separate pedestrians and non-motorized vehicles. D with sidewalks and non-motorized lanes, using solid white lines, guardrails, or greenbelts to separate motorized and non-motorized vehicles, and using height differences or guardrails to separate pedestrians and non-motorized vehicles. Due to the increase in the level of service of urban roads, the two cross-section settings of C and D are more common. Therefore, the presence of non-motorized lanes, the presence of non-motorized segregation, the presence of non-motorized segregation, and the presence of on-street parking areas were selected as potential factors affecting the riding vibration comfort.

#### 2.1.3. Influence of road longitudinal section on riding vibration comfort

The influence of road longitudinal section on the riding vibration comfort of non-motorized vehicles is mainly reflected in the size of the non-motorized roadway gradient, but the road longitudinal section gradient measurement is difficult, and the maximum urban roadway gradient set at 5% (the design speed of 15km/h) [24], the general control of the gradient in the range of 1.5% to 2.5%, which accounts for a very small percentage of the general, it can be assumed that the non-motorized roadway gradient of the transit vehicle driving The influence of non-motorized roadway gradient on the smoothness of bus travel is relatively small. Therefore, this paper does not consider the influence of road longitudinal section dimension on riding vibration comfort.

#### 2.1.4. Influence of road surface on ride vibration comfort

The influence of non-motorized road level road surface on the riding state is mainly reflected in the non-motorized road surface leveling degree, too many potholes, well covers, road articulation height difference will lead to drastic changes in non-motorized longitudinal acceleration under the riding state, the urban road surface is basically level, but the well cover and the road articulation height difference has a great influence. Therefore, this paper selects the number of manhole cover and pavement articulation protrusions as a potential factor affecting the riding vibration comfort.

### 2.2. Non-Motorized Transportation Characteristics

#### 2.2.1. Effect of Vehicle Type on Riding Vibration Comfort

Compared with motorized vehicles, non-motorized vehicles have smaller models and are more flexible to travel. Non-motorized vehicles are mainly two-wheeled vehicles with poor balance and lack of protection. The trajectory of non-motorized vehicles is very casual, and there are cluster

characteristics, when passing through the signal crossing, they are used to gather together to cross the road, and the driving space requirement is not big. Compared with bicycles, electric bicycles have greater speed and greater mass, so their stability is also worse, and there are greater safety problems with random swinging, and there are four main aspects of the basic characteristic differences between bicycles and electric bicycles. Therefore, this paper selects two models of bicycles and non-motorized vehicles as the potential factors affecting the comfort of riding vibration.

### 2.2.2. The influence of the proportion of different types of traffic flow on the comfort of riding vibration

The mixed traffic flow of electric bicycles, bicycles and pedestrians on non-motorized lanes is a very common phenomenon in the city, and non-motorized vehicles have the characteristics of unfixed driving lines, shaking while driving, high frequency of lane changing, etc. Pedestrians have the characteristics of walking together with many people, unstable walking paths, and the possibility of stopping or even making a U-turn. The average speed of electric bicycle traveling faster than the average speed of bicycles, while bicycles run several times the speed of pedestrians walking, there is an obvious speed difference between the three. When non-motorized vehicles and pedestrians mixed with, with the increase in pedestrian traffic, the probability of vehicle braking behavior will rise, non-motorized vehicles by the degree of influence of pedestrian traffic increased, which in turn led to non-motorized vehicle operating status fluctuations. The impact of pedestrians on non-motorized vehicles has been discussed above in terms of human non-segregation. Therefore, in this paper, the percentage of e-bikes (high or low) is selected as a potential factor affecting the riding vibration comfort.

### 2.2.3. Influence of speed on riding vibration comfort

On a non-motorized roadway, vehicle speed is closely related to the braking state of the rider. In passing through the same environment, faster speeds through inappropriate heights can cause the phenomenon of jumping. Therefore, this paper selects the speed as a choice of riding speed low (5~12km/h), medium (12~17km/h), high (17~25km/h) as a potential factor affecting the riding vibration comfort.

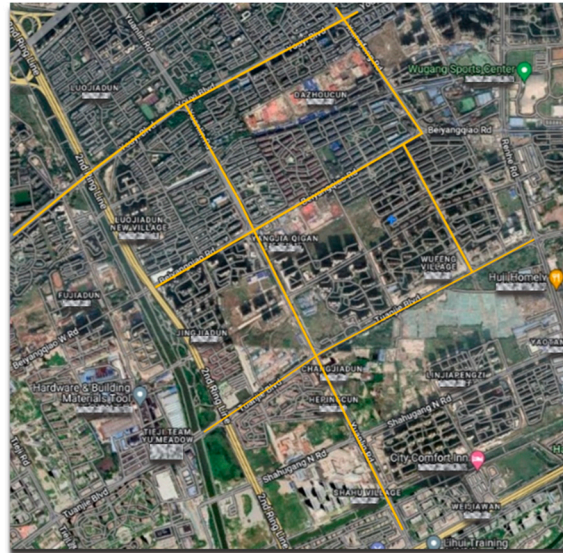
In summary, this paper mainly considers two aspects of road characteristics and traffic characteristics, road characteristics are divided into line direction, cross-section, longitudinal section and road surface dimensions, traffic characteristics are divided into models, model percentage, speed three dimensions, a total of selected bus stops, the number of intersections, the number of access points, the number of turns, the presence of non-motorized lanes, the presence of non-motorized segregation, the presence of non-motorized segregation, the presence of on-street parking areas, The number of manhole covers, the number of roadway articulation protrusions, non-motorized vehicle models, the proportion of electric bicycles, and riding speed are thirteen factors that are analyzed as potential factors affecting the comfort of riding vibration.

## 3. Experimental data collection and processing

### 3.1. Experimental Program

In this study, the smartphone is used as the data acquisition terminal, and the GPS position coordinates and three-axis acceleration data are acquired based on the global positioning system (GPS) module and acceleration sensor module of the smartphone. According to the official document of Android developer, the accuracy of the sensor module reaches 1 in 10,000, which is fully in line with the accuracy requirements of the data. In this paper, when collecting data, the experiments are conducted on two models of electric bicycles and bicycles respectively, and the method of vertically binding the cell phone to the torso of the experimenter in the seated position of riding is adopted. This study selected part of the route of Youyi Avenue in Wuchang District, Wuhan City, Wuhan City, as the object of investigation, through the Baidu Live Map to obtain the location of the stations along the route, intersections, access points, the route of the route with and without non-segregation and

non-motorized traffic lanes and other data. The data collection time is from 11:00 to 13:00 on weekdays, and the experimental survey method is to divide the non-motorized paths spatially, with every 100 meters as a calculation unit length. The stop and start moments of riding through stations and intersections were recorded. At the same time, in order to control the influence of irrelevant variables on the experimental results, vehicles of the same model were selected for each experiment, and the seat heights selected for each measurement were kept the same.



**Figure 1.** Schematic diagram of the experimental section.

### 3.2. Calculation of ISO 2631 Comfort Indicators

Mechanical vibration has a great impact on human health and comfort, and the degree of bumps in the vehicle is reflected by the smoothness of the ride, according to the evaluation standard of human body withstanding whole-body vibration given by the international standard "Evaluation Guidelines for Human Body Withstanding Whole-Body Vibration" (ISO 2631-74). During riding, assuming that the human body is in a seated position and ignoring the side-to-side swaying of the vehicle body, and considering that the non-motorized drivers have strong self-regulation ability during riding, the hand-transferred vibration can also be ignored [25–29]. In summary, the rider's vibration is affected by the effect of acceleration from  $x$  (forward direction),  $y$  (lateral direction perpendicular to the forward direction),  $z$  (vertical direction) three dimensions; due to the human body's sensitivity to acceleration in different vibration directions, the contribution of acceleration in each direction to the human body's comfort is different, so the calculation of total weighted acceleration needs to be based on the degree of influence of acceleration of the three axes on the comfort, respectively [30–32]. Therefore, when calculating the total weighted acceleration, it is necessary to assign different weights according to the degree of influence of the three-axis acceleration on the comfort:

$$a_v = (k_x^2 a_x^2 + k_y^2 a_y^2 + k_z^2 a_z^2)^{\frac{1}{2}} \quad (1)$$

Where:  $a_x$ ,  $a_y$ ,  $a_z$  correspond to the acceleration on the coordinate axes  $x$ ,  $y$ ,  $z$ , respectively;  $k_x$ ,  $k_y$ ,  $k_z$  is the direction factor, according to the standard sitting state, the  $x$ ,  $y$  direction factor is 1.4, and the  $z$  direction factor is 1. The correlation between the calculated total vibration and comfort is shown in Table 1.

**Table 1.** Relationship between total acceleration vibration and subjective perception.

Acceleration Vibration totals	Subjective perception
<0.315	No discomfort
0.315~0.63	Slightly uncomfortable
0.5~1.0	Quite uncomfortable
0.8~1.6	Uncomfortable
1.25~2.5	Very uncomfortable
>2	Extremely uncomfortable

The experimentally collected data were calculated to obtain the weighted acceleration according to Equation (1), and then the average value of the weighted acceleration in the running interval was taken as the characteristic parameter for evaluating the riding vibration comfort [33–36].

#### 4. Experimental results analysis

EpiData 3.1 software was used to check all the surveys by double entry, and SPSS 24.0 was used to delete the abnormal values and fill in the missing values, and the average weighted acceleration of riding was counted according to the intervals, and it was found that the distribution of its values was in the range of 0.32~0.95m/s<sup>2</sup>. In the correspondence between the grading of the comfort level and the range of the acceleration values (see Table 1), the values of 0.315~0.63m/s<sup>2</sup> were in the slightly uncomfortable level, and 0.5~1.0m/s<sup>2</sup> was in the relatively uncomfortable level. 0.63m/s<sup>2</sup> are at the slightly uncomfortable level, and 0.5~1.0m/s<sup>2</sup> are at the relatively uncomfortable level, so the vibration comfort level of the experimental line only exists in two grades: slightly uncomfortable and relatively uncomfortable. R-4.0.2 was used for statistical analysis, a random forest model was established, the data set was divided into a training set and a test set in a ratio of 3:1, the variables were ranked in order of importance, and multifactorial logistic regression was used to analyze the influence and degree of the optimal variables on the riding vibration comfort. The test level  $\alpha=0.05$ .

##### 4.1. Assignment of variables

With the comfort level as the dependent variable, the variables related to road characteristics and traffic characteristics were assigned values as shown in Table 2.

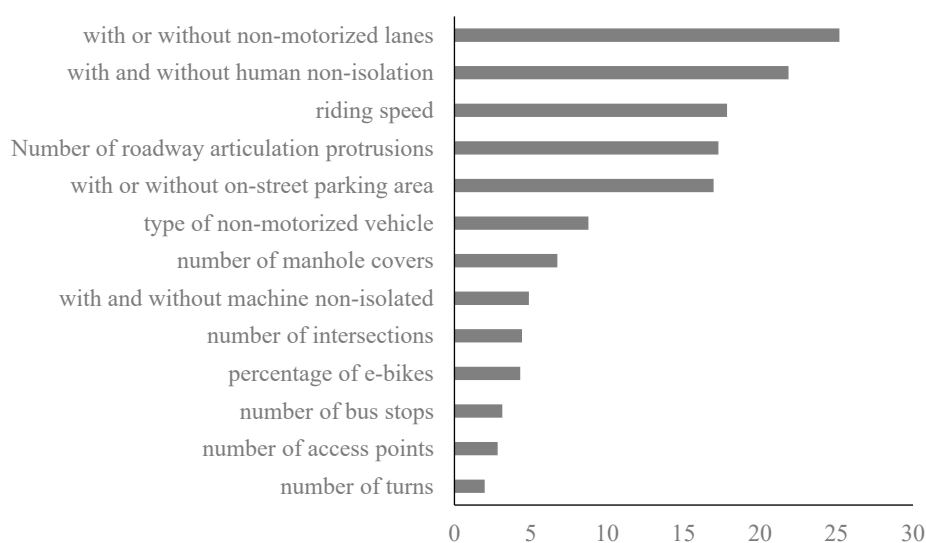
**Table 2.** Variable assignments.

Variable name	Value type	Variable type
comfort level	1=slightly uncomfortable, 2=very uncomfortable	dependent variable
number of bus stops	1=0~5, 2=6~10, 3=>10	independent variable
number of intersections	1=0, 2=1, 3=>1	independent variable
number of access points	1=0~5, 2=6~10, 3=>10	independent variable
number of turns	1=0, 2=1~3, 3=>4	independent variable
with or without non-motorized lanes	1=no, 2=yes	independent variable
with and without machine non-isolated	1=no, 2=yes	independent variable
with and without human non-isolation	1=no, 2=yes	independent variable
with or without on-street parking area	1=yes, 2=no	independent variable
number of manhole covers	1=0, 2=1~4, 3=>4	independent variable
Number of roadway articulation protrusions	1=0, 2=1~5, 3=6~10	independent variable
type of non-motorized vehicle	1=bicycle, 2=electric bicycle	independent variable

percentage of e-bikes	1=low, 2=medium, 3=high	independent variable
riding speed	1=low, 2=medium, 3=high	independent variable

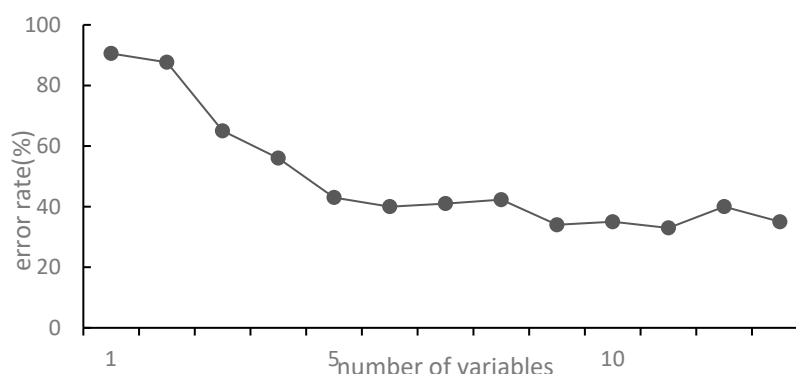
#### 4.2. Ranking of importance of random forest variables

The variables, in descending order of importance, were the presence of non-motorized lanes, the presence of non-motorized segregation, cycling speed, the number of articulated protrusions in the roadway, whether the non-motorized lanes were divided into parking zones, non-motorized types, the number of manhole covers, the presence of motorized and non-motorized segregation, the number of signal-controlled intersections, the percentage of e-bikes, the number of bus stops, the number of intersection entrances, and the number of turns (see Figure 2 for details).



**Figure 2.** Order of importance of variables.

Based on the results of the importance score ranking, a stepwise random forest was conducted starting from the variable with the highest score, and the results showed that the out-of-bag estimation error rate was relatively low and stable when the number of variables was six. The top six variables in the importance score ranking are, in order, no non-motorized lanes, no non-motorized segregation, cycling speed, the number of articulated protrusions on the roadway, whether the non-motorized lanes are divided into parking zones, and the type of non-motorized vehicles (see Figure3 for details). Therefore, this paper concludes that non-motorized lanes, human non-segregation, riding speed, the number of roadway articulation protrusions, whether non-motorized lanes are divided into parking zones, and non-motorized vehicle types have a significant effect on the comfort level on the comfort level of riding vibration, and that the effect of manhole covers, machine-non-segregation, signalized intersections, the proportion of electric bicycles, the number of bus stops, the number of intersection entrances, and the number of turns on the comfort level of riding vibration is not significant.



**Figure 3.** Out-of-bag estimation error rate.

#### 4.3. Multifactor Logistic Regression Analysis

Further according to the random forest variable importance ranking in order, the presence of non-motorized lanes, the presence of unmanned non-motorized segregation, riding speed, the number of roadway articulation protrusions, whether the non-motorized lanes are divided into parking zones or not, and non-motorized vehicle type were selected as independent variables, and the level of comfort as the dependent variable. The results showed that all six factors were related to non-motorized riding vibration comfort (all  $P < 0.05$ ), see Table 3.

**Table 3.** Multi-factor Logistic regression analysis of factors affecting riding vibration comfort.

Variable	B	S.E.	WaldX2	OR (95%CI)	P
Availability of non-motorized lanes					
Yes (control)				1.000	
No	0.244	0.122	4.000	1.276 (1.005~1.621)	0.046
with and without human non-isolation					
Yes (control)				1.000	
No	0.179	0.081	4.884	1.196 (1.020~1.402)	0.027
Riding speed					
Low (control)				1.000	
Medium	0.298	0.147	4.110	1.347 (1.010~1.797)	0.043
High	0.334	0.167	4.000	1.397 (1.007~1.937)	0.046
Number of roadway articulation protrusions					
0(control)				1.000	
1~5	0.100	0.047	4.527	1.105 (1.008~1.212)	0.033
6~10	0.231	0.113	4.179	1.260 (1.010~1.572)	0.041
With or without parking area					
No(control)				1.000	
Yes	0.102	0.048	4.516	1.107 (1.008~1.217)	0.034
Non-motorized Vehicle Type					
Bicycle (control)				1.000	
Electric Bicycle	0.334	0.101	10.936	1.397 (1.146~1.702)	0.001

The no non-motorized lane group is 1.276 times more uncomfortable than the one with non-motorized lanes in the comparative discomfort level, the installation of bus lanes can effectively improve the level of riding vibration comfort, and for the non-motorized routes without dedicated lanes, the riding comfort of cyclists can be guaranteed by improving the road surface smoothness.

The unsegregated non-segregated group is 1.196 times more uncomfortable than the segregated non-segregated group, so the increase of pedestrians under mixed conditions brings about a decrease in the level of riding vibration comfort, which clarifies the necessity of the installation of sidewalks.

Riding speed medium-speed, high-speed group in the comparative discomfort level is 1.347 times the low-speed group, 1.397 times, the faster the speed, the worse the smoothness of the vehicle operation, so you should comply with the laws and regulations of traffic safety, control the speed of the vehicle, and travel safely.

The number of roadway articulation protrusions 1~5 groups, 6~10 groups in the more uncomfortable level are respectively 1.105 times, 1.260 times without roadway articulation protrusions, in the articulation protrusion position for slope type transition, smooth articulation of pedestrian height difference, the intersection at the edge of the stone ramps transformed into a sloping type or full-width type.

There are curb parking area in the more uncomfortable level is not curb parking area of 1.107 times, can consider the implementation of "embedded" parking on the side of the road, that is, in the non-motorized road and motor vehicle lanes set up between the parking space, and close to the side of the motor vehicle road to consider enough safe space distance, not only to ensure that motor vehicle parking needs, but also ensure that the normal flow of non-motorized traffic. The normal passage of non-motorized traffic, do not affect each other, quite humane.

Non-motorized vehicle types in the electric bicycle in the comparative discomfort level is 1.397 times that of the bicycle group, the electric bicycle has become the main way of short-distance travel now, but many electric bicycles maximum speed exceeds the traffic safety regulations, and the electric vehicle modification threshold is low, the speed of the phenomenon of exceeding the standard is more serious, resulting in the speed difference between the electric vehicle and the bicycle in the non-motorized roadway can reach a maximum of 35 km/h; At the same time, the hot business of urban takeaway and express delivery has led to the speed of electric vehicles in non-motorized lanes as high as 40 km/h for professional riders such as takeaway workers, so it should focus on traffic control of non-motorized vehicles.

## 5. Conclusion

This paper analyzes the external factors affecting cycling vibration comfort from the perspective of non-motorized cycling. According to the non-motorized road characteristics and non-motorized traffic characteristics, the average weighted acceleration of non-motorized rider's body is calculated to evaluate the level of vibration comfort, and the factors that may affect the level of riding vibration comfort in each section are analyzed by using the Random Forest algorithm and multi-factor logistic regression. It was found that: the riding vibration comfort of the experimental route was at the level of slightly uncomfortable as well as relatively comfortable, and the riding vibration comfort of the non-motorized road was at the level of medium; the non-motorized lane, the human and non-motorized segregation, the riding speed, the number of articulated protrusions of the pavement, whether the non-motorized road was divided into parking areas, and the type of non-motorized vehicles had a significant influence on the comfort level to the level of riding vibration comfort, and the manhole cover, the mechanical and non-motorized segregation, the signal intersection, the electric bicycle, the bicycle, and the bicycle. Separation, signalized intersections, the proportion of electric bicycles, the number of bus stops, the number of intersection entrances, and the number of turns do not have a significant effect on the level of cycling vibration comfort. Through the study, we can better understand the influence aspects of non-motorized road cycling, which can help the urban non-motorized road refinement design, and better serve for people and non-motorized slow traffic.

Due to the experimental conditions, this paper selected fewer experimental lines, the sample to be added to enrich; at the same time, comfort is a subjective term, non-motorized riders personal

subjective feelings for most of the vibration is acceptable, then the traffic rider's age, gender, income, etc. on the level of vibration comfort may be differences in the degree of impact, the need for further research to demonstrate.

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