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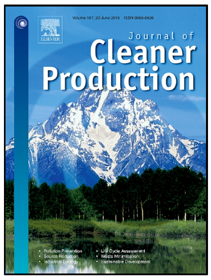

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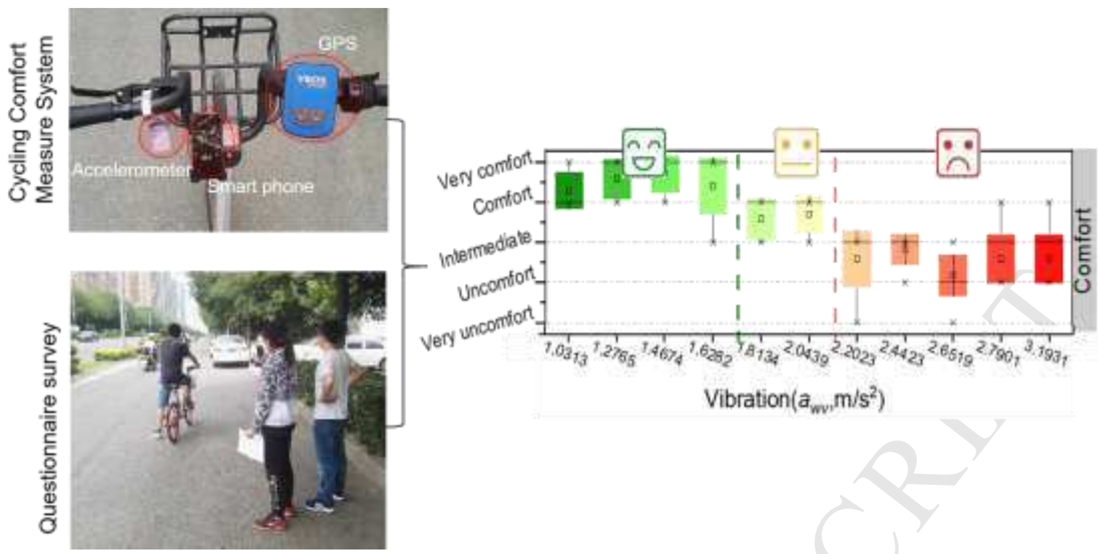

Cycling Comfort Measure System
GPS
Accelerometer
Smart phone
Questionnaire survey
Very comfort
Comfort
Intermediate
Uncomfort
Very uncomfort
1.0313
1.2765
1.4674
1.6282
1.8134
2.0439
2.2023
2.4423
2.6519
2.7901
3.1931
Vibration(a_{wv},m/s^2)
Comfort

Evaluating the cycling comfort on urban roads based on cyclists' perception of vibration

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Abstract: Attainment of cycling comfort on urban roads encourages people to use bicycles more frequently, which has social and environmental benefits such as to improve air quality, alleviate congestion and reduce carbon emissions. Vibration is perceived by cyclists as one of the most important indicators of cycling comfort, and it greatly influences people's choice of bicycles. However, a comprehensive correlation between cyclists' perception of comfort and cycling vibration has not yet been established in the current knowledge. In this study, a total of 46 sections of 24 urban roads (approximately 11,500m in length of asphalt pavements) in the city of Xi'an, China, were selected for field test. An innovative Dynamic Cycling Comfort (DCC) measure system consisting of an accelerometer, GPS logger and smart phone, was installed on the hand bar of a shared bicycle typically used in Xi'an, to record the dynamic data of vibration, trail, speed and mileage. Reliability of the DCC was verified, and the effect of test conditions (speed, bicycle type) on vibration evaluated. The vibration data were processed in accordance with ISO 2631 to quantitatively characterize the vibration level on each tested section. Furthermore, a total of 17 volunteers participated in this test, and the cyclists' perception of vibration in each section was obtained via a purpose-designed questionnaire. The volunteers' perception of environmental factors such as scenery, weather, road geometry, congestion and traffic condition were summarized to evaluate the influencing factors for cycling comfort. The thresholds of acceptable rate, comfort level and vibration perceptible level were established, based on the correlation between cycling vibration a_{wv} and subjective perception described in the questionnaire. In addition, the cycling comfort on the asphalt pavements (3,521 m) within Qujiangchi Park was mapped, to demonstrate the practical use of this study. Results showed that the DCC is able to capture the cycling data timely and accurately. K-means clustering analysis showed that the cycling vibration increases with the increase of cycling speed. Meantime, a heavier shared bicycle with solid tires results in higher cycling vibration compared with a lighter one with inflatable tires. In addition, the comfort level is proportional to acceptable rate, and inversely proportional to vibration perceptible level. The cycling comfort mapping for Qujiangchi Park proved that there is great potential to use the vibration (comfort) data to monitor pavement surface quality and for cyclists to determine their desirable cycling route. Results of this study should be interested by cyclists, bicycle manufacturers, transport planners and road authorities.

Key words: cycling comfort, shared bicycle, perception of vibration, urban roads

1. Introduction

In the past two decades, automobile-oriented transport planning and policy has resulted in a soaring number of motorized traffic which leads to congestion, parking problems, air pollution, fossil fuel depletion, climate change and road traffic injury. The uptake of non-motorized transport in an urban environment is gaining significant popularity recently across the globe, especially in developed countries. It is well acknowledged that cycling is a desirable transportation means for many reasons, including being environmentally-friendly, cost-effective, a way to keep fit and healthy and, on many occasions, associated with an enjoyable social activity (Zhang et al., 2015). The rapid development of shared bicycle schemes is gaining great attentions. Globally, bicycle sharing schemes have existed for nearly 50 years but only in the last decade have they grown significantly in prevalence and popularity in over 800 cities across the world (Ricci, 2015). In China, shared bikes only emerged at the end of 2015 but soon become commonly seen on streets in major cities. There are 77 companies currently in the market offering 23 million shared bicycles to more than 400 million customers (Luo, 2018). Apparently, bike-sharing is gaining popularity among cycling population around the world. The quality and level of service of urban bicycle lanes thus become more important not only for safety reasons but also for the cycling (dis)comfort.

Cycling comfort is a wide concept, it is jointly affected by the infrastructure and cyclist's perception of cycling in term of tactile, visual, auditory, olfactory and hygienic comfort (Rupp et al., 2015). According to previous studies, the condition of cycling infrastructures is considered a primary factor to influence the comfort. For instance, Calvey et al. (2015) designed a questionnaire to identify the most important factors among 24 indicators concerning almost every aspect of the cycling environment. Results showed that the pavement type, roughness and condition are primary factors to the cycling comfort. In addition, cyclists' choice of the desirable routes is often affected by the quality of pavement surface (Rybarczyk and Wu, 2010). In fact, the pavement's influence on cycling comfort is reflected in the vibration intensity according to the perception of cyclists (Giubilato and Petrone, 2012). However, comfort is a subjective term as individuals will have their own opinion on how much vibration is acceptable. Therefore, many studies aim to quantify the levels of vibration that cyclists experienced. For example, Bíl et al. (2015) designed an effective and novel index, dynamic comfort index (DCI), to describe the vibration characteristics of bicycle lane based on the acceleration signals collected from the bicycle. Hölzel et al. (2012) compared different pavement surface of asphalt, concrete slabs, bound gravel and cobblestones via an accelerometer mounted on the bicycle saddle. Other researches (Li et al., 2013; Thigpen., 2015; Wu., 2015) made remarkable progresses on studying the influence of pavement surface on bicycle ride quality, which demonstrated that the international roughness indexes (IRI), mean profile depth (MPD) and riding vibration are highly related with the comfort level. Generally, the vibration signals can be captured by installing one or multiple accelerometers on different parts of the bicycle, such as the handlebar, saddle or fork (Chou et al., 2015; Gomes and Savionek, 2014; Olieman et al., 2012).

Human perception on vibration varies with the vibrated position since the sensitivity to vibration differs between the body parts (Dim and Ren, 2017). Therefore, the international standard (ISO 2631) of Mechanical Vibration and Shock Evaluation of Human Exposure to Whole-body Vibration (International Organization for Standardization., 1997) classified the vibration into seated position, standing position and recumbent position. Based on this classification, the standard method for evaluating the riding comfort was developed to the seated position. The relationship between the vibration level and human comfort can be found in the Chinese standard for Method of Running Test: Automotive Ride Comfort (GB/T 4970-2009) and the ISO 2631. However, simply classifying the cyclist's body position as the seated position is not sufficient since the cycling position is much more complicated. Therefore, the effect of vibration on cyclists' perception should be studied more specifically. The following questions should be answered when addressing this issue faced by transportation professionals.

- How to characterize the intensity of cycling vibration?
- How to quantitatively determine the cycling comfort on a pavement?

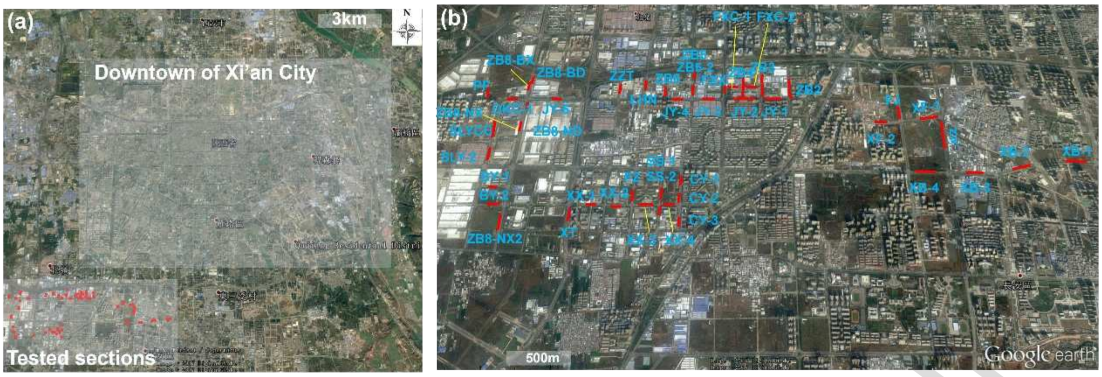
The above questions justified the need to carry out a field test following theoretical study of the factors that influence riding quality and comfort of cyclists. For this purpose, the cycling vibration levels on 46 sections of 24 urban roads (approximately 11,500m in length of asphalt pavements) were tested using a dynamic cycling comfort measure system. The cyclists' perception to vibration on tested section was obtained by questionnaires. The findings will add to the current knowledge by establishing the thresholds of acceptable rate, comfort level and vibration perceptible level. Outcomes of this study will help transport planners and road authorities to monitor pavement surface quality, for cyclists to determine their desirable cycling route, and for government to promote cycling and encourage people to use shared bicycles therefore improving the urban transport environment.

2. Experiments

2.1 Cycling vibration test

2.1.1 Tested road sections

Field tests were carried out on 46 sections of 24 urban roads, a total of 11,500 m in length all made of asphalt pavements. Tested sections are located in the South West of Xi'an city, China, as shown in Fig.1 (a). These locations were chosen for two reasons: (1) Diversity of pavement type. According to site investigation, the types of asphalt pavement in this area consist of dense-graded asphalt, stone mastic asphalt and open-graded asphalt. In addition, these 46 sections represent different service life, condition and traffic volume. (2) Low disturbance to traffic. Our experiments require a stable test environment for both vibration test and perception test, as the results may be interfered by external interruption, such as excessive number of vehicles and pedestrians passing which may bring stress to the testers and affect their riding behavior. The tested area is far away from the city's central commercial areas. Each section was named by its abbreviation for reference (see Fig.1 (b) and Table 2). Individual location and trial number of tested sections were recorded via a GPS logger. Furthermore, sections with severely damaged pavements, such as cracks or potholes, were not counted whilst pavements of minor defects were included. According to the design data provided by local transport department, the slope of tested sections is in range of 0.5 % – 1.5 % while the curve radius is between 600 m – 1200 m. Generally, the test sections are flat and straight since this area is located on a flat terrain.



(a) Location of tested sections; (b) ID for each section

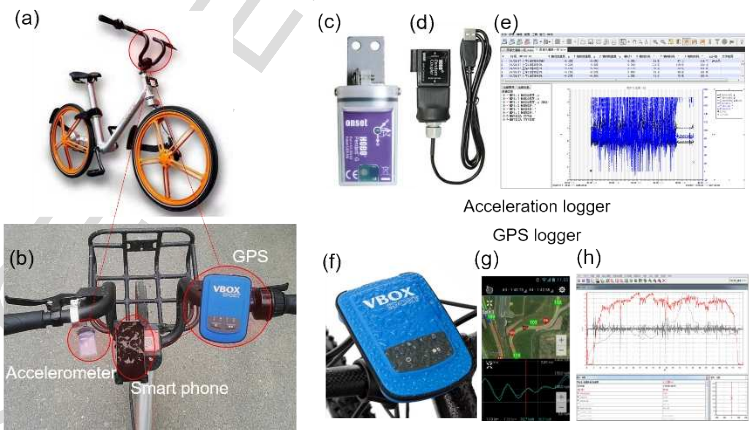
Note: maps supported by Google Earth^{TM} Pro

Fig.1 Distribution of tested pavement sections in Xi'an city, China

2.1.2 Measuring equipment

Cycling vibration data were collected from a Dynamic Cycling Comfort (DCC) Measure System developed at Chang'an University, as shown in Fig.2. This system consists of three parts: accelerometer, GPS coupled with a smart phone, and bicycle. The accelerometer adopted a HOBO Pendant G Acceleration Data Logger (as shown in Fig.2 (c)) which is a three-channel logger with 8-bit resolution and can record up to 21,800 combined x, y, and z axis acceleration. The technical parameters are: measurement range ± 29.4 m/s², accuracy 0.735 m/s², resolution 0.245 m/s². The accelerometer was firmly installed on the left handlebar of the bicycle by bolts, see Fig.2 (b). Before each experiment, these bolts were carefully checked to prevent sloshing. GPS employed a VBOX sport data logger (as shown in Fig.2 (f)) which was installed on the right handlebar. It records the following parameters in cycling test: time (accuracy 0.1 s, resolution: 0.01 s), position (2D position: ±5m*), velocity (accuracy 0.1 km/h, resolution: 0.01 km/h), height (5m*), accumulated distance (resolution 0.01 m), and heading (accuracy: ±0.2° s, resolution: 0.01° s). Meanwhile, a VBOX app was installed on a smart phone (as shown in Fig.2 (g)). The VBOX and smart phone are communicating via Bluetooth, as the smart phone functioned as a monitor that provided such info as velocity, trail and distance to the cyclist during testing. Cyclists therefore can adjust their riding behaviors to maintain a stable cycling and avoid sudden steering, acceleration and deceleration, etc. This DCC system was designed only to detect the vibration level on the hand-bar instead of saddle and peals, knowing that the human perception to vibration depends on the vibration position of human body (International Organization for Standardization., 1997). The hand-bar vibration was chosen to represent the overall vibration that a cyclist perceived, to simplify the test procedure, and to promote it for practical use. We had the DCC equipment verified for stability before it was used in field test.

In addition, the bicycle for experiment was a shared bicycle (see Fig.2 (a)) which is very common in Chinese cites. There was no mechanical fault in this selected bicycle. Moreover, a skilled cyclist was recruited from 11 candidates who were members of a local cycling club, for conducting the vibration test. The selected cyclist is a 28-years old heathy male (weight 83 Kg, height 177 cm) who has had over 6,000 km of cycling experience over the past 10 years.



(a) shared bicycle; (b) DCC installation; (c) acceleration logger; (d) controller and connecter of acceleration logger; (e) user interface of acceleration logger sofware; (f) GPS logger; (g) user interface of VBOX sport app installed on a smart phone; (h) user interface of VBOX tools installed on computer

Note: pictures (c), (d), (f) are sourced from the product brochure

Fig.2 Set-up for Dynamic Cycling Comfort (DCC) Measure System

2.1.3 Measuring procedures

The field testing consisted of three steps. Firstly, set up the accelerometer position using a levelling bubble in the laboratory, to keep *z* axis of the accelerometer perpendicular to the pavement. Examine the accelerometer position again upon arrival at test location and make any adjustment if necessary. Secondly, cyclist activates the acceleration logger by using its controller and connector (as shown in Fig.2 (d)). GPS logger starts logging when a speed higher than 0.8 km/h is detected and stops logging when the speed drops below this value. At last, the cyclist begins cycling along the assigned route with a constant speed (12~16 km/h). During the test, the cyclist refrains from shaking the bicycle handlebar, especially on the *z* axis. The experiment will be carried out again if there is a significant anomaly in the test data present in logger's software (as shown in Fig.2 (e) and (h)). The variation caused by cycling behavior is therefore minimized through above efforts. Each section was tested three times to reduce random error. The average sampling length for each test section was 250 m, the duration of each test exceeded 60 s.

2.1.4 Data processing

The quantitative assessment of human exposure to vibration was conducted in accordance with international standard ISO 2631 (International Organization for Standardization., 1997) using the vibration signals on *x*, *y* and *z* axis. The primary variable used to characterize a vibration is the *rms* acceleration. This *rms* acceleration should be weighted in frequency domain (recommended by the ISO Standard) and passed through a narrow band filter, thereby producing a value defined as weighted frequency *rms* acceleration: a_{wi} (in m/s^2). The vibration is measured in tri-axial coordinates, a value of frequency weighted *rms* acceleration was thus obtained for each axis, x, y and z, represented by a_{wx}, a_{wy} and a_{wz}, in m/s^2. The calculation follows Eq. (1) Where T is the duration of the measurement. According to ISO, these three values can be combined to calculate the a_{wv} (m/s^2) using Eq. (2).

$$a_{wi} = \left[\frac{1}{T}\int_0^T a_{wi}^2(t)dt\right]^{1/2}; i = x, y, z \quad \text{Eq. (1)}$$

$$a_{wv} = \sqrt{{a_{wx}}^2 + {a_{wy}}^2 + {a_{wz}}^2} \quad \text{Eq. (2)}$$

2.2 Cyclist' perception of vibration

2.2.1 Questionnare design

Comfort is a subjective experience depending on individuals' perception. We recruited a total of 17 volunteers to complete the questionnaire and recorded their assessments of vibration (and comfort) after cycling on each selected pavement section. As recommended by Li et al. (2013)**,** the questionnaire used in this survey contained pre-ride and in-ride questions. The pre-ride survey asked participants about behavioral questions, such as cycling skill, attitude towards cycling, purpose for cycling, acceptable cycling distance as well as frequency of cycling. The in-ride survey asked cyclists to rate each section in four questions. The first is whether they considered the cycling experience "acceptable" or "unacceptable". There are 6 aspects involved in the second question. They are scenery, vibration, weather, road geometry, congestion and traffic condition; each is an overall concept concerning their experience of cycling. Specifically, scenery includes the natural environmental factors, such as appearance of the surrounding buildings and green facilities, or tidiness of the street. Vibration indicates the intensity of bumpy road sections perceived by cyclists. Weather describes the overall perception of temperature, wind speed, humidity, sunlight, etc. Road geometry reflects the slope and curvature of the tested pavements.

Congestion means the degree of crowdedness or traffic volume on the tested pavement. Traffic condition includes the segregation (or integration) of tested sections from motorized lanes such as shared lanes. The options for the second question are from 'very poor (1)' to 'very good (5)'. The third question is to rate the overall comfort level on the setions they had ridden. A scale of 1 to 5 was used for the answers, with 1 being the worst possible condition and 5 being the best. The fourth question is to discribe their preception of vibration; available choices are: non-perceptible (1), just perceptible (2), easily perceptible (3), strongly perceptible (4) and extremely perceptible (5).

2.2.2 Volunteers

There were 17 volunteers (3 female and 14 male) involved with this field test. Their ages are between 22 and 36 which represents 77.6% of the cycling populatin (TalkingData, 2016). In addition, 7 out of the 17 volunteers are postgraduate students enrolled in MSc Road and Railway Engineering programme at Chang'an University (X'an), who clearly understand the questions in the survey. The rest of the volunteers are recruited from a local cycling club, who have received induction and necessary explanations of the questionnaire prior to field test. The volunteers' profiles concerning their cycling experiences are shown in Fig.3, these profiles are obtained by summarizing their answers to questions in the pre-ride survey.

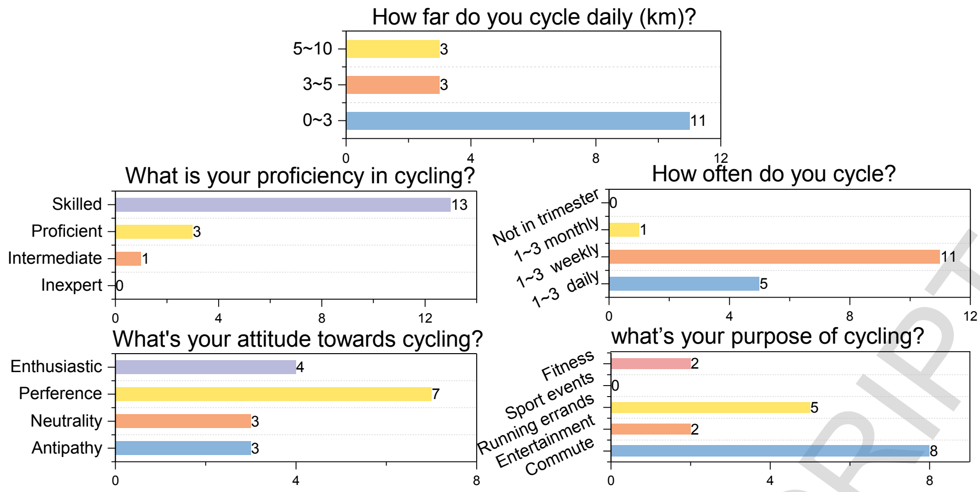


Fig.3 Pre-ride survey results

2.2.3 Procedures of perception test

Testing the perception of vibration for all 46 pavement sections is a time-consuming task, most volunteers were not available for the entire testing period. Meantime, several pavement sections have very close a_{wv} values, thus removing a few sections with similar a_{wv} values from the test sample would help with efficiency withough compromising the representativeness of the results. Therefore, 11 pavement sections were selected for perception of vibration test based on their a_{wv} (the sections can be fund in Table 2) , which varied from 1.03 m/s^2 to 3.19 m/s^2 (roughly at 0.2 m/s^2 interval).

Volunteers were put in the scenario that they have cycled 3 km on the road prior to the test, then they cycled at least 500m on each selected section at their comfortable speed. During the test, volunteers were instructed not to discuss their point of view with each other. This is to ensure their views were independent. In additon, volunteers were transportd between test sections by vehicles instead of cycling to ensure their perception was consistent and not affected by a decline of physical strength.

2.2.4 Reliability assessment of questionnaire results

The Cronbach's *a* examination was employed to vertify the reliability of answers present in the questionnares. Cronbach's *a* can be calculated by Eq. (3), and the Cronbach's *a* for each item is presented in Table 1. Generally, Cronbach's *a* above 0.7 indicates that the results in questionnaires are reliable (de Vet et al., 2017). It can be seen from Table 1 that, the questionnaire designed for the perception test has enough reliability (minimum α of 0.739).

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K}\sigma_{Y_i}^2}{\sigma_X^2}\right) \qquad \text{Eq. (3)}$$

Where σ_X^2 is the variance of observed test scores, and $\sigma_{Y_i}^2$ is the variance of component *i* for the current sample (person), *K* is the number of questions.

Table 1 Reliability (Cronbach's *a*) of questionnaire results

Comfort			Acceptable	Perception	Comfort score
0.937					
Scenery	Road geometry	Vibration			
0.772	0.771	0.905	0.749	0.910	0.846
Congestion	Weather	Traffic			
0.769	0.739	0.803			

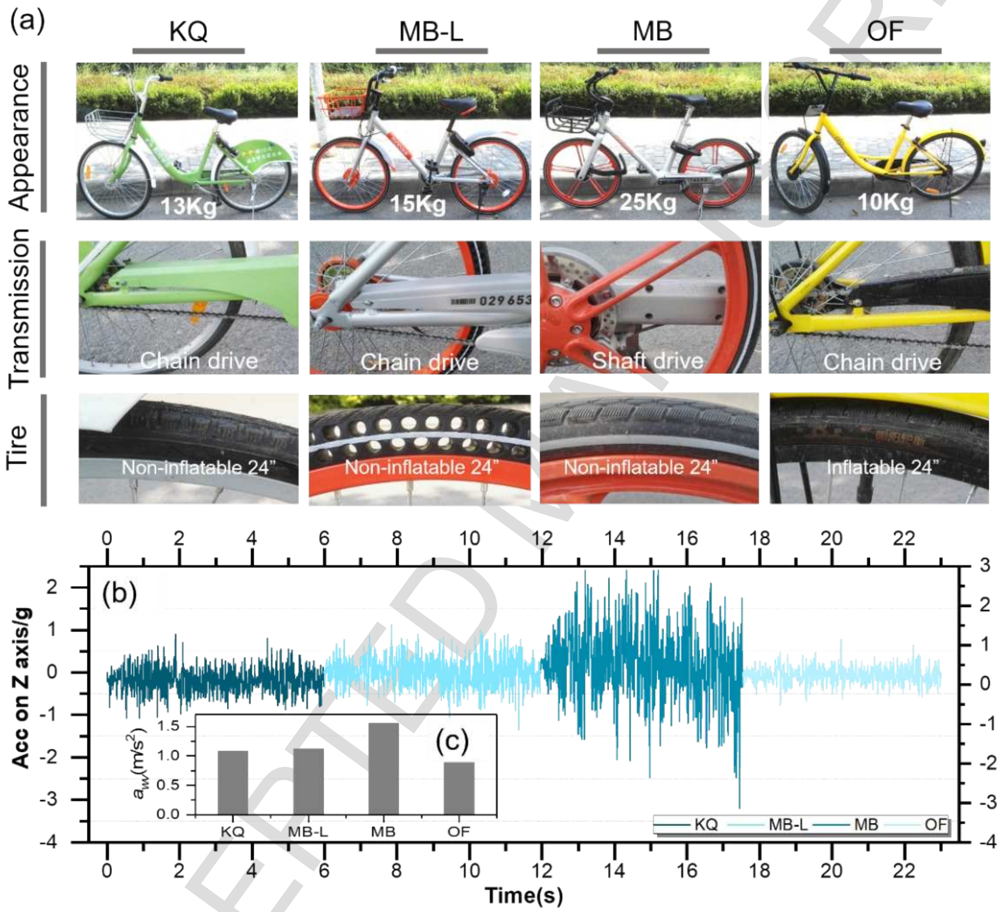
3. Results and discussion

3.1 Effect of bicycle and speed on cycling vibration

3.1.1 Bicycle type

The bicycle type is one of the key factors that influence the cycling vibration level (Petrone and Giubilato, 2013). Therefore, it is imperative to clarify the bicycle type for the tests. The commonly used bicycles can be roughly divided into road bicycle, track bicycle, mountain bicycle and touring bicycle according to their build or design purpose. Touring bicycles are adopted by the vast majority of shared bicycle brands in Chinese market. A total of four bicycle models (KQ, OF, MB-L and MB) which belong to three shared bicycle brands were selected, they are very commonly seen on Chinses urban roads and have high market share. Details of the bicycle models used in field test are demonstrated in Fig.4 (a) where the appearance, weight, transmission and tire size are provided.

To evaluate the vibration levels on different bicycles, the cyclist was asked to cycle along the same prescribed route using four bicycle models, and the results are shown in Fig. 4 (b). It can be seen that the vibration pattern on *z* axis over four bicycle models is clearly different. The signal on MB is more intense than of the other three models. The quantified results are shown in Fig. 4 (c) where the a_{wv} value on MB is 1.56 m/s^2 and is 1.08 m/s^2, 1.12 m/s^2 and 0.89 m/s^2 in KQ, MB-L and OF, respectively. This is due to the structural design of MB shared bicycle. The MB shared bicycle is the most durable model of the four as it is designed to be maintenance-free once used in the shared bicycle scheme. It has stronger frame, non-inflatable tires and rigid shaft drive system. However, the downside of being maintenance-free is, as the results indicated, the increased vibration level and undesirable cycling experience. Previous studies have similar results concerning the effect of bicycle's structural characteristics on cycling vibration. Richard et al. (2015) reported that higher tire pressure led to stronger shock absorption by the cyclist's hands. This study concluded that non-inflatable tires (solid tires) contribute to higher cycling vibration because of higher tire pressure compared with inflatable tires. The results shown in Fig.6 also indicate that bicycle (such as OF) with inflatable tire has better cycling comfort than others (such as MB, KQ and MB-L). Meanwhile, several studies showed that heavier bicycles not only require more man power from the cyclist but also are responsible for higher vibration level (Li et al., 2012; Olieman et al., 2012). The shaft drive system and reinforced aluminum frame designed for the MB bicycle significantly increased the bicycle weight (25 Kg) which is a primary factor for its poor riding comfort. After evaluating the four shared bicycle models, the MB bicycle was selected for subsequent tests in order to derive the vibration data under the most disadvantageous condition.



(a) Features for tested bicycles; (b) Vibration on the z axis; (c) a_{wv} results

Fig.4 Riding comfort results of public-shared bicycles

3.1.2 Cycling speed

To investigate the correlation between cycling speed and vibration, the cyclist was required to cycle on a pavement section for three times at different speeds. The cycling speeds selected in the test were 10 km/h, 15 km/h and 20 km/h. The speeds were selected based on the conclusions from previous research (Boufous et al., 2018), which reported that more than 50% of the cyclists prefer cycling at a speed of 10 - 16 km/h on urban shared-path while nearly 80% of the cyclists are travelling at 20 km/h or less. Meanwhile, another survey showed that cyclists are more comfortable with a speed of 8 - 16 km/h (Joo et al., 2015). Higher speeds are not considered in this research because shared bicycles have structural features making it strenuous and unpleasant for cyclists to maintain a higher speed (more than 25 km/h) for long cycling period. The tested pavement sections were CY-1, ZB8-BX and ZB8-NX2, which represent different age, surface condition, slope and curvature. Fig.5 shows the profile of cycling speed, distance and vibration data for three pavement sections. The recorded cycling speeds show slight fluctuation because of the difficulty in maintaining an absolute uniform speed.

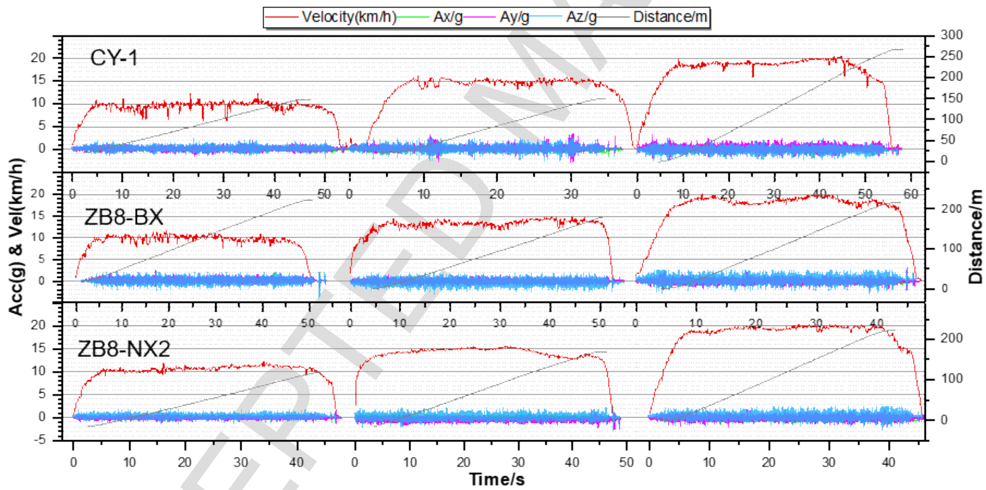


Fig.5 Riding profiles for three pavement sections with different velocities

It can be seen that each test took more than 45 seconds, which is divided into three 15 s segments. The average value for the speed contained in each 15 s segment is used to represent the speed of this period, then the a_{wv} for this segment can be calculated using Eq. (1) and Eq. (2). The average speeds are classified into three categories: low speed (8 – 12 km/h), intermediate speed (12 – 16 km/h) and high speed (17 – 20 km/h). Fig. 6 shows all segments grouped by velocity, it is clear that the a_{wv} value in each speed category presents in a range. The K-means clustering analysis was used to determine the a_{wv} in different cycling speed category (cluster center, as shown in Fig. 6). Obviously, the vibration level a_{wv} increases significantly with the increase of cycling speed, representing an almost linear correlation. The cycling vibration a_{wv} are 1.71 m/s^2, 2.31 m/s^2 and 3.12 m/s^2 for the clustered cycling speed of 9.95 km/h, 14.49 km/h and 18.63 km/h, respectively. Considering the average cycling speed reported by previous study (Joo et al., 2015) and the relationship between speed and vibration, an intermediate cycling speed of 12 – 16 km/h was selected for subsequent perception test.

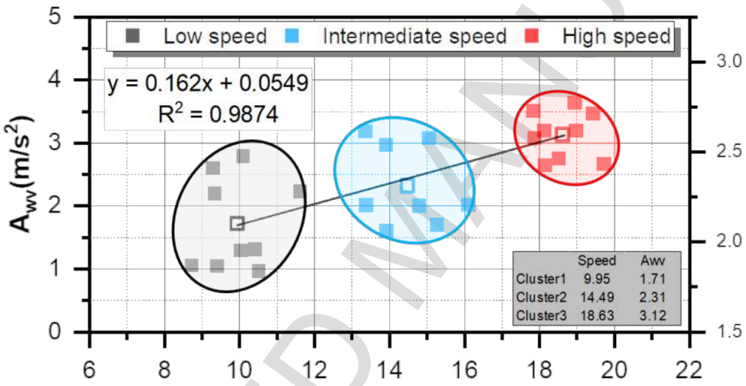


Fig.6 K-means clustering analysis results of a_{wv} at different riding velocity

3.2 Cycling vibration on tested road sections

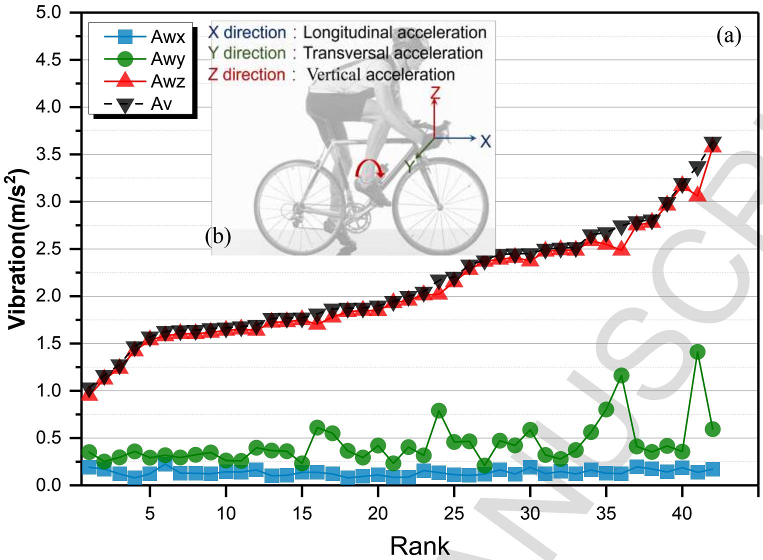
The cycling vibration a_{wv} on each pavement section can be calculated from the cycling profiles, the results are presented in Table 2. The a_{wv} is essentially related to the acceleration power during cycling. Higher a_{wv} values indicate less comfortable riding and higher vibration. Thus, the comfort level of the 46 pavement sections can be ranked by their a_{wv}, which are shown in Table 2. The a_{wv} value range from 1.031 m/s^2 (XB-4) to 3.193 m/s^2 (XXDD-1), showing that the cycling comfort among these sections is quite different. However, these values alone are unable to indicate whether a pavement section can provide a comfortable riding experience, unless a threshold is defined for comfort.

Table 2 Cycling vibration (a_{wv}) of each tested section

Section ID	XB-4	ZB8-NX	FZ	DKC1	JY-5	ZB8-BX	PF	FXC-1
Ranking	1	2	3	4	5	6	7	8
a_{wv} (m/s^2)	1.031	1.163	1.270	1.276	1.308	1.451	1.467	1.628
Section ID	CY-2	ZB3	XF-1	CY-3	ZB6	XB-3	ZB4	FJ
Ranking	9	10	11	12	13	14	15	16
a_{wv} (m/s^2)	1.636	1.640	1.658	1.665	1.678	1.693	1.718	1.766
\Section ID	FXX	JY-2	ZB5	ZZTB	JY-1	SS-2	ZB2	CY-1
Ranking	17	18	19	20	21	22	23	24
a_{wv} (m/s^2)	1.769	1.771	1.813	1.865	1.874	1.875	1.897	1.946
Section ID	SS-1	XXDD-2	JY-3	ZB8-ND	XB-2	BY2	LHN	XXDD-4
Ranking	25	26	27	28	29	30	31	32
a_{wv} (m/s^2)	1.999	2.043	2.063	2.173	2.202	2.303	2.331	2.381
Section ID	JY-4	XXDD-3	SLY1-2	XF-2	BY1	XT	XB-1	SLYCC
Ranking	33	34	35	36	37	38	39	40
a_{wv} (m/s^2)	2.442	2.449	2.451	2.499	2.509	2.516	2.651	2.665
Section ID	FXC-2	ZB5-2	ZW	ZB8-NX2	ZB8-BD	XXDD-1		
Ranking	41	42	43	44	45	46		
a_{wv} (m/s^2)	2.674	2.746	2.790	2.808	2.858	3.193		

Note: the highlighted represent the pavement sections selected for perception of vibration test (see Section 3.4 and 3.5).

According to the definition, the a_{wv} value is jointly influenced by the vibration on *x*, *y* and *z* axis. However, it needs more evidence to tell which direction is playing the most important role in determining the a_{wv} and therefore contributing to the perception of vibration when cycling. Generally, accelerations on the *x, y* and *z* axis of the sensor are referred to as the longitudinal, transversal and vertical motion of the bicycle (Joo and Oh, 2013). Characteristics of measurement on each axis are illustrated in Fig. 7 (b). The impact of acceleration on each axis on the cycling vibration a_{wv} can be derived by comparing the respective trends of a_{wx}, a_{wy}, a_{wz} with the a_{wv}. Fig. 7 (a) shows the data of a_{wx}, a_{wy}, a_{wz} and a_{wv} over the 46 tested pavements in ascending order of the a_{wv} value. Obviously, a_{wx} and a_{wy} have limited contribution to the a_{wv} value. On the other hand, the trends of a_{wv} and a_{wz} are alike and their values are very close, indicating the vibration perceived by a cyclist mainly depends on the acceleration in the vertical direction rather than longitudinal or transversal directions.



(a) Calculated results of a_{wx}, a_{wy}, a_{wz} and a_{wv}; (b) Three directional acceleration on the bicycle hand-bar

Fig.7 Comparisons of a_{wx}, a_{wy}, a_{wz} and a_{wv}

3.3 Effect of environmental factors on cycling comfort

The evaluation of volunteers' comfort in association with scenery, vibration, weather, road geometry, congestion and traffic condition of the cycling environment is made based on the answers collected from the questionnaires, the results are demonstrated in Fig.8. The 11 tested sections are ranked on the x axis by their a_{wv} value (cycling vibration, see Table 2), and the y axis represents volunteers' rate of the cycling environment in which 1 stands for very uncomfortable and 5 indicates very comfortable.

To determine the primary factor that influences the cyclists' perception of comfort, correlation analysis was conducted between each item in Fig.8 to derive the overall comfort score that volunteers had on the tested sections. The correlation coefficients of scenery, vibration, weather, road geometry, congestion and traffic condition with the overall comfort score are 0.741, 0.986, 0.750, 0.641, 0.433 and 0.503, respectively. It can be seen that the primary factor to influence the cyclists' comfort is vibration, followed by weather (2nd) and scenery (3rd). Road geometry, congestion and traffic condition are considered less important to affect cycling comfort. It is worth knowing the difference in results from other researches. For instance, Winters et al. (2010) compared 15 factors from a survey sample of 73 in Metro Vancouver, Canada and found that the top influencing factors for cycling are ease of cycling, weather conditions, route conditions and interactions with motor vehicles. Ayachi et al. (2015) conducted an online survey on cycling comfort which involved 244 frequent cyclists living in Canada, United States, France, Switzerland, Australia and South Africa, the results indicated that their cycling comfort is mainly based on the quality of bicycle, the road and external (e.g. weather, temperature) conditions. Therefore, the primary factor for cycling comfort is varied across the globe, and the aforementioned factors are not independent in affecting the cyclists' opinions. For example, the cyclists may not pay attention to the scenery, vibration etc. if they cycle in an area with extremely high traffic volume. Similarly, road geometry (e.g. steep gradient) and scenery (e.g. garbage on road) may change the rider's assessment of comfort.

The pavement surfaces of each tested section are shown in Fig. 9. It can be seen that there is little difference between measured sections in terms of scenery, road geometry, congestion and traffic condition, as they were all straight, relatively flat and of low traffic volume. The most significant difference concerning weather is the air temperature, the perception tests at DKC-1, PF, FXC-1 and ZB5 were carried out in the morning at lower temperature (23 – 26 °C) as opposed to the tests conducted at noon at higher temperature (35 – 38 °C) at other sections, which can explain the influence of temperature on the cycling comfort. At last, surface roughness of the 11 sections can be observed in Fig.9. In summary, vibration is considered the primary factor that affects cyclists' comfort after analyzing the influence of various factors.

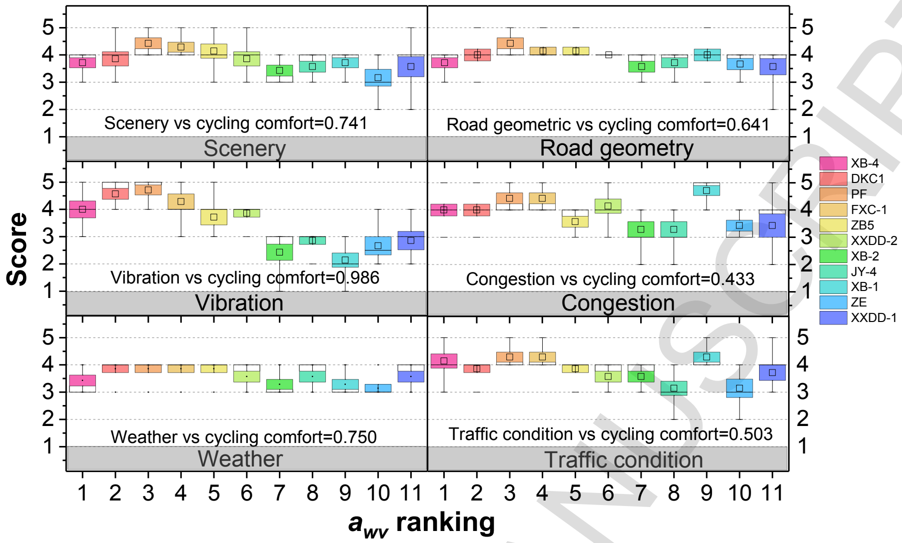


Fig. 8 Volunteers score on scenery, road geometry, vibration, congestion, weather and traffic condition (1-very poor, 5-very good)

Fig.9 Outlook of each measured section

3.4 Cyclist's perception of vibration

After analyzing the results from the questionnaires completed by volunteers based on their cycling experience on all tested sections, their opinions on vibration can be evaluated in terms of acceptable rate, comfort and vibration perceptible level, results are shown in Fig.10.

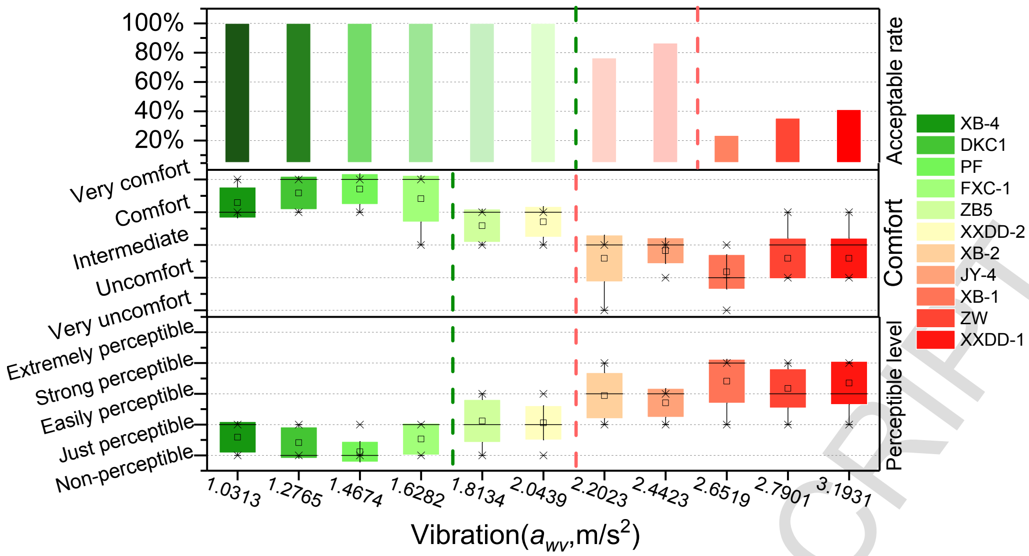
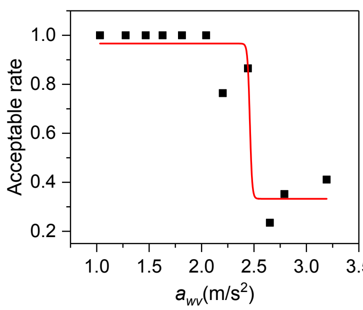


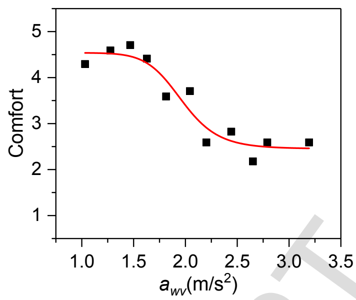
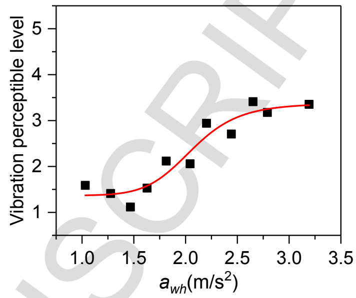
Fig. 10 Vibration in tested sections: acceptable rate, comfort and vibration perceptible level

It can be seen from Fig.10 that all cyclists considered the vibration to be completely acceptable when the a_{wv} was less than 2.04 m/s^2; the acceptable rate decreased to around 80% when the a_{wv} increased to 2.44 m/s^2; the acceptable rate further dropped to below 40% when the a_{wv} exceeded 3.19 m/s^2. Noteworthy, the a_{wv} and acceptable rate do not present a consistent linear correlation, for example, they demonstrated linear correlation when a_{wv} was above 2.65 m/s^2, but no linear correlation when a_{wv} was below 2.04 m/s^2. This is because the difference in perception of vibration among volunteers is only sensitive to a certain range of a_{wv} values. As for the comfort level, it decreased with the increase of a_{wv}. Specifically, the cycling vibration was described to be 'comfortable' to 'very comfortable' when the a_{wv} was less than 1.62 m/s^2, 'intermediately comfortable' when the a_{wv} was between 1.81 m/s^2 and 2.04 m/s^2, and 'uncomfortable' when the a_{wv} was greater than 2.20 m/s^2. In addition, no pavement section has been classified as 'very uncomfortable' although a few volunteers rated such for some sections. Meantime, the correlation between vibration perceptible level and a_{wv} is similar to that of the comfort, indicating that the perception of vibration strongly influences the cycling comfort.

The cycling vibration threshold of acceptable rate, comfort and vibration perceptible level can be defined using satistical method, the results are demonstrated in Table 3. Futhermore, the mathmatical model for acceptable rate, comfort and vibration perceptible level can be developed via logistic regression (as shown in Table 3). The models developed in this reaserch are valid with four specific conditions which are bicycle type (MB shared bicycle), cycling speed (12 – 16 km/h), pavement type (asphalt pavement) and cyclist (age 22 – 36, male in marjority). Once a road authority obtains the a_{wv} value on a cycling track though field test, the acceptable rate, comfort and vibration perceptible level can be determined by the established threshold.

Table 3 Threshold of acceptable, comfort and vibration perceptible level and their regression models

<table>
<tr><th colspan="6">Threshold (in a_{wv} m/s^2)</th></tr>
<tr><td>Completely acceptable</td><td>(0,2.12)</td><td>Very comfortable-Comfortable</td><td>(0,1.72)</td><td>Barely perceptible-Just perceptible</td><td>(0,1.72)</td></tr>
<tr><td>Acceptable</td><td>[2.12,2.54)</td><td>Comfortable-Intermediate</td><td>[1.72,2.12)</td><td>Just perceptible-Easily perceptible</td><td>[1.72,2.12)</td></tr>
<tr><td>Unacceptable</td><td>[2.54,)</td><td>Intermediate-Uncomfortable</td><td>[2.12,3.19)</td><td>Easily perceptible-strongly perceptible</td><td>[2.12,3.19)</td></tr>
<tr><th colspan="6">Logistic regression model</th></tr>
<tr><td colspan="2">Equation</td><td>Reduced Chi-Sqr</td><td>Adj. R^2</td><td colspan="2">Fitting line</td></tr>
<tr><td colspan="2">a_{wv} VS Acceptable rate</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td colspan="2">$$y = 0.3326 + \frac{0.643}{1 + \left(\frac{x}{8.078}\right)^{168.99}}$$</td><td>0.009</td><td>0.900</td><td colspan="2">
</td></tr>
<tr><td colspan="2">a_{wv} VS Comfort</td><td>0.123</td><td>0.857</td><td colspan="2"></td></tr>
</table>

$y = 2.530 + \frac{2.002}{1 + \left(\frac{x}{1.937}\right)^{12.309}}$			
a_{wv} VS Vibration perceptible level			
$y = 3.373 + \frac{-2.005}{1 + \left(\frac{x}{2.063}\right)^{9.055}}$	0.077	0.923	

3.5 Mapping of cycling-track vibration

In recent years, great efforts have been made by the Chinese government, both central and local, to promote cycling as an alternative to motorized transportation, by development of cycling-track and other infrastructure in cities. Currently, despite of the rapid growth of shared bicycle schemes in China, an increasing number of cyclists are complaining about the poor pavement condition which results in unacceptable cycling vibration. Road authorities in China are responsible for the maintenance and improvement of cycling tracks to meet the demands by cyclists. However, an imminent task faced by road authorities is to develop an effective, science-based (quantitative) method to evaluate the cycling infrastructure against the comfort criteria, such that the results can be used to inform road authorities of maintenance needs, and to enable cyclists to select their preferred routes.

Inspired by digital mapping technologies, in particular, traffic volume mapping, a cycling comfort mapping on the urban roads can be developed as a result of this research. As an exploratory and preliminary attempt, the Qujiangchi Park was selected for cycling comfort mapping. The park is located in the South East of Xi'an city, which is a famous tourist attraction to both domestic and foreign visitors. The cycling paths in this park are made of asphalt pavement, a total of 3,521 m long path was mapped. The data for cycling comfort were obtained by aforementioned DCC system, the thresholds used in mapping were consistent with those in the cycling vibration test. Specifically, the cycling comfort level is represented by the calculated a_{wv} value, the color of the bar in the comfort map indicates the a_{wv} in accordance with the comfort threshold established in Section 3.4. The a_{wv} values are calculated using the vibration data recorded every 20 seconds. The cycling route and the trail can be obtained from the DCC system in the format of (x, y) coordinates which can be used to draw the map, the mapping results are shown in Fig.11. The cycling comfort levels in this park are indicated as red (uncomfortable to intermediate), yellow (intermediate to comfortable) and green (comfortable to very comfortable). The red, yellow and green sections account for 3%, 49% and 48%, respectively, of the total length indicating that this park is largely considered comfortable for cycling. Nonetheless, manager of the park can carry out some maintenance or local patching to improve the cycling comfort for the 'red' sections. As a small-scale cycling comfort mapping, the exercise carried out for Qujiangchi Park shows significant advantages over the conventional measurements (visual survey or individual feeling). The mapping system enables the civil department to quantitatively evaluate the cycling comfort of their road infrastructure, such that necessary investments can be made to improve the service level of cycling paths. An enhanced cycling environment is also conducive to tourism and the development of cycling events, and contributes to sustainable urban transport in Chinese cities like Xi'an.

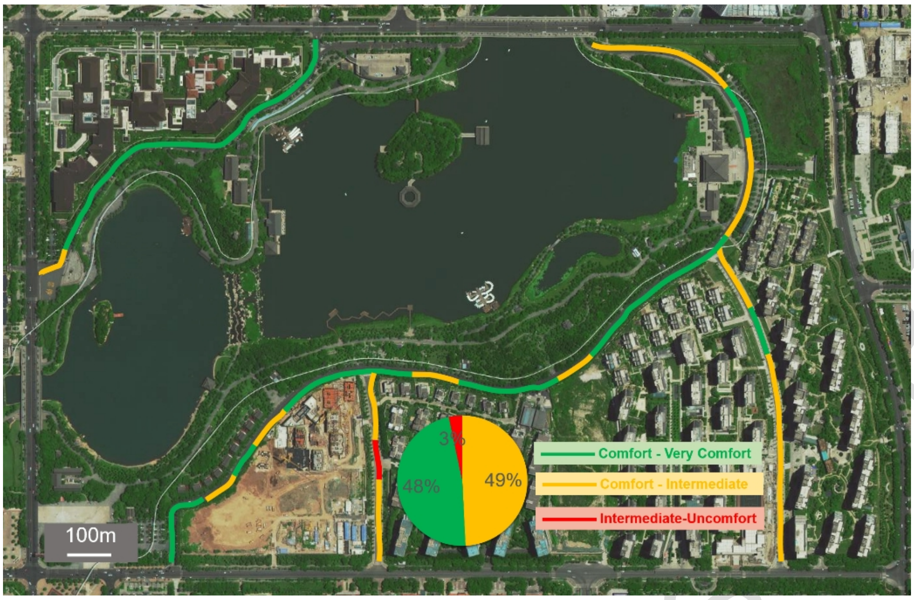


Fig.11 The cycling comfort map for Qujiangchi Park, Xi'an city, China

4. Conclusions and Recommendations

In this study, the method for evaluating the cycling comfort on urban roads was established based on cyclists' perception of vibration. The following conclusions can be drawn:

The self-developed Dynamic Cycling Comfort (DCC) measuring system is adequate to capture the vibration data in the longitudinal, transversal and vertical directions, and the GPS position data are accurate. The DCC system adopted the modular products, GPS and accelerometer as the core components which are available for purchase across the globe therefore the DCC system can be applied widely.

The cycling vibration is sensitive to the cycling speed and bicycle type. The results of K-means clustering analysis indicate that the cycling vibration a_{wv} increases significantly with the increase of cycling speed. The a_{wv} value at low speed (8 – 12 km/h), intermediate speed (12 – 16 km/h) and high speed (17 – 20 km/h) are 1.64 m/s^2, 2.31 m/s^2 and 3.01 m/s^2, respectively. As revealed by a comparison between four popular types of shared bicycle, a heavier bicycle with solid tires comes with higher cycling vibration compared with a lighter one with inflatable tires.

In the area studied, the vibration sensed by cyclists played a more important role in determining the cycling comfort than scenery, road geometry, congestion, weather and traffic condition. The primary environmental factor responsible for determining cycling comfort varies with countries and regions around the world because of the natural (topography, temperature), social (culture) and economic (traffic mix and volume) environment.

The comfort level is proportional to acceptable rate, and inversely proportional to the vibration. In addition, the cycling comfort can be defined in accordance with the a_{wv} value such as: very comfortable to comfortable (up to 1.72 m/s^2), comfortable to intermediate (1.72 m/s^2 to 2.12 m/s^2), intermediate to uncomfortable (above 2.12 m/s^2).

At last, the mapping technology can potentially help to establish the road network database in relation to cycling comfort, to provide a science-based, easy-to-follow guidance to both the road authorities and transport planners, in order to monitor the quality of pavement surface and to enhance the cycling experience on urban roads. This in return will stimulate local economic development and promote sustainable urban transport.

This research made a preliminary study of the correlation between cycling comfort and the vibration. The aforementioned results are believed to be accurate, although there is room to improve accuracy and representativeness of the findings. Firstly, the number of volunteers involved in the comfort perception tests was small due to limited resources available to this study, larger scale investigation will benefit the development of national or international standards for testing and the generalization of findings. In addition, the diversity of volunteers in terms of gender, age and profession can be enriched. Thirdly, the data capture system (device and mounting position on the bicycle) and its effect on the results can be further studied. Lastly, in areas where the roads and cycle paths are typically paved with concrete materials, separate studies potentially using different device need to be carried out to find the new correlation(s).

Acknowledgement

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Reference

Ayachi, F.S., Dorey, J., Guastavino, C., 2015. Identifying factors of bicycle comfort: An online survey with enthusiast cyclists. Appl Ergon 46 Pt A, 124-136.

Bíl, M., Andrášik, R., Kubeček, J., 2015. How comfortable are your cycling tracks? A new method for objective bicycle vibration measurement. Transportation Research Part C: Emerging Technologies 56, 415-425.

Boufous, S., Hatfield, J., Grzebieta, R., 2018. The impact of environmental factors on cycling speed on shared paths. Accid Anal Prev 110, 171-176.

Calvey, J.C., Shackleton, J.P., Taylor, M.D., Llewellyn, R., 2015. Engineering condition assessment of cycling infrastructure: Cyclists' perceptions of satisfaction and comfort. Transportation Research Part A: Policy and Practice 78, 134-143.

Chou, C.-P., Lee, W.-J., Chen, A.-C., Wang, R.-Z., Tseng, I.C., Lee, C.-C., 2015. Simulation of Bicycle-Riding Smoothness by Bicycle Motion Analysis Model. Journal of Transportation Engineering 141(12), 04015031.

de Vet, H.C.W., Mokkink, L.B., Mosmuller, D.G., Terwee, C.B., 2017. Spearman–Brown prophecy formula and Cronbach's alpha: different faces of reliability and opportunities for new applications. Journal of Clinical Epidemiology 85, 45-49.

Dim, N.K., Ren, X., 2017. Investigation of suitable body parts for wearable vibration feedback in walking navigation. International Journal of Human-Computer Studies 97, 34-44.

GB/T 4970-2009, 2009. Method of Running test: Automotive Ride Comfort in China. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Beijing.

Giubilato, F., Petrone, N., 2012. A method for evaluating the vibrational response of racing bicycles wheels under road roughness excitation. Procedia Engineering 34, 409-414.

Gomes, H.M., Savionek, D., 2014. Measurement and evaluation of human exposure to vibration transmitted to hand-arm system during leisure cyclist activity. Revista Brasileira de Engenharia Biomédica 30(4), 291-300.

Hölzel, C., Höchtl, F., Senner, V., 2012. Cycling comfort on different road surfaces. Procedia Engineering 34, 479-484.

ISO 2631, 1997. Mechanical vibration and shock Evaluation of human exposure to whole-body vibration - Part 1 General requirements. International Organization for Standardization.

Joo, S., Oh, C., 2013. A novel method to monitor bicycling environments. Transportation Research Part A: Policy and Practice 54, 1-13.

Joo, S., Oh, C., Jeong, E., Lee, G., 2015. Categorizing bicycling environments using GPS-based public bicycle speed data. Transportation Research Part C: Emerging Technologies 56, 239-250.

Li, H., Harvey, J., Thigpen, C., & Wu, R. (2013). Surface Treatment Macrotexture and Bicycle Ride Quality (Vol. Research Report: UCPRC-RR-2013-07): University of California Pavement Research Center: Davis, CA.

Li, H., Harvey, J., Wu, R., Thigpen, C., Louw, S., Chen, Z., Rezaie, A. (2013). Preliminary Results: Measurement of Macrotexture on Surface Treatments and Survey of Bicyclist Ride Quality on Mon-198 and SLO-1 Test Sections (Vol. Technical Memorandum: UCPRC-TM-2013-07): University of California Pavement Research Center: Davis, CA.

Li, Z., Wang, W., Liu, P., Ragland, D.R., 2012. Physical environments influencing bicyclists' perception of comfort on separated and on-street bicycle facilities. Transportation Research Part D: Transport and Environment 17(3), 256-261.

Luo Wangshu., 2018. Autonomous cars, shared bikes due for improvement. Chinadaily. Available at: http://www.chinadaily.com.cn/a/201802/07/WS5a7b0330a3106e7dcc13b608.html. (Accessed in 2018

Feburary 8).

Olieman, M., Marin-Perianu, R., Marin-Perianu, M., 2012. Measurement of dynamic comfort in cycling using wireless acceleration sensors. Procedia Engineering 34, 568-573.

Petrone, N., Giubilato, F., 2013. Development of a Test Method for the Comparative Analysis of Bicycle Saddle Vibration Transmissibility. Procedia Engineering 60, 288-293.

Ricci, M., 2015. Bike sharing: A review of evidence on impacts and processes of implementation and operation. Research in Transportation Business & Management 15, 28-38.

Richard, S., Champoux, Y., Lépine, J., Drouet, J.-M., 2015. Using an Alternative Forced-choice Method to Study Shock Perception at Cyclists' Hands: The Effect of Tyre Pressure. Procedia Engineering 112, 361-366.

Rupp, R.F., Vásquez, N.G., Lamberts, R., 2015. A review of human thermal comfort in the built environment. Energy and Buildings 105, 178-205.

Rybarczyk, G., Wu, C., 2010. Bicycle facility planning using GIS and multi-criteria decision analysis. Applied Geography 30(2), 282-293.

TalkingData, 2016. Analysis Report of Shared Bicycle User in China. Beijing Tendcloud Tianxia Technology Co., Ltd, Beijing. Available in: http://www. mi.talkingdata.com/report-detail.html?id=462 (accessed 31/01/2018).

Thigpen, C., Li, H., & Harvey, J. (2015, January 11-15, 2015). Modeling the Impact of Pavement Roughness on Bicycle Ride Quality (15-3542). Paper presented at the Transportation Research Board 94th Annual Meeting, Washington, D.C.

Winters, M., Davidson, G., Kao, D., Teschke, K., 2010. Motivators and deterrents of bicycling: comparing influences on decisions to ride. Transportation 38(1), 153-168.

Zhang, L., Zhang, J., Duan, Z.-y., Bryde, D., 2015. Sustainable bike-sharing systems: characteristics and commonalities across cases in urban China. Journal of Cleaner Production 97, 124-133.

Wu, R., Louw, S., Li, H., Thigpen, C., & Harvey, J. (2015, January 11-15, 2015). Bicycle Vibration and Pavement Ride Quality for Cyclists (15-4672). Paper presented at the Transportation Research Board 94th Annual Meeting, Washington, D.C.

Appendix A

Urban Cycling Questionnaire

Section ID:___ Name:___ Gender:___ Age:___ Date:___

Pre-ride Survey					
How often do you cycle?	☐Not in trimester	☐1-3 Monthly	☐1-3 Weekly	☐1-3 daily	
How far do you cycle daily?	☐0-3 km	☐3-5 km	☐5-10 km		
What's your attitude towards cycling?	☐Enthusiastic	☐Preference	☐Neutrality	☐Antipathy	
What's your purpose of cycling?	☐Fitness	☐Sport events	☐Running errands	☐Entertainment	☐Commute
What's your proficiency in cycling?	☐Skilled	☐Proficient	☐Intermediate	☐Inexpert	
In-ride Survey					
Please indicate your level of cycling comfort (1- 5, 1=Uncomfortable; 5=Comfortable) _______					
Please mark the following items for the section you have just ridden.					
	Very poor (1)	Poor (2)	Neutral (3)	Good (4)	Very good (5)
Scenery	☐	☐	☐	☐	☐
Road Geometric	☐	☐	☐	☐	☐
Vibration	☐	☐	☐	☐	☐
Congestion	☐	☐	☐	☐	☐
Weather	☐	☐	☐	☐	☐
Traffic condition	☐	☐	☐	☐	☐
How do you rate the vibration during your cycling?	☐Acceptable	☐Unacceptable			
Please pick one option to describe your perception of vibration.					
☐Non-perceptible	☐Just perceptible	☐Easily perceptible	☐Strongly perceptible	☐Extremely perceptible	

Highlights

The highlights of this study can be summarized as follows:

(i) An innovative Dynamic Cycling Comfort (DCC) measure system was established;

(ii) Cycling vibration on 46 road sections was quantitatively characterized;

(iii) Volunteers' perception on each road section was summarized via questionnaires;

(iii) Thresholds of acceptable rate, comfort and vibration perceptible level were obtained; and

(iv) Cycling comfort mapping for Qujiangchi Park was carried out to show a potential use of the DCC measure system.