INVESTIGATING THE RELATIONSHIP BETWEEN PAVEMENT ROUGHNESS AND HEART RATE VARIABILITY BY ROAD DRIVING TEST

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ABSTRACT

Traffic safety and driving comfort are the key service performances of pavements, and they depend on the pavement roughness to a certain extent. In this study the relationship between pavement roughness and heart rate variability (HRV) of drivers were investigated based on road driving tests. A total of 12 road sections with international roughness index (IRI) ranging from 1.06 to 5.53 mm/m were selected. A KF2 electrocardiogram tester was used to determine the heart rate variability of driver and a three-direction vibration acceleration tester was also used for determining the vibration felt by the driver. Test results show that HRV parameters, such as RMSSD (square root of the mean squared difference of successive NN intervals) and HF (High Frequency components of HRV spectrum), changed obviously when the pavement roughness and travel speed of the vehicle changed. If the vehicle moves with a constant speed, high pavement roughness makes the RMSSD of the driver decrease. Moreover, if the vehicle moves on a road section with constant pavement roughness, the increase of speed makes the RMSSD of the driver decrease too. Decreasing RMSSD of the driver indicates that the functions of the vagus nerve reduce and the driver will feel uncomfortable accordingly. Test results also show that the vibration acceleration of the vehicle increases when the travel speed of vehicle or the pavement roughness increases, and it is obviously related to the RMSSD of the driver.

Key words: pavement roughness, heart rate variability, driving test, driving comfort.

INTRODUCTION

Traffic safety and driving comfort are the key service performances of pavements, and they depend on the pavement roughness to a certain extent. Asphalt pavement roughness is an important indicator to describe road service quality and driving comfort (Haas, 1994).Therefore the suitable and accurate evaluation of pavement roughness is very important for driving comfort, driving safety and the management of pavement. In China, international roughness index (called IRI) is used to evaluate pavement roughness, and the IRI grade system is established according to engineering experience and expert scoring, which is much influenced by the experts' individual factors and the level of construction technology. Therefore the IRI evaluation results cannot objectively and accurately reflect driver response, driving comfort and driving safety currently.

For evaluating the pavement roughness objectively, some interesting experiments were performed to investigate the influence of pavement roughness on driver response. For example, Baba (2002) and Okutsu (2002) investigated the influence of road steps on the brainwaves of passengers. Fukuyama (2001) investigated the evaluation method of driving comfort using frequency-weighted r.m.s. (root mean square) acceleration and proved that there is good relationship between IRI and vibration acceleration. Tateki (2007) used a driving simulator to evaluate the road surface roughness, and studied the quantitative evaluation of ride comfort in 2008. Wang (2010) used the HRV parameters to study the influence of IRI on a driver's physiological reaction. Wang's test result shows that, the average heart rate of driver has no obvious regular response to the vehicle travel speed and pavement roughness, so it is not a suitable parameter to indicate the effect of pavement roughness on driver discomfort induced by the vibration of a vehicle. However, test results also show that a change in pavement roughness and the travel speed of a vehicle can cause significant differences in heart rate variability of a driver, so the vibration induced by a change in pavement roughness and travel speed of a vehicle has an obvious impact on driver response. A new HRV parameter is needed to show the driver response to pavement roughness and travel speed of a vehicle.

The literature review shows that the importance of the evaluation method of pavement roughness based on driver response has been recognized, but the relationship between pavement roughness and driver response has not been quantitatively obtained, especially by thorough road driving tests in the field.

This paper selects two indexes to evaluate the driving comfort of the driver by field driving tests on asphalt pavement, including driver's HRV and frequency-weighted r.m.s. acceleration. In the field driving test, three kinds of data are collected simultaneously. The first one is driver's dynamic ECG (electro-diagram) data for analyzing the driver's HRV that represents the human body's reaction to the vehicle vibration; the second one is the vibration acceleration data caused by the IRI of pavement and the travel speed of the vehicle, which is measured by the three-axis acceleration meter; the third one is the pavement roughness measured by the laser road condition test vehicle. The purpose of this paper is to investigate the adaptability of HRV parameters for evaluating pavement roughness by thoroughly analyzing the relationships between IRI of the pavement, travel speed of the vehicle, HRV of the driver and frequency-weighted r.m.s. acceleration of the vehicle.

TEST PROGRAM

In order to study the influence of pavement roughness and travel speed of the vehicle on driving comfort, several road sections with different pavement roughness are selected and road driving tests are performed on these road sections in different travel speeds. In the experiment, the drivers with more than 5 years driving experience are employed for the driving test, and the KF2 electrocardiogram tester is attached to the driver's body for measuring the ECG data. Moreover, the three-axis acceleration meter is placed under the driver's seat to measure the vibration acceleration of vehicle.

Test Equipment

Multi-Function Laser Road Condition Test Vehicle

The multi-function laser road condition test vehicle used in this paper is shown in Figure 1. There are five laser sensors in the test vehicle, which can measure the pavement roughness and rut depth of the pavement surface automatically.

Figure 1 Multi-function laser road condition test vehicle

A real-time processing software system (shown in Figure 2) is used to collect, process, display and store test data simultaneously, such as the position of the driving test, travel speed of the vehicle, IRI of the pavement, σ (standard deviation of roughness) of the pavement, RQI (riding quality index) of the pavement and so on. The IRI is determined at 20m intervals and the average IRI of all IRI data is calculated as the final IRI value for each road section. The road driving test shows that the test result is effective and stable when the travel speed of the vehicle changed from 20 km/h to 100 km/h.

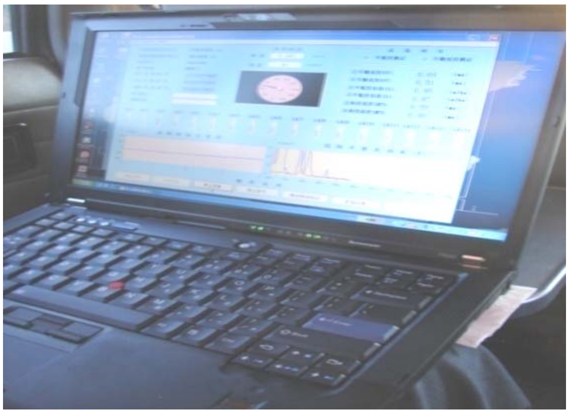
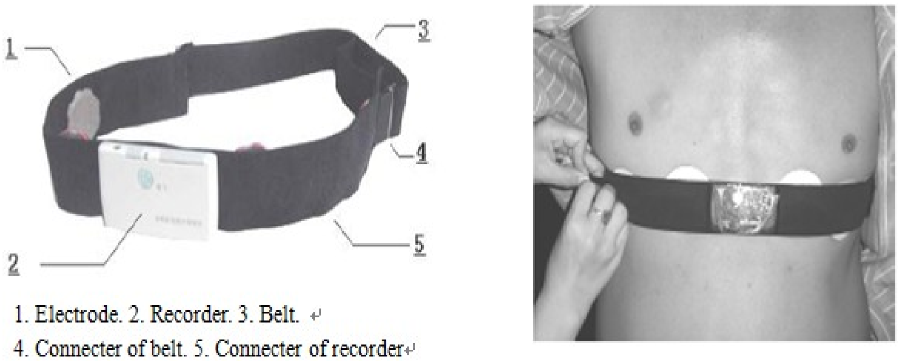


Figure 2 Data collection system for driving test

Electrocardiogram Tester

The KF2 electrocardiogram tester used in this study is shown in Figure 3(a), which is composed of detector main engine, auxiliary belt, software CD and charger. The KF2 electrocardiogram tester is used to determine the human's physiological parameters under working and resting conditions within long time duration. It is widely used in the medical area, physical examinations, medical research, special population health, family health, psychological evaluations and so on. The KF2 electrocardiogram tester is attached to the driver's body as shown in Figure 3(b) and can measure the ECG data, respiration, and skin temperature of the driver.



(a) (b)

Figure 3 KF2 electrocardiogram tester

The Accelerator Tester of Vibration

A three-direction vibration accelerator tester is used to measure the three-axial vibration acceleration signal of a vehicle, as shown in Figure 4. The three-direction vibration accelerator tester is comprised of a three-axis acceleration transducer and put under the seat of the driver during the test. The direction from the back to the chest of the driver is marked as the Y axis, the direction of the body's spine as the Z axis, and the direction from the left to the right side of the driver as the X axis.

Signal analysis software, called E-TestLab systems, is used to detect the signal of vibration acceleration, as shown in Figure 5. The E-TestLab system is a popular software for analyzing the vibration acceleration signal because it can collect three axial vibration acceleration signals of the body in real-time.

Figure 4 Three-direction vibration accelerator tester

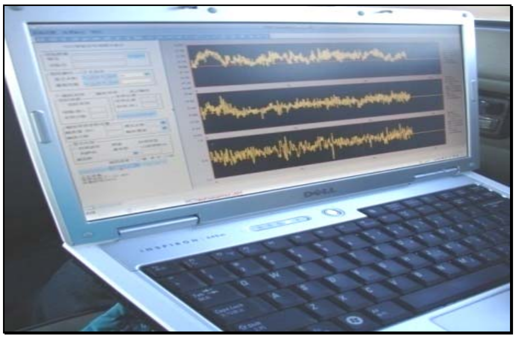


Figure 5 E-TestLab systems for analyzing the vibration acceleration signal

Test Conditions

Referencing "Method of random input running test - Automotive driving comfort" (GB/T 4970, 1996), "Mechanical vibration and shock - evaluation of human exposure to whole-body vibration – Part 1: general requirements" (ISO2631-1, 1997) and medical literature (Liu, 1998; HRV Co-operation Study Group of China, 2000), the road sections, test vehicles and drivers are selected as follows.

1) Road. The length of each test road section was 2km to 3km with a 30~50m changeover section before and after each test road section. The road surface should be dry, and the longitudinal slope is smaller than 1%. The driving test should be done when the traffic volume is smaller than 100 pcu/h. The pavement roughness of each test road section is almost the same, but different test road sections should have obviously different pavement roughness. A total of 12 test road sections with IRI ranging from 1.06 to 5.53 mm/m were selected in this study.

2) Vehicle. The Beijing Jeep is used in this study. Calibration of equipment should be done before each experiment. The parts and attachments of the vehicle and the load quantity should be the same for every driving test. Tire pressure should conform to the technical specification of the automotive vehicle, and the error of tire pressure is less than ± 10 kPa for each driving test. The travel speed of the vehicle should be controlled to the designed speed and the deviation of speed is within ± 4%.

3) Personnel. Skilled and healthy drivers from 25 to 29 years of age and more than 5 years driving experience are employed in the driving test. The irritant food, smoking and strenuous exercise is not permitted for the drivers within 12 hours before driving test. The interior of the vehicle should remain quiet and the interior temperature should be controlled to 25±2℃ during the driving test. The driver should relax the whole body, and the hands are naturally placed on the steering wheel. The driver should maintain the same posture during the driving test as much as possible.

Scheme of Test Combination

The aim of the driving test is to study the influence of pavement roughness on driving comfort based on analyzing the relationships among pavement roughness, driver's heart rate variability index and vibration acceleration. While the driver drives on the road sections with IRI ranging from 1.06 mm/m to 5.53mm/m at the speed 30km/h, 50km/h and 70km/h separately, the driver's ECG data and the vibration acceleration data are collected simultaneously. A total of 17 combinations of vehicle travel speed and pavement roughness are investigated, as shown in Table 1.

Table1 Scheme of test combination

IRI (mm/m)	Speed (km/h)		
	30	50	70
1.06	1	7	13
1.81	2	8	14
2.87	3	9	15
3.68	4	10	16
4.61	5	11	17
5.53	6	12	——

TEST RESULTS AND ANALYSIS

Relationship between IRI and HRV Index

Referencing the test result of Wang (2010), this study selects other HRV parameters, such as RMSSD, HF, LF (Low Frequency components of HRV spectrum) and LF/HF (ratio of LF to HF), to indicate the physiological response of the driver in order to evaluate the driving comfort of the driver.

HRV is the key parameter to describe the balance state of sympathetic-parasympathetic tension, representing a cyclical phenomenon of heart rate within a certain time period. There are two analysis methods for HRV, i.e. the time domain analysis method and the frequency domain analysis method.

The time domain analysis method takes the variability of R~R interval as an analysis object, and commonly selects standard deviation, variance, range and variance coefficient to express the analysis results. In this study, RMSSD is selected to indicate the driver's physiological response as a time domain index, which is defined as the root-mean-square of two adjacent normal R~R interval difference.

The frequency domain analysis method separates the heart rate signal into different frequency components, defines the relative intensity as a power and offers the power spectrum of a variety of frequency components.

This paper selects the HF, LF and LF/HF as frequency domain index to indicate the driver's physiological response, and they are defined as follows.

HF——High frequency component of the ECG signal, which equals the integral area of power frequency spectral density curve in the 0.15Hz~0.40Hz frequency band.

LF——Low frequency component of ECG signal, which equals the integral area of power frequency spectral density curve in the 0.04～0.15Hz frequency band.

Referencing the related literature (Liu, 1998; HRV Co-operation Study Group of China, 2000; Wang, 2010), the normal range of the HRV index within 5min. for 20~29 years old male driver is shown below.

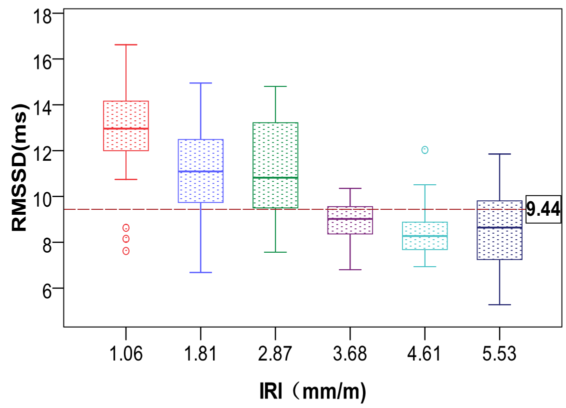
RMSSD=9.44~77.45 (ms)
HF =10.00~2621.00 (ms^2)
LF =38.78~1755.93 (ms^2)
LF/HF=0.15~15.14

According to cardiac electrical theory, when the value of the HRV index is beyond the normal ranges, the body may feel discomfort. So this range can be used to evaluate the driving comfort response of the driver during the road driving test and the threshold value of vehicle travel speed and IRI that makes the driver uncomfortable can be obtained accordingly.

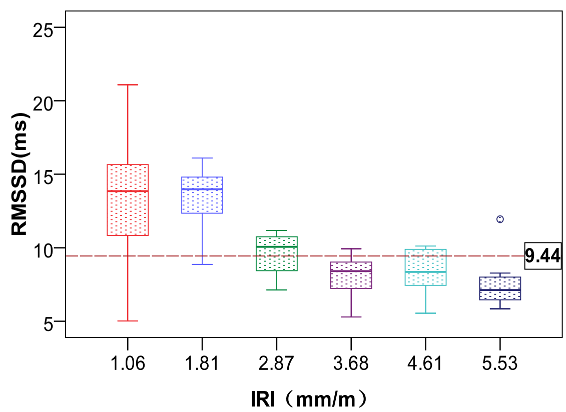
Relationship between IRI and RMSSD

Figure 6 shows the test results of RMSSD expressed in a box-plot diagram. It is shown that there is a tendency for RMSSD to decrease as the IRI and the travel speed increase. In particular, the 75th percentile value of the RMSSD has a very obvious declining curve as the IRI and the travel speed increase.

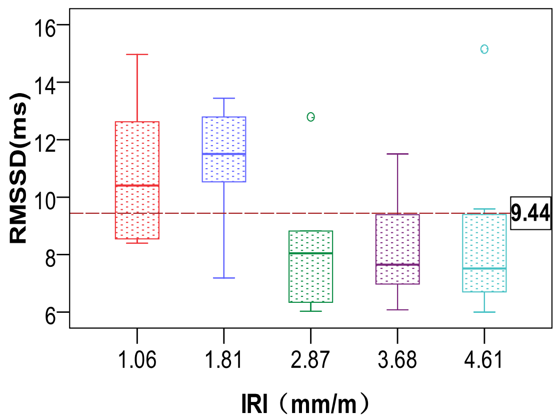
According to the research result from Liu (1998), the RMSSD value between 9.44~77.45(ms) is the normal range for a man of 20 to 29 years of age. When the RMSSD value is located outside of this normal range, the body would feel uncomfortable or even as if there is a widespread danger of disease. According to Figure 6, when the 75th percentile value of RMSSD is 9.44, the critical IRI value is different under different travel speeds of the vehicle. And the higher the speed is, the less the critical IRI value is.



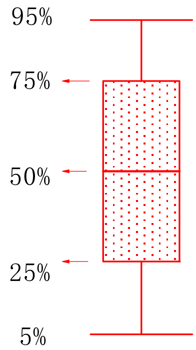
(a) V=30km/h



(b) V=50km/h



(c) V=70 km/h



Legend

Figure 6 Change of RMSSD value with IRI and travel speed

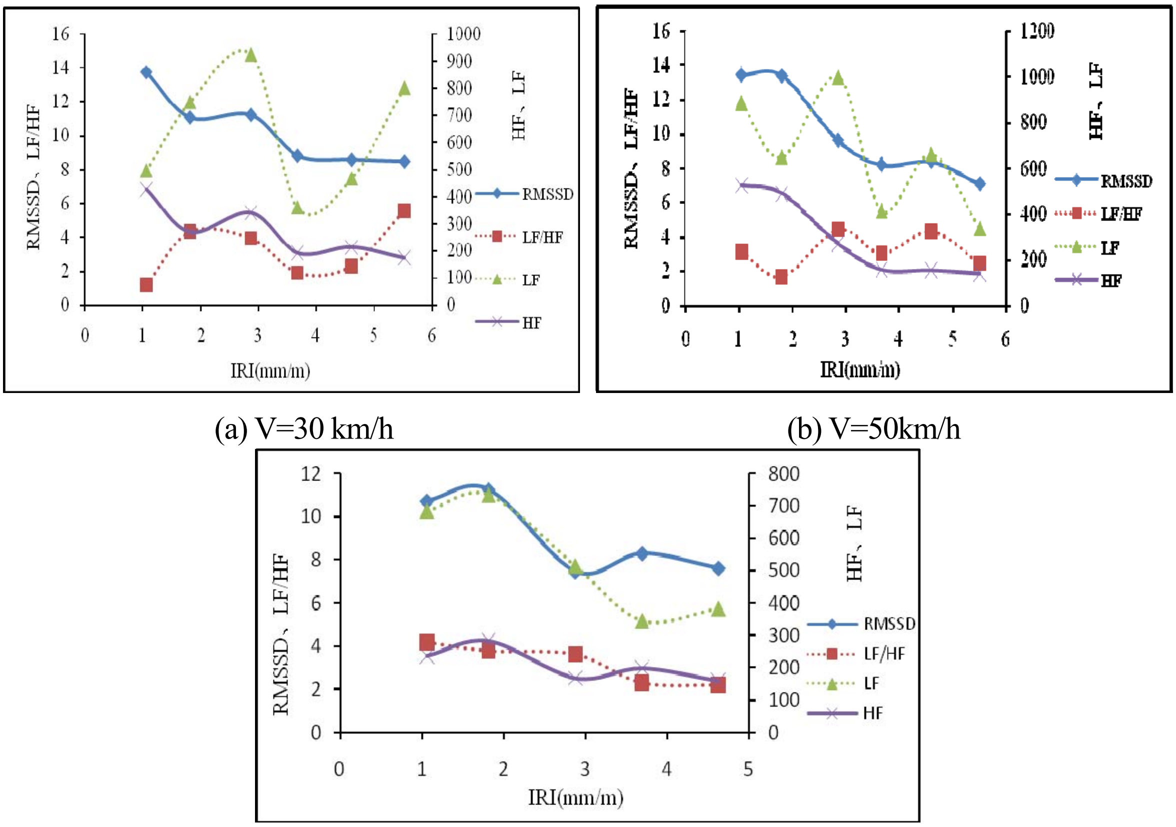
Correlation between HRV Index and IRI

By analyzing the test results of LF, HF and LF/HF, it can be seen that the pavement roughness and vehicle travel speed has a little influence on both LF/HF and LF, and the value of LF/HF and LF is always in the normal range without appreciable change in regulation. The change of HF value is basically similar to that of the RMSSD value, but the HF value changed in a wide range and was always located within the normal range for the HF value.

The test results of 75th percentile value of the HRV index at different travel speeds and IRI of road is shown in Figure 7. It is shown that RMSSD and HF obviously decrease together with the increase of

IRI, but the change of LF/HF and LF is not clear. When the travel speed increased up to 70km/h, the change of LF/HF and LF become more and more clear. In other words, when the vehicle speed is high enough, all HRV indexes will have good correlation with IRI and vehicle travel speed.

Based on the analysis stated above, it can be seen that RMSSD is the most effective index for characterizing the influence of IRI and vehicle travel speed on driver's response among RMSSD, HF, LF and LF/HF. Therefore, this paper suggests that RMSSD can be used as an index to evaluate the driving comfort and safety of a driver induced by pavement roughness.



(a) V=30 km/h (b) V=50km/h

(c) V=70km/h

Figure 7 Relationship between IRI and 75th percentile value of HRV index at different travel speeds

Correlation between α_{wo} and IRI

The frequency-weighted r.m.s. acceleration (α_{wo}) is suggested to evaluate driving comfort by ISO 2631-1(1997). Figure 8 shows the test result of α_{wo} changing with IRI at different travel speeds. It is shown that the frequency-weighted r.m.s. acceleration (α_{wo}) tends to a linear increase if the IRI increases. Meanwhile, the higher the travel speed is, the more the value of α_{wo} is at the same IRI. The more the travel speed is, the more obvious the linear trend of α_{wo} increasing together with IRI is as well.

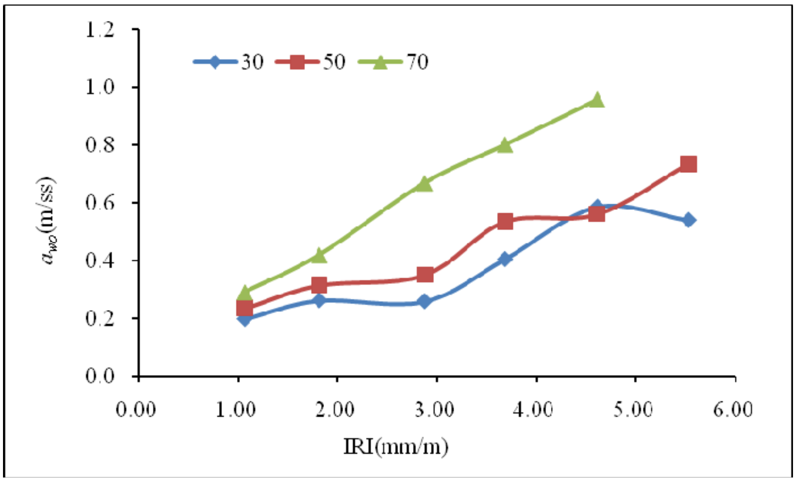


Figure 8 Relationship between α_{wo} and IRI at different speeds

Because both pavement roughness and vehicle travel speed have an obvious impact on vibration acceleration, a partial correlation is used to analyze the influence of pavement roughness and vehicle travel speed on the HRV index of the driver in this study. Results show that the partial correlation coefficient between frequency-weighted r.m.s. acceleration (α_{wo}) and IRI is 0.913, excluding the influence of vehicle travel speed, and the partial correlation coefficient between frequency-weighted r.m.s. acceleration (α_{wo}) and vehicle travel speed is 0.756, excluding the influence of IRI. All analysis results show that IRI has more influence on vibration acceleration than the vehicle travel speed, but all of them have a good correlation with vibration acceleration by linear regression analysis.

The multiple linear regression method is employed to analyze the three variables, and the regression equation is obtained as Equation 1.

$$\alpha_{wo} = 0.121IRI + 0.006V - 0.186 \quad (R^2 = 0.849,\ p < 0.01) \tag{1}$$

Where:
α_{wo} = the frequency-weighted r.m.s. acceleration, m/s^2
V = vehicle travel speed, km/h
IRI = international roughness index, mm/m

The Correlation between α_{wo} and RMSSD

Based on the test results shown in Figure 6 and 8, the relationship between α_{wo} and RMSSD is derived and indicated in Figure 9, which illustrates that the RMSSD of the driver is obviously affected by the α_{wo} of the vehicle caused by a change of pavement IRI or vehicle travel speed.

ISO 2631-1(1997) (International Organization for Standardization, 1997) has given the evaluation standard for human comfort as shown in Table 2. According to Table 2, when the frequency-weighted r.m.s. acceleration is located in the range from $0.315 m/s^2$ to $0.63 m/s^2$, the driver feels a little uncomfortable. It can be reasonably supposed that the threshold value of frequency-weighted r.m.s. acceleration in which the driver begins to feel uncomfortable is the average of 0.315m/s^2 and 0.63 m/s^2. By using the correlation equation shown in Figure 9, the critical value of RMSSD in which the driver begins to feel uncomfortable can be calculated, and the result of 9.26 ms can be obtained, which is similar to that shown in medical literature ((Liu, 1998).

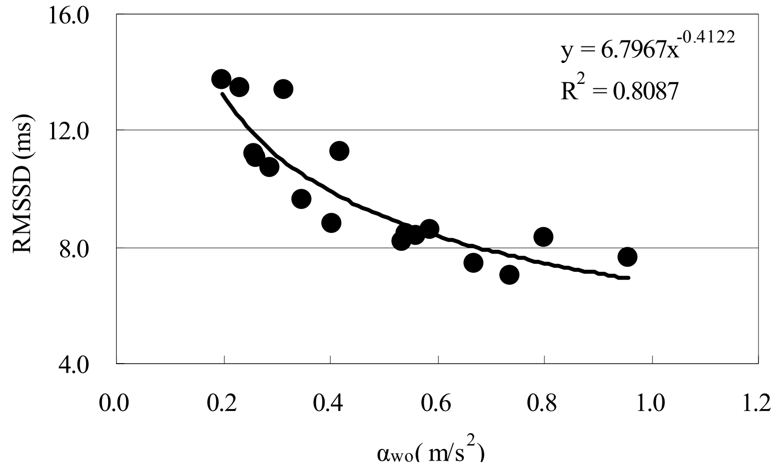


Figure 9 Relationship between α_{wo} and RMSSD

Table 2 Human comfort perceptions to vibration environments

Frequency-weighted r.m.s. acceleration	Uncomfortable degree
Less than 0.315m/s^2	Not uncomfortable
0.315m/s^2 to 0.63 m/s^2	A little uncomfortable
0.5m/s^2 to 1m/s^2	Fairly uncomfortable
0.8m/s^2 to 1.6m/s^2	uncomfortable
1.25m/s^2 to 2.5m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

All test results show that, while the IRI value of the pavement or the travel speed of a vehicle increases gradually, the RMSSD value of the driver will decrease at first and then will go beyond the normal scope of the driver, which makes the driver feel uncomfortable. The bigger the IRI value is, the greater the uncomfortable feeling of driver is. In the serious condition, the driving safety of the driver will be affected and the probability of a traffic accident may increase. Therefore, the method based on the driver's HRV characteristics is suitable for evaluating pavement roughness, which provides a new theoretical method for pavement maintenance and management other than the present theories.

CONCLUSIONS

Through the analysis of the relationship among pavement roughness, HRV index and frequency-weighted r.m.s. acceleration (α_{wo}), the following conclusions can be obtained.

The heart rate variability index, RMSSD, can be successfully used to evaluate the effects of pavement roughness on the driving comfort of a driver.

As one HRV index, RMSSD shows a decreasing trend with increasing IRI and vehicle travel speed. The different combinations of vehicle travel speed and pavement roughness have different effects on the RMSSD value of the driver.

There was an obvious linear correlation between the vibration acceleration of the body and the IRI of the pavement, also between the vibration acceleration of body and the vehicle travel speed. The frequency-weighted r.m.s. acceleration (α_{wo}) increases together with the increase of vehicle travel peed and IRI of the pavement. The frequency-weighted r.m.s. acceleration (α_{wo}) can be predicted by determining the vehicle travel speed and IRI of the pavement according to the binary linear regression equation as follows: α_{wo}=0.121IRI+0.006V-0.186, with the related coefficient R^2=0.849.

It is proved that α_{wo} and RMSSD have sound negative correlation through analyzing the relationship between vibration acceleration and RMSSD value, and the correlation coefficient approaches 0.90.

Through the analysis mentioned above, both critical ranges of the RMSSD value and the comfort level of vibration acceleration established by ISO2631 can be used to determine the threshold value of IRI with satisfied driving comfort and safety, which can hopefully establish a new evaluation system of pavement roughness and provide theoretical support to pavement maintenance and management.

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