Implementation of Pavement Ride Quality Assurance Based on a Driving Simulator and Physiological Signal

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ABSTRACT: Road users as well as administrators identify the serviceability of a pavement surface depending on its roughness related to vehicle ride quality. However, the relationship between a user's ride quality rating and the physical characteristics of roughness has not been completely clear due to the limitation on a subjective assessment survey in actual road conditions and the lack of objectivity in the questionnaire-based subjective rating. The objective of this study was to establish an implementation method for confirming the pavement ride quality assurance. To achieve the objective, we employed a sophisticated driving simulator called KITDS and applied the physiological information of participants for a simulator experiment. The performance of the KITDS allows the participants to evaluate pavement ride quality in a safe and tightly controlled operational condition. A validation result of the performance proved that the KITDS provided the same ride characteristics as a common passenger car. To gain the better interpretation of a road user's rating on pavement ride quality, we proposed the use of heart rate variability (HRV) to measure physiological information indicating the mental stress of the participants in the ride quality rating panel. As the result of the simulator experiment, the information of HRV derived 11% more accurate rating of ride quality than the traditional questionnaire-based evaluation. The findings of this study contribute to the accuracy improvement in the user-oriented monitoring strategies of road surfaces.

KEY WORDS: Ride quality, roughness, panel rating, driving simulator, heart rate variability.

1 INTRODUCTION

Road roughness has a strong impact on the judgments of road users on the serviceability of a pavement surface because it is directly related to the ride quality and driving safety of road vehicles. Many studies all over the world have attempted to correlate the severity of roughness with the ride quality ratings of users based on a questionnaire (Dahlstedt 2003, Hassan et al 2003, Ishida et al. 2007, Ishida et al. 2008). However, the relationship between a user's ride quality rating and the physical characteristics of roughness has not been completely clear due to limitations on a subjective assessment survey in actual road conditions.

Against the above background, our laboratory has developed a sophisticated driving simulator called KITDS (Kitami Institute of Technology Driving Simulator) as a new tool for road surface evaluation (Kawamura et al. 2004). The main feature of the KITDS allows an experiment to use the actual data such as vehicle motion of six degree-of-freedom and road profile. The progress of road monitoring technologies with better sensors and data recording and processing facilities has contributed to gain the physical properties of a road surface in the driving simulator. The KITDS enables participants in a subjective assessment survey to rate the different degree of road roughness in a safe and tightly controlled operational condition. This paper provides the descriptions of the KITDS, including distinct functions, a data collection system, and the reproducibility of vehicle acceleration data induced by the different levels of roughness.

In a subjective assessment survey, a ride quality rating has so far relied on the individual response of participants based on the questionnaire such as a numerical scale from 0 to 5. However, the correlation between the participants' subjective ratings and the physical measurements of roughness is understandably complex due to the lack of objectivity in the questionnaire-based rating. To gain better understanding of the ride quality rating of participants, in this study, we propose the use of heart rate variability (HRV) to measure the physiological response of participants to vehicle vibrations induced by the different degree of road roughness.

HRV refers to the beat-to-beat fluctuations of heart rate and represents one of the most promising markers of an autonomic nervous system (ANS) that is associated with the mental stress of humans (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996). The activity of different parts of the ANS, sympathetic and parasympathetic branches, affects the HRV. The high- and low-frequency oscillations (HF and LF; 0.15-0.4 and 0.04-0.15 Hz, respectively) are usually related with the activity of the parasympathetic and sympathetic nervous system, respectively.

A main interest in a HRV signal is that mental stress inactivates the parasympathetic activity (HF oscillation). Thus, traditional spectral analysis techniques, such as Fourier transform and autoregression, have been used to investigate the behavior of the ANS in different experimental situations. However, these techniques are based on the assumption of steady-state conditions in an analyzed signal and yield data in the amplitude and frequency of heart rate oscillations as existing over the entire time interval but yield no data on their temporal localization. On the contrary, continuous wavelet transform (CWT) enables an analysis to overcome the shortcoming of the traditional techniques (Mallat 1999). The CWT of a HRV signal performs the time-frequency decomposition of the signal and produces the time-dependent version of typical HF and LF peaks. This paper also describes a method for assuring the ride quality of a pavement surface based on the CWT of participants' HRV signals measured in a subjective assessment survey by the KITDS.

2. KITDS

The prototype of the KITDS was introduced in 2001 to provide driver trainees with instruction in safety driving techniques. A compact, low-height configuration was achieved while still adopting the 6-axis motion base system as shown in Figure 1. The KITDS includes a full vehicle dynamics model based on the road-vehicle interaction and adopted to run in real time. The hardware is comprised of five networked computers and three interfaces. One computer processes the motion equations of a vehicle, while the others generate the images that are three mirrors and a forward view. The hardware interfaces include a steering wheel, pedals, and a gearshift lever. They are mounted on an automobile-cabin with an automobile dashboard and an instrument panel to create a realistic driving environment.

Figure 1: Overview of the KITDS.

The 6-axis motion base system consists of a cockpit with 6 cylinders activated by electric motors. The position and slant of the cockpit can be changed (six degree-of-freedom) by expanding and contracting the cylinders. The motion base system has an ability to generate the vehicle vibration induced by road profiles as well as the action of a driver on the brake, the accelerator, and the steering wheel. The road scenario is projected onto a Cinema-Scopic screen with high-quality images. The usual field of view is 138°. The resolution of the visual screen is 1024x768 pixels, and the refresh rate is 30 to 60 Hz. The visual computer, with the real-time vehicle simulation output, generates and displays realistic graphic images of the driving environment corresponding to driving conditions. The system is also equipped with a three-dimensional stereo sound system and body sonic sound system reproducing the sounds of the engine and road noise.

2.1 Specific Features

The KITDS has two specific functions for its driving and riding system. The first is to input the six degree-of-freedom vehicle motion data measured when actual traveling, and using the device to play back the digital video (DV) recorded during measurement in synchronization with the vehicle motion data. This function also allows the simulator to reproduce the motion data obtained from external mathematical simulation models of a vehicle, e.g. CarSim® (Mechanical Simulation Corporation 2006), including animation images of the simulated vehicle behavior. The other function is the loading of actual road surface data into the simulator, and letting a driver freely drive that road surface. The former function is applied in this study. More attractive information about the functions of the KITDS is shown elsewhere (Kawamura et al. 2004).

2.2 Data Collection System

Two approaches are available to collect vehicle motion data for the KITDS. One is an in situ-based system that measures actual vehicle motion data and the video images of a forward view by a probe car traveling over a roadway. The probe car is equipped with a gyro sensor and a DV camera to measure vehicle vibration data and forward images. The other approach is a laboratory-based system that calculates theoretical vehicle motion data by a mathematical simulation model of a vehicle using measured profile data. The data collection system of the KITDS is shown in Figure 2.

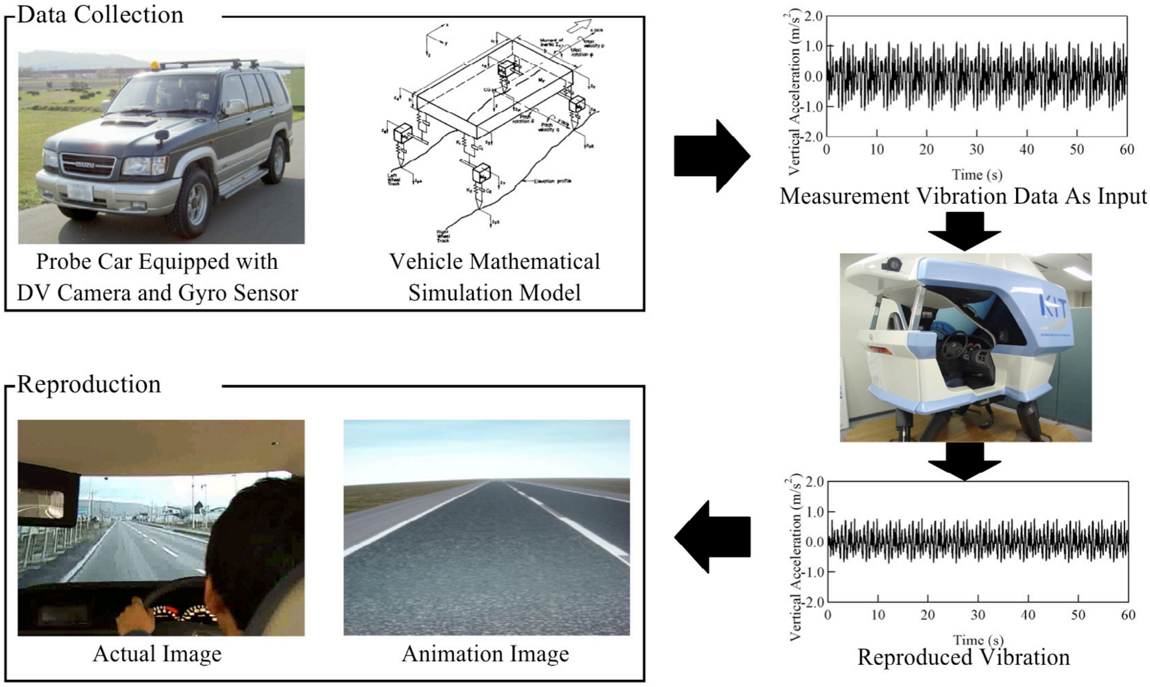


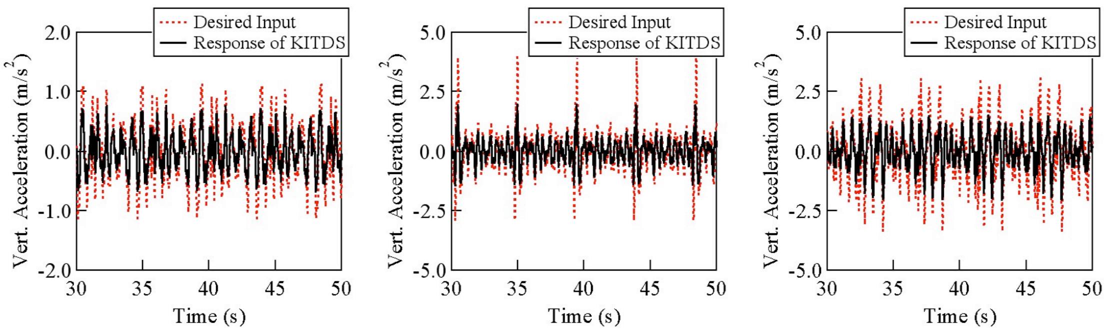
Figure 2: Data Collection System of KITDS.

2.3 Validity of Ride Characteristics

The reproducibility of vertical acceleration in the simulator platform is important for identifying the ride characteristics responded to road roughness because passengers evaluate the ride quality through the vibration of the platform. Three vertical acceleration data of a typical passenger vehicle induced by the different roughness levels, IRI (International Roughness Index) values are 2, 3, and 5 mm/m, are simulated by the CarSim® as desired inputs to verify the acceleration response of the KITDS. In the simulation, vehicle forward speed is set to 80km/h assuming highway condition, and the duration of the vibration is 60sec.

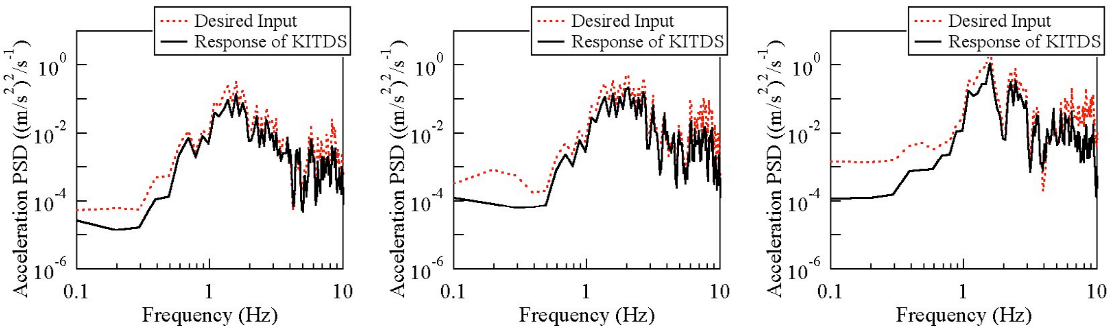
Figure 3 shows the comparisons of the vertical acceleration between the desired input and the response of the KITDS in the time-domain. As shown in the figure, the response of the KITDS closely corresponds to the desired input but the amplitude of the reproduced acceleration is 38% smaller than the desired input in the root-mean-square value.

Figure 4 shows the comparisons of the power spectral density (PSD) of the desired input and the reproduced vibration for the vertical acceleration. As shown in the figure, the amplitude of the reproduced vibration corresponds approximately to that of the desired input in the frequency range above 0.8Hz. Here it should be noted that we have calibrated the motion system of the simulator taking into consideration that the maximum sensitivity of human body to vertical vibration occurs in the frequency range between 4 and 8Hz (Griffin 1996). Accordingly, it is possible to obtain the same ride characteristics of the actual passenger vehicle with regard to vertical acceleration in the platform of the KITDS.



(a) (b) (c)

Figure 3: Comparisons of vertical acceleration between desired input and response of KITDS: (a) IRI= 2 mm/m, (b) IRI = 3 mm/m, and (c) IRI = 5mm/m.



(a) (b) (c)

Figure 4: Comparisons of the PSD function between desired input and response of KITDS: (a) IRI= 2 mm/m, (b) IRI= 3 mm/m, and (c) IRI= 5 mm/m.

3. PHYSIOLOGICAL APPROACH

This chapter describes a driving simulator experiment to verify the applicability of HRV for ride quality evaluation. In the experiment, the KITDS simulated three vehicle motion data which were the same as the data as shown in Figure 3. Participants of the experiment experienced the vehicle vibrations in the KITDS. Heart rate signals of the participants are recorded during the duration of each vibration.

3.1 Driving Simulator Experiment

(1) Experimental Protocol

The simulator experiment was performed on three different road conditions which were shown in Figure 3. The duration of each vibration is 60sec. with 120sec. and 30sec. rest periods occurring at the beginning and end of the vibration. Therefore, the total time of one trial is 210sec. Immediately after each trial, the participants were asked to fill out a subjective rating questionnaire about the ride quality represented by “acceptable”, “neither acceptable nor unacceptable”, and “unacceptable”.

(2) Participants

Thirty-seven participants (twenty-one healthy people in their twenties and sixteen people in their sixties and over) agreed to the purpose of the experiment and to measure the heart rate.

No participants suffered motion sickness in the experiment. Eight participants were not able to obtain the heart rate signals due to an error of its measurement. Two participants did not fill out the questionnaire. Therefore, the sample size used for the analysis was twenty-seven.

(3) Recording of Heart Rate
The modern technology of electrocardiogram (ECG) recording contributes to measure the heart rate in the various situations such as in a driving simulator. The recording equipment is small and easy to handle. We used the Polymate II AP216 produced by TEAC Corporation to measure the heart rate. Two small electrodes were connected on the right and left chest of the participants, and another two electrodes fixed on right arm grounded the participants. Then, the heart rate data of participants were recorded with a precision of 0.001sec.

3.2 Data Processing of Heart Rate

The period of heart rate is not constant and changes over time. HRV refers to the beat-to-beat (R-R interval) alterations in the heart rate as shown in Figure 5. First, R-waves were extracted from the ECG, and then the R-R intervals were calculated. After that, the R-R interval trace was re-sampled with a sampling period of 0.1sec. to produce a uniformly sampled HRV signal. Finally, the CWT performed a time-frequency decomposition of a HRV signal to investigate the parasympathetic activity of the ANS.

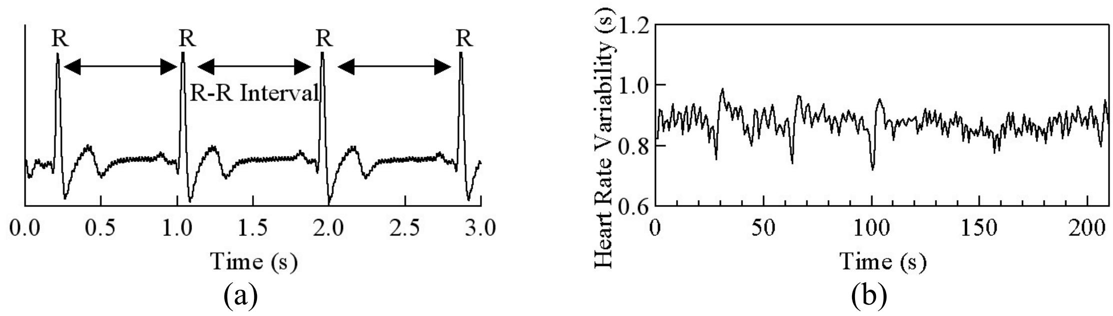


Figure 5: Heart Rate Variability (HRV): (a) Heart Beat, (b) Heart Rate Variability.

The CWT of a signal $f(t)$ at time u and scale s is shown in Equation (1) (Mallat 1999).

$$Wf(u,s) = \int_{\infty}^{-\infty} f(t)\frac{1}{\sqrt{s}}\psi^{*}\left(\frac{t-u}{s}\right)dt \tag{1}$$

where, in this study, mother wavelet $\psi(t)$ is Morlet defined as

$$\psi(t) = \pi^{-1/4}e^{-t^2/2}\cos(5t) \tag{2}$$

Here, * indicates complex conjugate. The relationship between scale and frequency of a signal is described as

$$F_s = \frac{F_c}{s\cdot \Delta} \tag{3}$$

where

F_s is the frequency corresponding to the scale s, in Hz.
F_c is the center frequency of mother wavelet in Hz.
Δ is the sampling period.
We used the IGOR Pro 6.0 produced by WaveMetrics, Inc for the implementation of the CWT (WaveMetrics, Inc. 2007).

3.3 Physiological Interpretation of HRV

In the frequency-domain, a HRV signal has two spectral peaks at the HF (0.15-0.4 Hz) and the LF (0.04-0.15 Hz) associated with the parasympathetic and sympathetic activity, respectively as shown in Figure 6. In particular, the HF peak is easier to interpret rather than the LF peak. The main issue, which must be addressed, is that the mental stress reduces the HF peaks corresponding to the parasympathetic activity of humans.

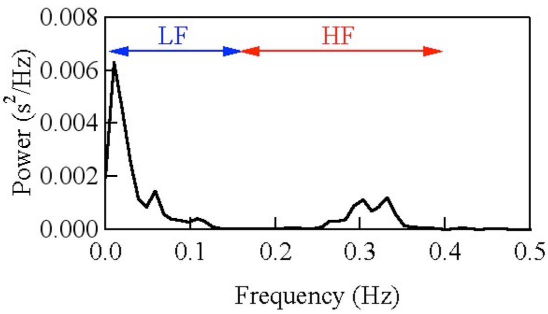


Figure 6: Heart Rate Variability in the Frequency-Domain

As for the result of the simulator experiment, Figure 7 shows spectrograms of wavelet coefficients computed from the HRV signals which indicate typical examples of autonomic activity. A spectrogram is a distribution of the energy of a signal in the time-frequency plane expressed in the color scale corresponding to the amplitude of the signal. In the figure, the stimulation caused by the roughness was provided in the periods from 120 to 180sec. The HF in Figure 7(a) was unchanged during the experiment, whereas the HF in Figure 7(b) was reduced after the stimulation started. In the particular case in which the HF is reduced, the roughness causes the mental stress of the participant even if the panel rating is acceptable. To interpret the reaction of the participants to the vehicle vibration induced by the roughness, we categorize the relationship between the response of HRV and the subjective panel rating into three classes (Class I, Class II, and Class III) as following:

- Class I. The panel rating corresponds to the response of HRV, that is, the panel rating is "acceptable" with which the response of the HF is unchanged or the HF is reduced with the rating of "unacceptable". In this class, both of the panel rating and the response of HRV reflect the ride quality perspective of participants.

- Class II. There is no relationship between the panel rating and the response of HRV. That is, although the panel rating is "unacceptable", the HF is unchanged. In this case, we recommend that the result of experiment should refer to the panel rating correlating with participant's perception of ride quality rather than the response of HRV.

- Class III. There is an opposite correlation between the panel rating and the response of HRV. In other words, although the HF is reduced, the panel rating is "acceptable" or "neither acceptable nor unacceptable". The other case is that the panel rating is "neither acceptable nor unacceptable" when the response of HRV is unchanged or reduced. In these cases, we strongly recommend the use of the HRV response to interpret the experiment result in terms of the mental stress of participants caused by the roughness.

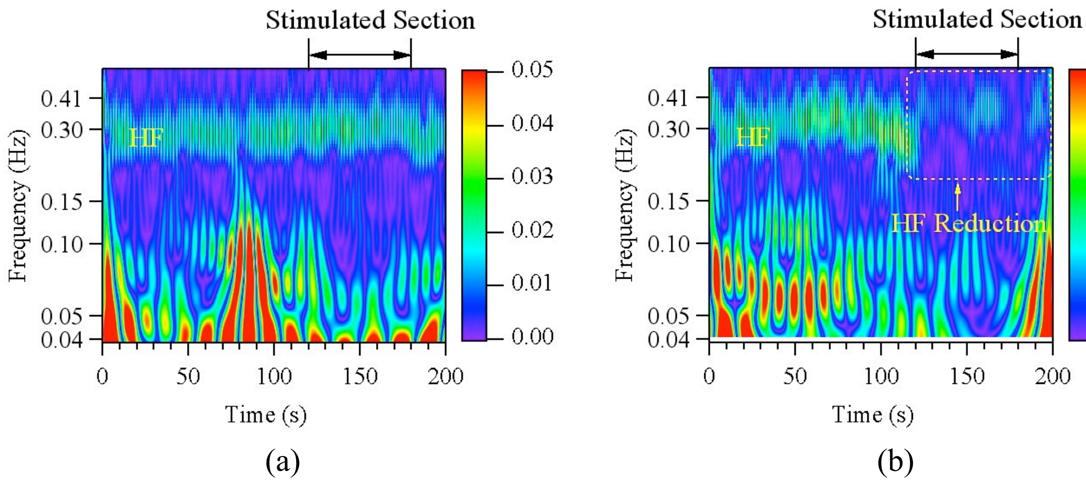


Figure 7: Typical Examples of Autonomic Behavior in Time-Frequency Plane (the frequency-axis is logarithmic scale): (a) High-frequency component (HF) is unchanged during the experiment and (b) HF is reduced after the stimulation started.

3.4 Modification of Experiment Result

Table 1 shows the rating results of the participants in the simulator experiment and its classifications based on the above categories. As shown in the table, 49% of the whole is classified into Class I with statistical 95% confidence interval (CI) of 38-61%, and the proportions of Class II and Class III are 21% (CI: 13-31%) and 30% (CI: 20-41%) of the whole, respectively. Approximately half of the rating is classified into Class I, however, it is noticeable that one-third of the whole is categorized into Class III. We repeatedly propose the employment of the HRV response to visualize the mental stress of participants to the vehicle vibration caused by the roughness. To implement the ride quality assurance of a pavement surface, the panel rating classified into Class III should be modified based on the following regulations (Class III regulations):

- If the HF is reduced and the rating is "acceptable", then the rating should be substituted for "unacceptable".

- If the HF is unchanged and the rating is "neither acceptable nor unacceptable", then the rating should be changed for "acceptable".

Applying the regulations to the experiment result shown in Table 1 modified the ratings categorized into Class III (30% of the whole rating) at the 10% statistical significance level (P=0.064, binomial exact test). As a result of the modification, the acceptable proportions of Stimulation 1, 2, and 3 are decreased by 11% by comparison with the questionnaire-based ratings as shown in Figure 8. Consequently, the modification of the panel rating based on the regulations contributes to accurately implement the ride quality assurance of a pavement surface by the road users' point of view.

Table 1: Experimental Result and its Classification.

Participant	Stimulation 1 (IRI=2 mm/m)			Stimulation 2 (IRI=3 mm/m)			Stimulation 3 (IRI=5 mm/m)		
	Rating	HF	Class	Rating	HF	Class	Rating	HF	Class
1	-1	-	II	1	-	I	-1	-	II
2	1	-	I	1	-	I	1	-	I
3	0 **[1]**	-	**III**	-1	↓	I	-1	↓	I
4	1	-	I	1	-	I	-1	↓	I
5	1	-	I	-1	-	II	-1	-	II
6	1 **[-1]**	↓	**III**	-1	↓	I	-1	-	II
7	-1	-	II	1	-	I	-1	↓	I
8	-1	-	II	-1	↓	I	-1	↓	I
9	1 **[-1]**	↓	**III**	1 **[-1]**	↓	**III**	1 **[-1]**	↓	**III**
10	1	-	I	1	-	I	1	-	I
11	1	-	I	1	-	I	1	-	I
12	1	-	I	1	-	I	0 **[-1]**	↓	**III**
13	-1	-	II	-1	-	II	-1	-	II
14	1 **[-1]**	↓	**III**	1 **[-1]**	↓	**III**	-1	↓	I
15	1	-	I	1	-	I	-1	-	II
16	0 **[1]**	-	**III**	1 **[-1]**	↓	**III**	1 **[-1]**	↓	**III**
17	1 **[-1]**	↓	**III**	1 **[-1]**	↓	**III**	-1	↓	I
18	-1	↓	I	-1	↓	I	-1	↓	I
19	1	-	I	0 **[1]**	-	**III**	-1	-	II
20	0 **[1]**	-	**III**	0 **[1]**	-	**III**	-1	-	II
21	1 **[-1]**	↓	**III**	1 **[-1]**	↓	**III**	1 **[-1]**	↓	**III**
22	1 **[-1]**	↓	**III**	1 **[-1]**	↓	**III**	-1	↓	I
23	1	-	I	-1	-	II	-1	-	II
24	1	-	I	1	-	I	1	-	I
25	1	-	I	1	-	I	1	-	I
26	0 **[1]**	-	**III**	0 **[1]**	-	**III**	-1	-	II
27	1 **[-1]**	↓	**III**	-1	-	II	1	-	I

- Rating 1: Acceptable, 0: neither acceptable nor unacceptable, -1: unacceptable
- HF: High-frequency component of autonomic activity, -: unchanged, ↓: reduced
- **[ ]** indicates the modified rating based on the Class III regulation.

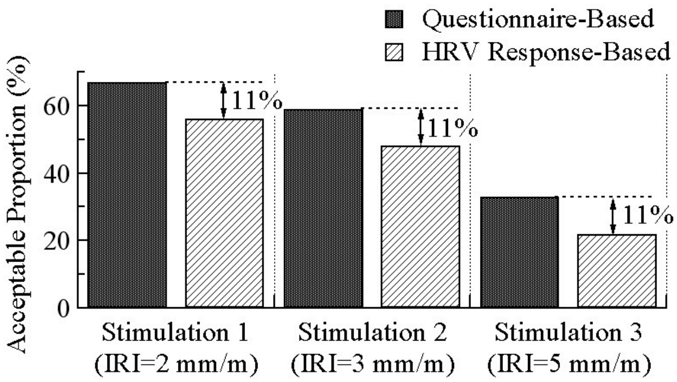


Figure 8: Comparison between Questionnaire-Based and HRV Response-Based Rating.

4. CONCLUSIONS

In recent years, road users' demand for the maintenance and improvement of pavement surfaces rises in quality rather than quantity, and also the maintenance criteria are obliged to change from the detailed specification toward the performance specification. This study contributes to the pavement management strategies such as the prioritization of maintenance and rehabilitation projects, smoothness assurance for newly constructed or overlaid pavements and budget allocation. The conclusions of this study are summarized as follows:

- We introduced the KITDS for road surface evaluation, including its distinct features and the data correction system. The specific function of the KITDS enables participants in a subjective assessment survey to rate the pavement ride quality in a safe and tightly controlled operational condition. According to the validation result for the reproducibility of the vehicle motion for vertical acceleration, it is proved that the KITDS generates the same ride characteristics of the actual vehicle on its platform.

- To gain better understanding of the ride quality rating of the participants, this study proposed the use of HRV to measure the physiological response of the participants to vehicle vibrations induced by road roughness. The relationship between the response of HRV and the subjective panel rating was categorized into three classes (Class I, Class II, and Class III). In the case of Class III, we strongly recommend the employment of the HRV response to visualize the mental stress of participants to the vehicle vibration caused by the road roughness. As the result of the simulator experiment, 30% of the whole evaluation was classified into Class III with CI of 20-41%.

- In the case in which the panel rating is classified into Class III, the panel rating should be modified based on the proposed regulations. The modification of the panel rating derives 11% more precise ride quality assurance of pavement surfaces than the normal questionnaire-based rating based on the road users' point of view.

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