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Original Research Paper

Measuring and evaluating of road roughness conditions with a compact road profiler and ArcGIS

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ABSTRACT

With a wide range of requirements throughout the world, high-quality road management is subject to increasing demand from a perspective of customer-oriented levels of service. In recent years, road administrators are requested to create a visual map of a road network to monitor conditions. To fulfill these requirements, this study conducted as follows. Firstly, this paper introduces a new compact road profiler to collect the profile data at ease. Using the international roughness index (IRI) to assess public roads in local cities of Japan's Hokkaido prefecture, this study also provides real-time monitoring of pavement roughness conditions. Moreover, this study deals with an effective method for visualizing collected IRI data as an attribute in a geographic information system (GIS) and the database of Japan digital road map (DRM). Secondly, the authors present the measurement results of IRI at two different cities during different seasons by using GIS to compare the road conditions. According to the results clarified on different statistical characteristics of road profiles, this study recommends that it is necessary to establish pavement management system (PMS) in consideration of road class, network of local city, and evaluation and management of road conditions in winter quantitatively. Finally, the authors measure and evaluate ride quality by assessing differences between the inner wheel path (IWP) and outer wheel path (OWP) of the vehicle into account, using the previously mentioned profilers and the driving simulator, which is called KITDS. Results show that information from both wheel paths contributes to improve current monitoring process regarding pavement surface, and expects to construct a high level of PMS for road administration in the future.

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1. Introduction

Nowadays, systematic pavement management has become increasingly important as pavements continue to age and deteriorate while funding levels have decreased due to reduced funding or increased competition for funds. PMS provides roadway managers with a systematic process for generating solutions to many of their pavement management questions (Wolters et al., 2011). The roughness of the road surface can affect the ride quality (RQ) and vehicle operating costs. Rough surfaces considerably impacts vehicle speed, fuel consumption, tire wear, and more and increase maintenance costs of road surface. Thus, it is necessary to gather the roughness data of road network to operate PMS accurately (Flintsch et al., 2012). According to the present conditions of the municipal roads in Japan, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has promoted a strategy for the full-inspection of road stocks and an implementation guide for municipal roads since 2013 (MLIT, 2013). Based on monitoring road surface conditions of municipal roads, this strategy has motivated local road administrators to develop and improve their PMS in order to provide a better ride environment. During a half century of development, engineers and researchers have invented several techniques and methods for measuring road roughness. The measurement devices can be divided in to four general types: response-type road roughness measuring systems (RTRRMS), direct profile measurements, indirect profile measurements, and subjective rating panels (Sayers et al., 1986a, 1986b). Most highway agencies collect IRI data using a laser sensor or high speed profiler. This equipment measures surface profiles at normal traffic speeds and provides excellent results for use in network analysis for PMS. However, because these devices are mounted on a full-size van, auto mobile, or trailer, they are difficult to use on roadways for short periods of time. In addition, these devices are rather expensive and delicate (Du et al., 2014). In order to satisfy these requirements, the authors have provided a low-cost road surface profile measuring system. The profiler consists of two small accelerometers set up to a vehicle suspension system, while conventional high-speed profilometers which use laser sensors (ASTM, 2004). This system enables the measurement of surface profiles using the back calculation method, which is based on the measured acceleration of a vehicle without empirical correlations between roughness profiles and vehicle motion. Then, the measured profile data in the proposed system can be immediately converted into a summary roughness index such as the IRI. The roughness information is instantaneously displayed on an onboard computer in real time, unlike with a conventional RTRRMS (Tomiyama et al., 2011). This study focuses on a method for providing basic information about road roughness and IRI on municipal roads, which may assist and improve the implementation of PMS in municipalities. The overall objectives of this study are as follows.

(1) To introduce the principle of a new compact road profiler to measure IRI and roughness condition of municipal roads in different cities during different seasons.
(2) To introduce the use of GIS and Japan digital road map (DRM) so as to visualize the survey results linking land-use and road classification.
(3) To develop statistical analyses and evaluation methods based on a comparison study using local cities, road classes, road directions, wheel paths and different conditions of road roughness.
(4) To analyze and evaluate the ride quality of the road surface, the KITDS and ISO standard 2631 are applied, respectively (ISO, 1997).

2. Monitoring and evaluation of road profile

2.1. *Basic knowledge of quarter-car model to measure IRI*

The IRI was developed in 1986 using the results from the International Road Roughness Experiment performed in Brazil in 1982 (Sayers et al., 1986a, 1986b). Since then, it has become a well-recognized standard for the measurement of road roughness.

The main advantages of the IRI are that it is stable over time and transfer able throughout the world. The IRI is an index defined by applying the algorithm proposed by Sayers (1995) to a measured realization of the longitudinal profile. The IRI is a mathematical model applied to a measured longitudinal road profile. The model simulates a quarter-car model is shown in Fig. 1 (Kawamura, 2011). The quarter-car model predicts the spatial derivative of a suspension stroke in response to a profile using standard settings for speed and the vehicle dynamic depicted in Fig. 1.

2.2. *Compact mobile profiler in pavement monitoring*

The conventional profilers are not used to collect profile data frequently (every day or week), because data collection requires too much cost and time for operation. In recent years, with the development of pavement survey technology, a lot of countries have their own high-speed profilers, which are mainly used as laser sensor technology. These profiles have grown more powerful and become easy to operate, but the response-type profilers are still difficult to maintain the

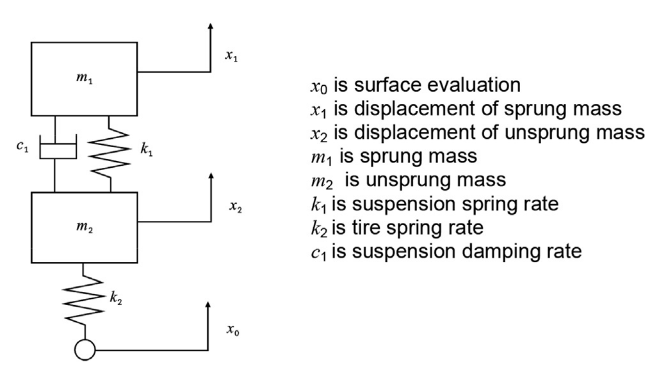

Fig. 1 – Quarter-car model.

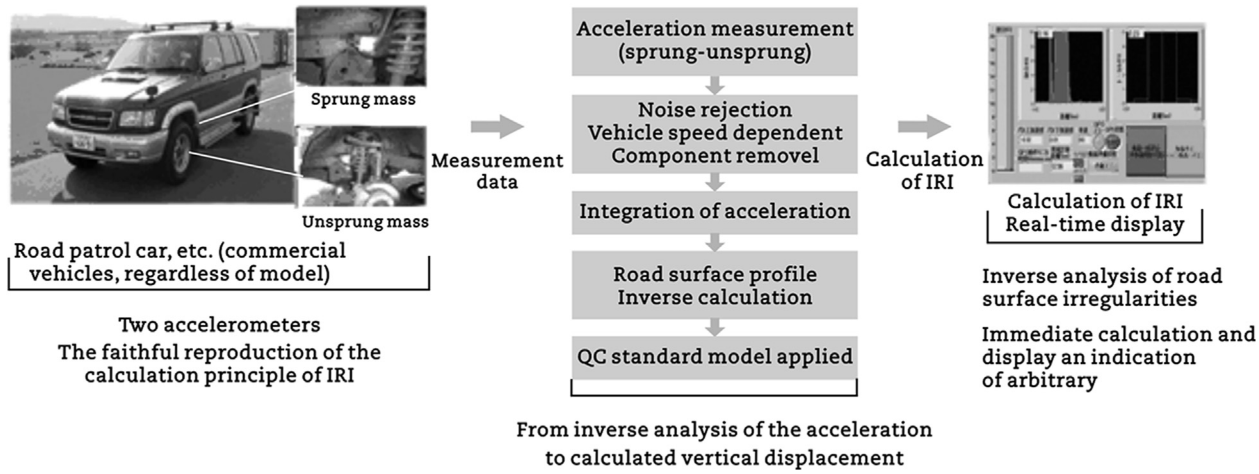

Fig. 2 – Overview of the mobile profiler system (STAMPER).

accuracy and save the effort to obtain a valid calibration. Against this background, Kitami Institute of Technology developed a new, cost-effective, time-stable, and easily workable compact mobile profilometer (MPM) to address the demand known as "system with two accelerometers for measuring profile, enabling real-time data collection" (STAMPER). The new system consists of two small accelerometers, a global positioning system (GPS) sensor, an amplifier and a portable computer. A small GPS sensor can be placed at any corner of a vehicle's front panel to obtain traveling speed and measurement position. Two small accelerometers are mounted on the sprung and unsprung masses on the suspension system of a survey vehicle. A transducer converts the strain of accelerometers into the electrical signal, and then the information of road evenness is displayed on a PC screen in real-time, as shown in Fig. 2.

To find the IRI algorithm, the road profile is calculated by the dynamic response of vehicles, and then simulated by a quarter car (QC). Acceleration is measured by the accelerometers attached to the body and front wheel-axle of a measuring vehicle. When using the road displacement per horizontal distance interval x_0, the acceleration is the response acceleration of the vehicle masses m_1 and m_2. The value x_0 is derived from the sampling time and the speed of the vehicle when measuring the acceleration. The QC model incorporates the vibration parameter of the measuring vehicle. The following procedure shows how IRI is calculated.

1) Determine the speed of the masses $\dot{x}_1$ and $\dot{x}_2$, and displacements from the measured acceleration of x_1 and x_2. Next, calculate the road displacement, x_0, backward with the equation of motion (a) in Fig. 3 that contains the vibration parameter of the measured QC model.

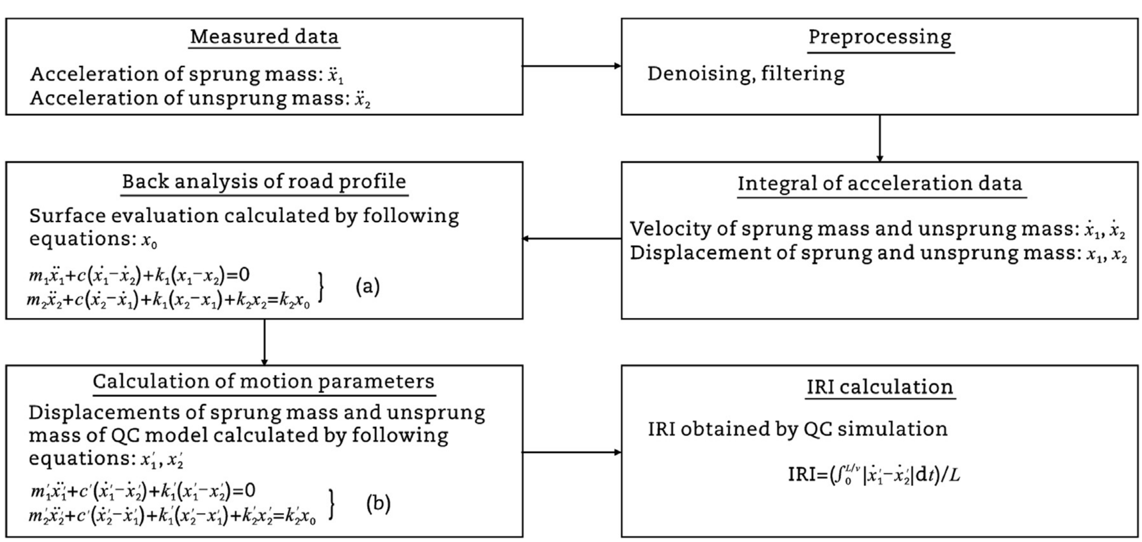

Fig. 3 – Steps of IRI calculation.

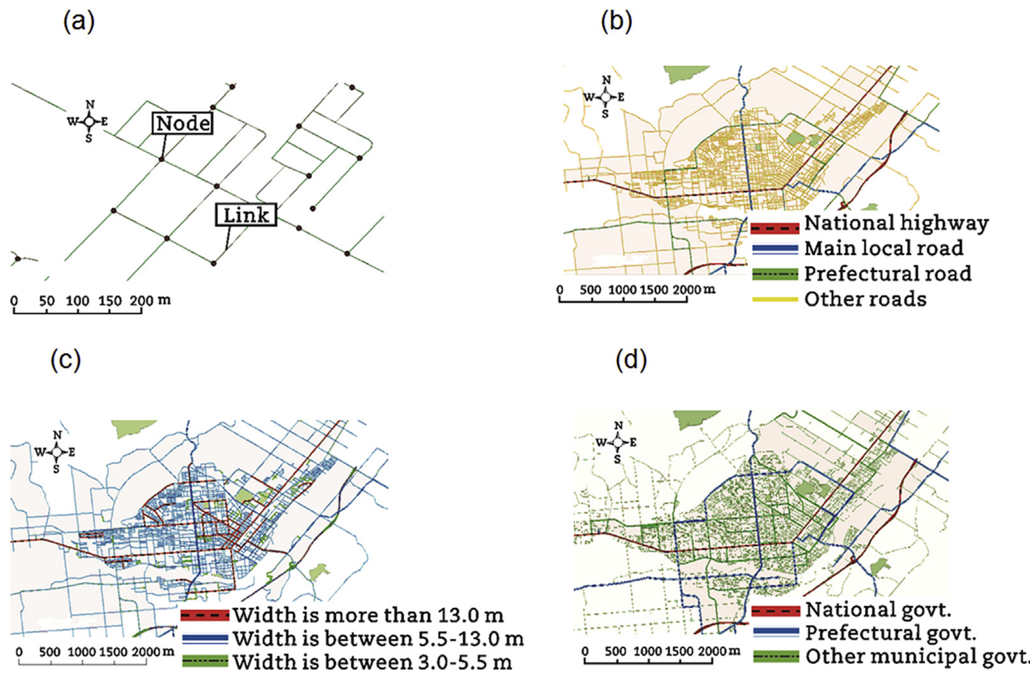

Fig. 4 – Summary of the road information by using DRM and GIS. (a) Node and link of road network. (b) Road category. (c) Road width. (d) Classification of road administrators.

2) Convert the horizontal distance interval x_0 to the horizontal distance interval at the vehicle speed of 80 km/h. Then, add this to the equation of motion (b) in Fig. 3, which has the vibration parameter of the standard QC model used for the IRI calculation by determining the response displacement values, x_1' and x_2'.

Fig. 3 shows the sequence of the algorithm (Kawamura, 2011).

2.3. *Overview of the DRM and GIS*

The digital road map (DRM) database is the standard national digital road map database supported by Japan DRM Association (1988). Since then, it plays a key role in various systems for road management. The main purpose of DRM database is devoted to intelligent transportation system (ITS), vehicle information and communication system (VICS), national integrated analysis system (NITS) and so on. The database includes significant information related to pavement management such as road administrators, lane widths, and locations of road structures. Therefore, it contributes to visualize the surface roughness conditions. The database is basically composed of nodes and links of road networks as shown in Fig. 4(a). ArcGIS is a commercially based geographic information system (GIS) which is used to compile geographic data, analyze mapped information, share and discover geographical information, and manage geographic information in a database. The system provides an infrastructure to make maps and geographic information available throughout an organization, across a community, or openly on the web (ESRI Japan Co., Ltd, 2012). Fig. 4(b)–(d) shows road category, width, and administrator, respectively, for urban areas that have a population of more than 100,000 in Hokkaido, Japan.

In these figures, the road categories are classified based on the following criterion.

Notes of road category in Fig. 4(b).

- Expressway is not included in national highways.
- Major local roads means arterial prefectural highway specified by the Road Act, MLIT.
- Prefectural road means ordinal prefectural highway, which does not include exceptional roads.
- Other roads are municipal roads or roads exempt from the Road Act.

Notes of road width in Fig. 4(c).

- Width is more than 13.0 m.
- Width is between 5.5 and 13.0 m.

Fig. 5 – Overview of KITDS.

- Width is between than 3.0–5.5 m.

Notes of classifications of road administrators in Fig. 4(d).

- National government.
- Prefectural government.
- Other city, town and village governments.

2.4. *Advantages of DS for road surface evaluation*

A lot of driving simulators (DS) have been developed nationally and internationally since the beginning of 1990. Scale-down DS showed an improvement in demand for introduction to a driving school associate with revision of a road traffic act for a period of time in Japan (Shiraishi, 2001). DS examine various topics, such as safety training at a driving school (Lonero et al., 1995; Wicky et al., 2001), car design and development (Löwenau et al., 2001), road sign design (Espié et al., 2001), evaluation for physiology of the human body (Mourant and Thattacherry, 2000; Stanney et al., 1999), and ITS (Stall and Bourne, 1996).

In the past, the main road data were used for geometric design. Kitami Institute of Technology introduced a new DS (KITDS) in 2003, which was initially developed to evaluate road safety and comfort (Kawamura et al., 2004). Known as KITDS, the prototype was based on a conventional DS used to evaluate traffic safety for driver training.

Fig. 6 – IRI based on the digital road map and GIS examples of city A. (a) In 2011. (b) In 2013.

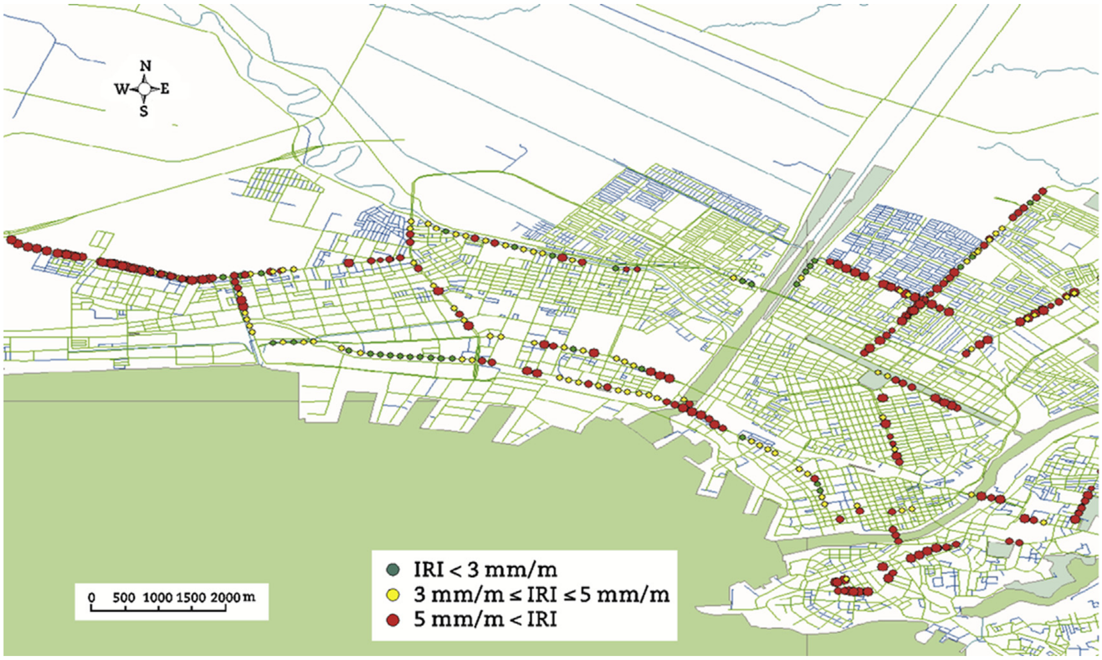

Fig. 7 – IRI based on the digital road map and GIS example during November 2012 (city B).

Since then, KITDS acquired many advanced functions, such as the evaluation of actual road surface characteristic data and vehicle actual motion data. It also enables the replay of visual images while driving to evaluate the comfort of the passenger's safety, stability, and controllability of the vehicle, vehicle fuel consumption and tire noise associated with the roughness of actual road and so on. KITDS specializes in road surface evaluation. It is the first device in the world that can evaluate the relationship between the road surface characteristics and vehicle behavior. Fig. 5 shows the overview of KITDS.

3. Applications of electronic road map and GIS on road monitoring

3.1. *Electronic road map and GIS results of two cities road conditions*

Figs. 6 and 7 represent pavement roughness measurement results using STAMPER to show IRI during November 2011 and March 2013 in city A, and November 2012 in city B (Tomiyama et al., 2012). Both two cities have populations of over 100 thousands, and are core cities in Hokkaido. The IRI data are measured for each 100-m interval, with the ArcGIS system plotting along an electronic road map. According to differently colored central areas seen in Figs. 6 and 7, the road administrator can investigate pavement situations based on the land-use plan at a glance. The IRI is a common international roughness evaluation index, which makes it possible to evaluate the pavement roughness objectively by IRI scale in Fig. 8 (Sayers and Karamihas, 1998). Criteria of IRI classification depend on the management objectives and road category.

3.2. *IRI conditions classified by road category*

The IRI conditions in local cities of Hokkaido are clarified by a histogram and cumulative curve as shown in Figs. 9 and 10. In order to calculate histograms and cumulative curves, IRI data is used for each 100-m section of the road. The breakdown is that national highways 95, major local roads 83, prefectural roads 177 and other roads (municipal roads mainly) 542 in 2011, and national highways 91, major local roads 64, prefectural roads 208 and other roads 461 in 2013 in city A, and

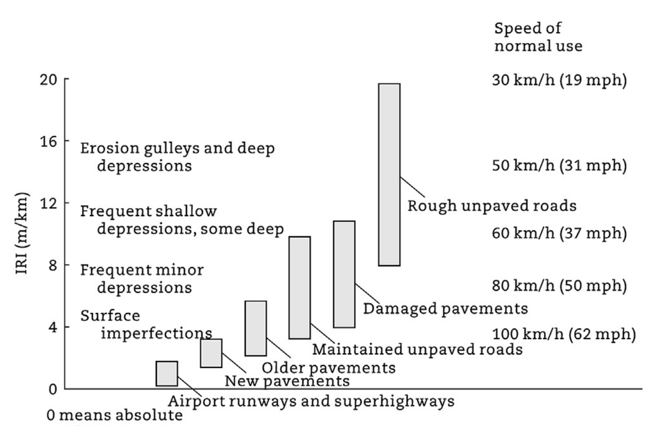

Fig. 8 – IRI scale.

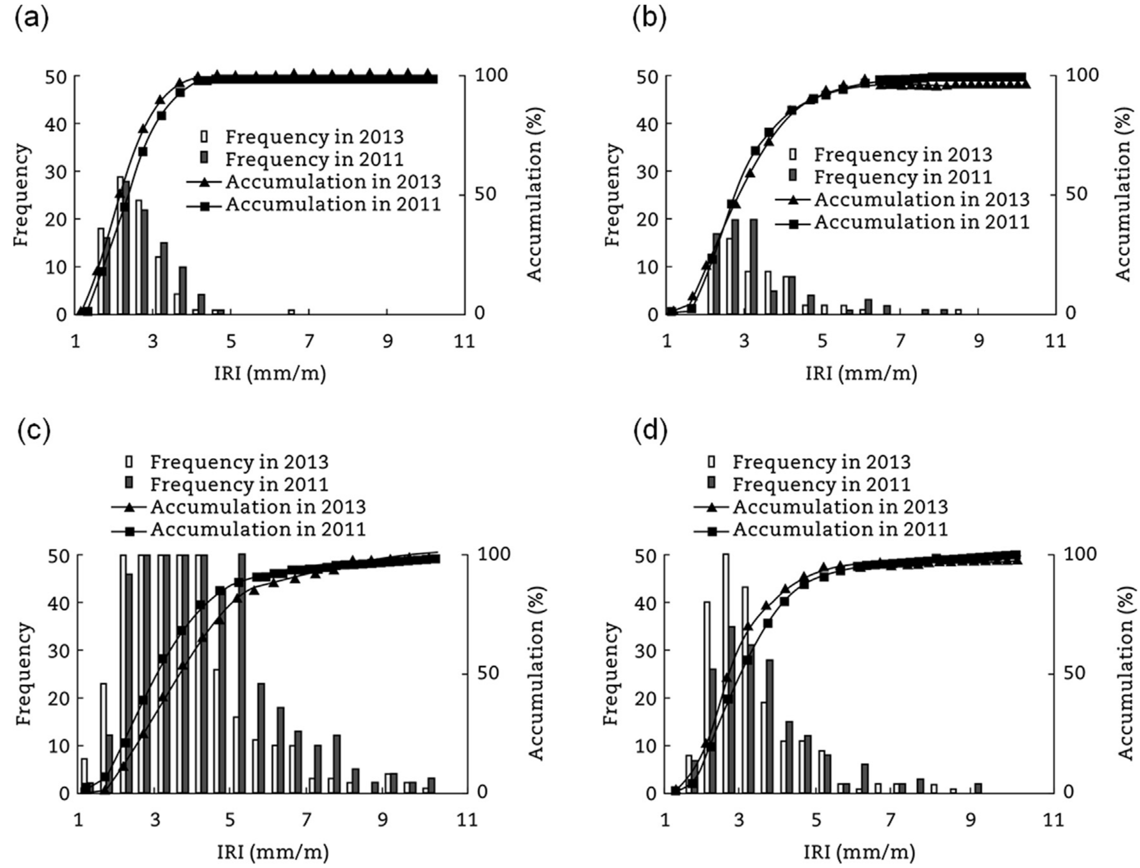

Fig. 9 – Histogram and cumulative curve of IRI in 2011 and 2013 (city A). (a) National highways. (b) Major local roads. (c) Other roads. (d) Prefectural roads.

national highways 164, major local roads 41, prefectural roads 17 and other roads 217 in city B in 2012.

Concerning the four different road classes in city A, the surface conditions of national highway and prefectural road in 2013 are better than those in 2011. Major road situations are not that generally different. On the other hand, situations of other roads are deteriorating year by year. Of special note is that no IRI data less than 5 m/km are observed for national highways. In city A, 9.64% and 14.74% of the IRI data exceed 5 m/km for main local roads, and prefectural roads, respectively. Moreover, a comparative study between the road conditions of city A and city B has demonstrated that the road evenness of the city A is better than that of city B in general.

3.3. *Visualization and analysis of the measuring results by ArcGIS in different seasons*

In order to respond to the strategy from MLIT, improvement of traffic safety and flow in winter season, and comparative study on seasonal variation of IRI were conducted during November 2013 and February 2014. In this case, the targeted city in Hokkaido, Japan, is a local core city with a population of about 124,000. And the city covers 1500 square kilometers, with a total road mileage of 1900 km for municipal roads. The IRI data are measured at 100-m intervals, and shown on a digital map using ArcGIS software. Figs. 11 and 12 show the results of dry and snow-covered road conditions on a major municipal road to compare and find out the reasons of road surface deterioration during two different seasons. In this case, IRI levels are classified based on the Implementation Manual of General Inspection for Pavement Surface presented by MLIT (MLIT, 2013). Fig. 11 shows an example of IRI road map detailing a southbound (SB) direction in comparison with road surfaces in different seasons. Fig. 12 shows those for northbound (NB). Clearly, dry road conditions are better than those of snow roads, as seen in both figures.

3.4. *Statistical analysis*

Figs. 13 and 14 show results from the histogram and cumulative curve, obtained from municipal roads using the same IRI data for each 100 m. Each figure also shows the seasonal changes of road conditions. According to histogram and cumulative distribution function curve (CCDF) of the southbound directions, dry road condition for southbound direction (SB) is better than snow-covered one. According to the northbound direction road conditions, using same analysis method to compare seasonal road conditions, the results much clearly show that the dry road condition is better than snow one.

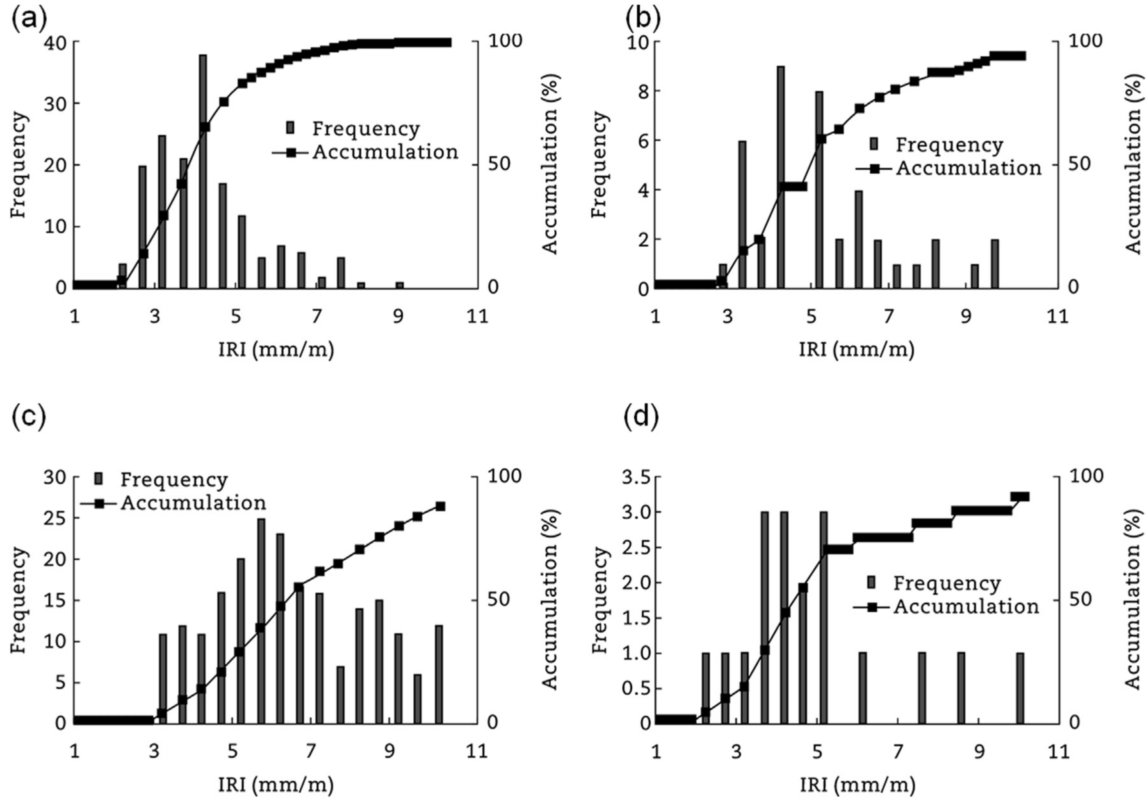

Fig. 10 – Histogram and cumulative curve of IRI during November 2012 (city B). (a) National highways. (b) Major local roads. (c) Other roads. (d) Prefectural roads.

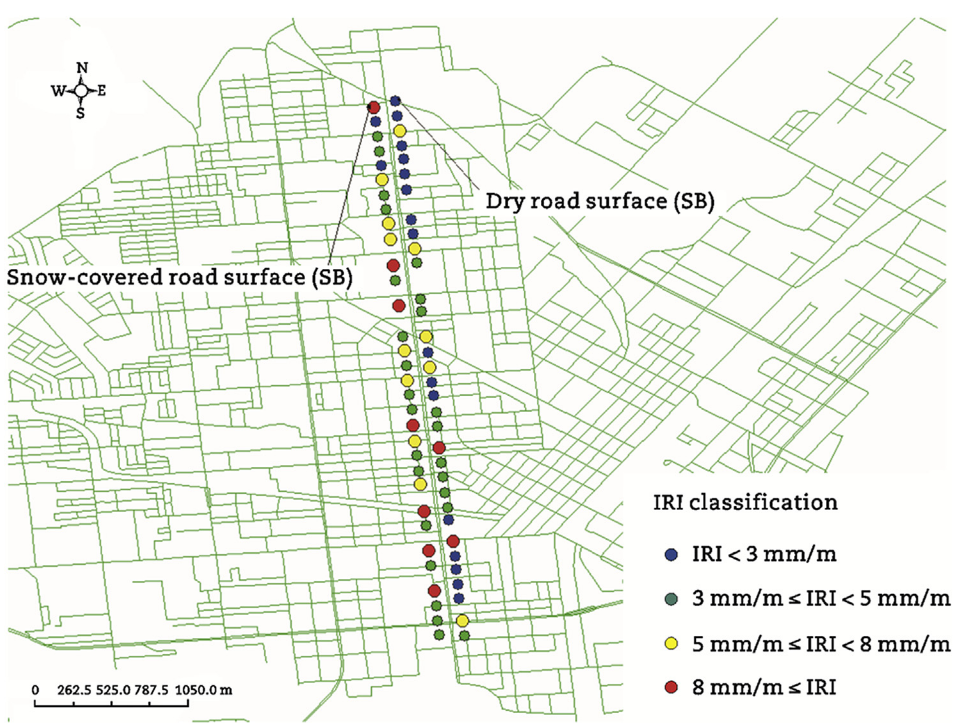

Fig. 11 – Seasonal change of road roughness condition (SB).

Fig. 12 – Seasonal change of road roughness condition (NB).

4. Overview of the pavement evaluation

Pavement evaluations are conducted to determine the functional and structural conditions of a highway section, either for purposes of routine monitoring or planned corrective action. Functional condition is primarily concerned with the ride quality or surface texture of a highway section. Structural condition is concerned with the structural capacity of the pavement as measured by deflection, layer thickness, and material properties. At the network level, routine evaluations can be used to develop performance models and prioritize maintenance or rehabilitation efforts and funding. At the project level, evaluations are more focused on establishing the root causes of existing distress in order to determine the best rehabilitation strategies.

4.1. *IRI as ride quality parameter*

IRI can measure pavement smoothness. The lower the calculated IRI, the smoother the pavement will ride. The higher the IRI, the rougher the pavement will ride. The units of

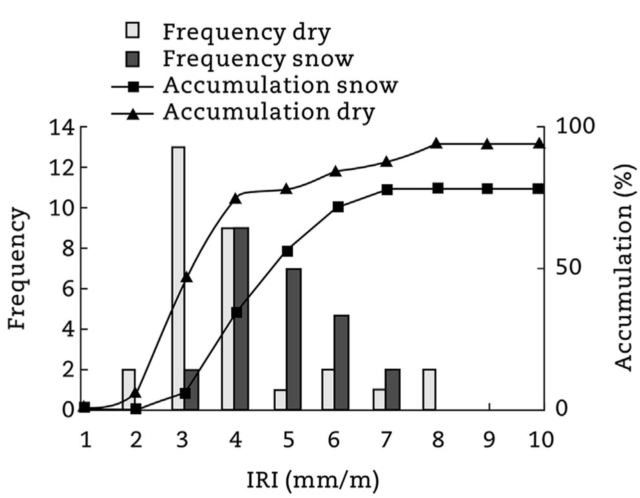

Fig. 13 – Statistical analysis of roughness condition (SB).

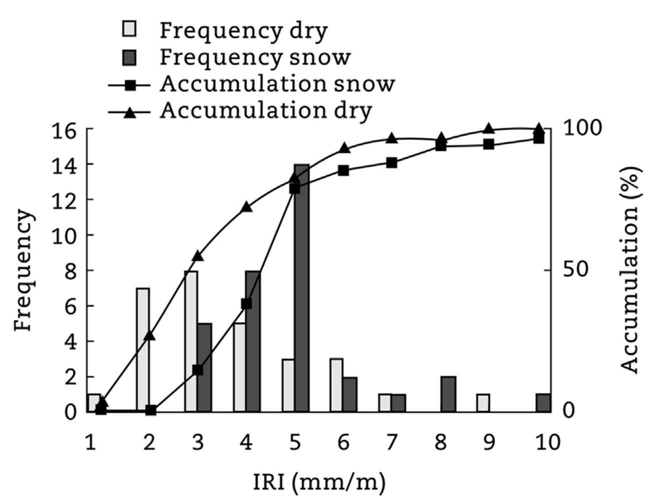

Fig. 14 – Statistical analysis of roughness condition (NB).

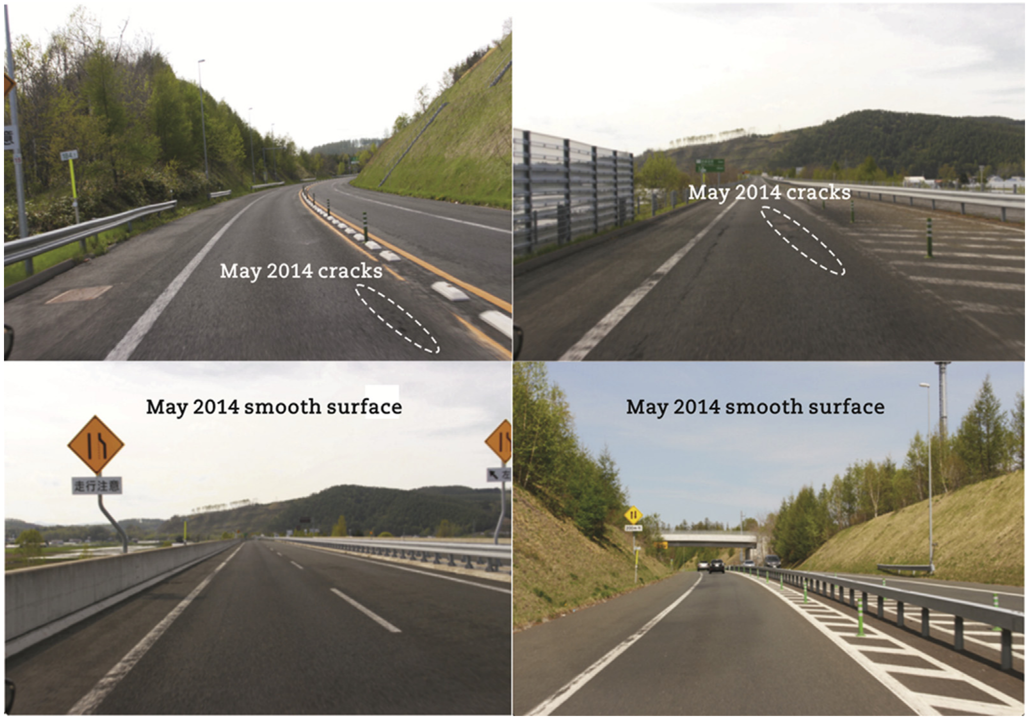

Fig. 15 – Surface conditions of the measurement location.

IRI are usually in/mile, m/km, or mm/m. The equation of calculate IRI is presented in Eq. (1).

$$\mathrm{IRI}=\frac{\int_0^{L/v}|\dot{z}_\mathrm{s}-\dot{z}_\mathrm{u}|\mathrm{d}t}{L} \tag{1}$$

where L is traveling distance, v is vehicle speed, $\dot{z}_s$ is vertical speed of the sprung mass, $\dot{z}_u$ is vertical speed of the unsprung mass, dt is time increment.

4.2. *Analyzing the ride quality on an object route line*

Using two compact road profilers at 70 km/h, the roughness data were measured on 7800-m road sections of a high standard highway in a local area of Hokkaido during May 2014. The profilers were mounted at inner and outer wheel paths of the survey vehicle. The ride quality was evaluated by using profile viewing and analysis (ProVAL), on eight different, smooth and rough sections. Fig. 15 is the results of them.

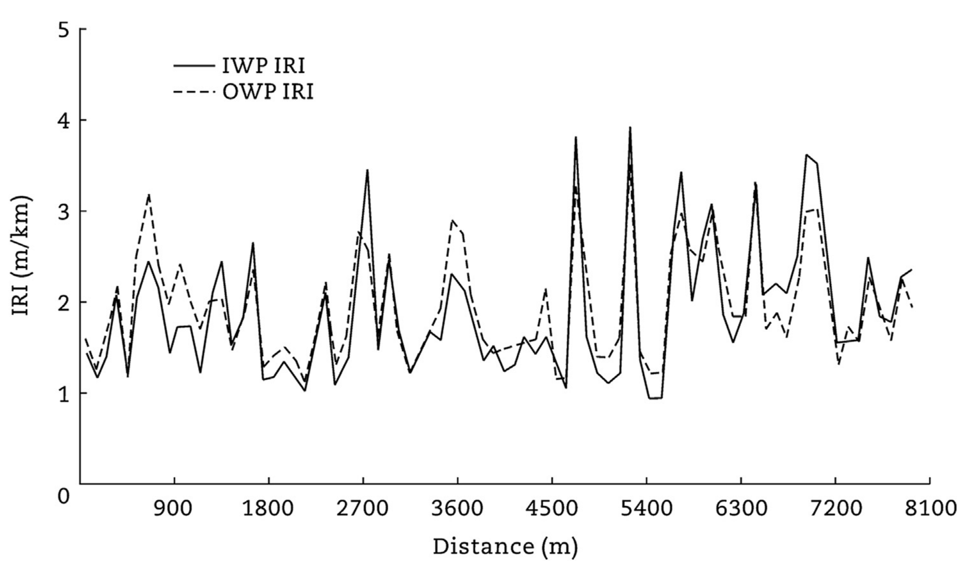

Fig. 16 – Road roughness conditions of both wheel paths.

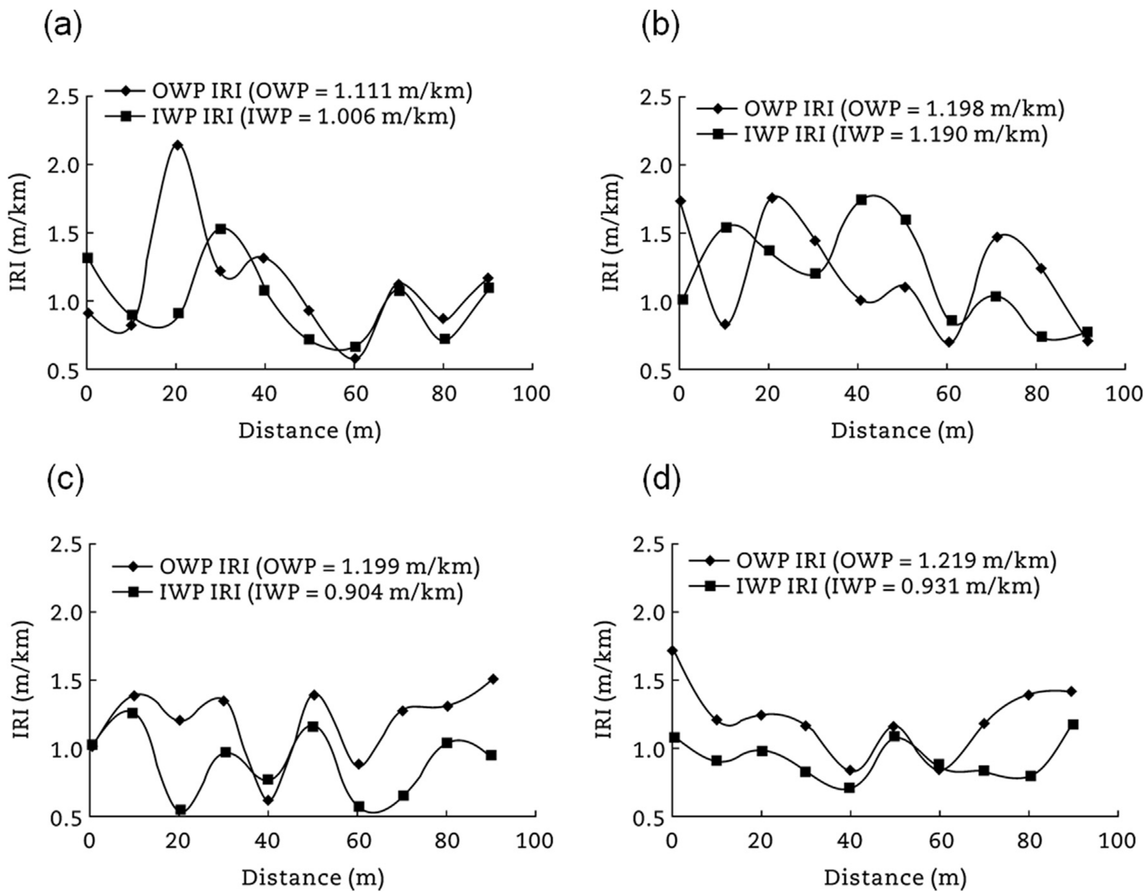

Fig. 17 – Ride quality conditions for smooth sections. (a) 2100–2200 m smooth section. (b) 3100–3200 m smooth section. (c) 5400–5500 m smooth section. (d) 5500–5600 m smooth section.

For improving the driving safety, secure and comfortability on highway and expressway, MLIT strongly requested the local road administrations to improve road surface conditions from a viewpoint of the material and construction process. In contrast, the Nippon Expressway Company (NEXCO) introduced a maintenance standard for expressway in Japan. Specially, an IRI over 3.5 m/km signifies the need to rebuilt while an IRI less than 3.5 m/km is acceptable.

Fig. 16 is a summary of the high-standard highway's object section, clearly showing that, the most smooth and rough sections are used to evaluate and compare the ride quality by NEXCO road maintenance standard.

Fig. 17 shows the results of IRI on smooth section. Fig. 17(a)–(d) clearly shows that the IRI range is less than the maintenance standard. However, the comparison results between the inner and outer wheel paths show that the inner wheel path is better than those of outer wheel path.

Fig. 18 presents the IRI results on rough section. Fig. 18(a)–(d) clearly shows that the majority IRI range is over the maintenance standard. Road administrators should rebuilt construction and improve the ride quality on these sections. In addition, the comparison results between the inner and outer wheel paths show that there are no significant differences between the wheel tracks. The road surface under both wheel paths is deteriorating year by year.

4.3. *Ride quality analysis*

As introduced in the previous section, KITDS is possible to evaluate and study different kind of topics, such as evaluation of comfortability of the riders based on biological signal. To deeply evaluate the riding comfort, actual road profile data were used, which is measured on a high standard highway in a local area of Hokkaido by using two compact mobile profilometer to evaluate the RQ. To evaluate and compare of the RQ of both wheel paths, KITDS are used to obtain vertical acceleration data and calculate Root Mean Square (RMS) and Crest Factor (CF) to completely identify the ride comfort.

Mathematically, RMS can be expressed as Eq. (2).

$$\mathrm{RMS} = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)\mathrm{d}t} \tag{2}$$

where T is measurement duration, $a_w(t)$ is frequency weighted acceleration at time t.

CF can be expressed as Eq. (3).

$$\mathrm{CF} = \frac{\max(a_w(t))}{\mathrm{RMS}} \tag{3}$$

Fig. 19 shows the correct positions and sensitive ranges of the whole acceleration data as highest, middle and lowest

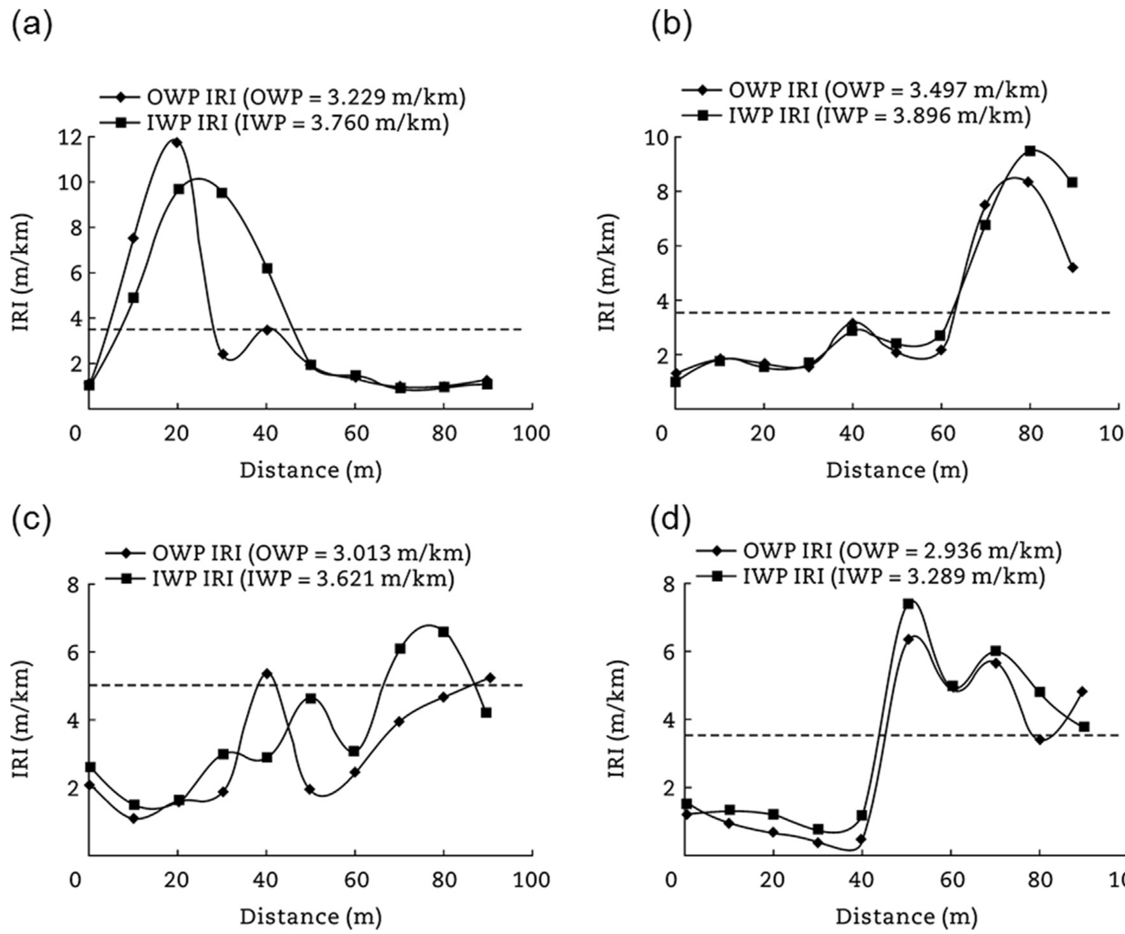

Fig. 18 – Ride quality conditions for rough sections. (a) 4700–4800 m rough section. (b) 5200–5300 m rough section. (c) 6900–7000 m rough section. (d) 7000–7100 m rough section.

level, respectively. And the different results of these three levels of RMS and CF are shown in Table 1.

ISO 2631-1 standard is especially used to assess ride quality levels by weighted RMS acceleration (ISO, 1997). RMS range for evaluating comfort is categorized in Table 2.

According to the last RMS results, highest, middle and lowest levels are applicable for "fairly uncomfortable", "a little uncomfortable" and "comfortable", respectively. Those results show that the ride quality of the measuring location is acceptable because no value can be in included to represent "uncomfortable" or over this.

5. Conclusions

Essentially, pavement management is a series of steps to provide information on the current and future states of pavement conditions. It is helpful for promoting rehabilitation options while taking into account the relative economic advantages and disadvantages as much as possible. PMS assists with the technical issues of choosing suitable times, places, and techniques to repair pavements, provide those in charge of maintaining and improving roads with the data and other technical justifications, which is needed to support for adequate road maintenance. The methodology of obtaining roughness data in road networks for operating PMS is an important issue for road administrators. With the development of visualization technology, it is not difficult to establish the road network monitoring for different classes of roads. From data collection to analysis, this study provides basic information about the road surface conditions of different road classes and seasons by using a mobile profilometer and advanced monitoring systems such as STAMPER, DRM database and ArcGIS. In order to enhance the credibility of this study, the authors have shown the variability of IRI by using a frequency distribution function. For the purpose of this study, the IRI measurement as a 100-m interval was carried out, based on four different road levels in two cities and two different seasons. Road profile measurements were also conducted by using two STAMPERs in high standard highway to evaluate ride quality.

The summary of this study are shown as follows.

As previously stated, regarding the frequent measurement of road surface at ease, the STAMPER has proven a significant advantage by enabling road surface profile measurement without a special vehicle and in real time. It also possible to acquire road profiles not only one-side wheel path but also for both wheel paths, IRI and acceleration data at one time.

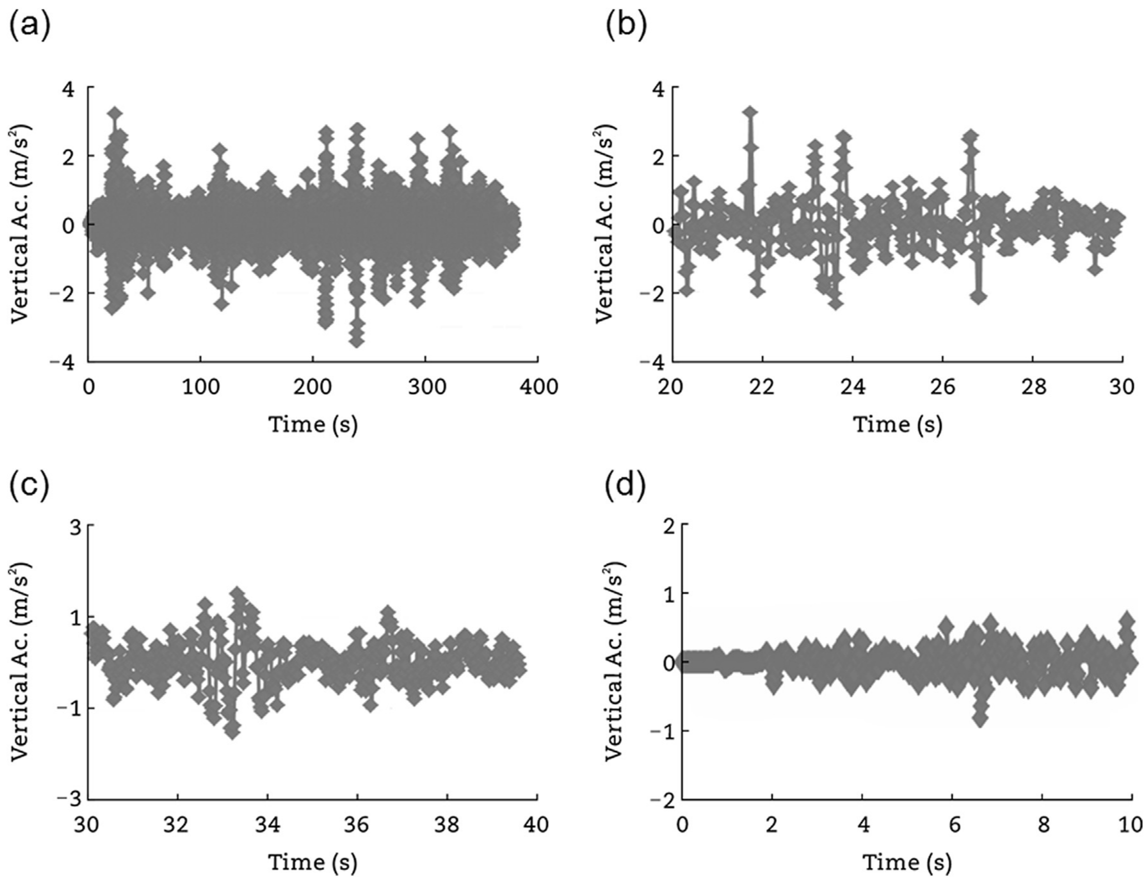

Fig. 19 – Vertical acceleration data from DS. (a) Whole level. (b) Highest level. (c) Middle level. (d) Lowest level.

Table 1 – Results of RMS and CF.

Level	RMS (m/s^2)	Peak acceleration (m/s^2)	CF
Highest	0.74	3.25	4.39
Middle	0.46	1.50	3.28
Lowest	0.17	−0.81	−4.76

Table 2 – Category of ISO 2631-1 standard.

Ride quality level	RMS (m/s^2)
Comfortable	≤0.315
Slightly uncomfortable	0.315–0.630
Fairly uncomfortable	0.5–1.0
Uncomfortable	0.8–1.6
Very uncomfortable	1.25–2.50
Extremely uncomfortable	≥2

DRM data plays an important role for road administrators to obtain and classify the critical information on road structures such as road class, road width, and road administration. Based on precedent studies, DRM clarifies road roughness conditions. Also, it is possible to edit IRI data for each land-use classification and application on city planning strategy as well.

As described above, the roughness of each road route is easily clarified by the implementation of the DRM data with GIS. It is strongly expected that application of the results in this study can contribute to monitor the road roughness and identification of the road distress conditions to establish the sophistication of the PMS.

Moreover, the results from measuring and evaluating road roughness conditions, in terms of ride quality summarized as below.

KITDS has special feature to record actual profile data to analyze the road surface condition from the standpoint of ride quality of the passengers. Results of RQ analysis under the ISO 2631 standard show the different levels of RMS far from "uncomfortable" or "extremely uncomfortable", which means that ride quality at the measuring locations is acceptable for passengers. The results suggest that the methodology, combined with DS and road profile, leads to an innovative problem-solving approach. It is better suited for the evaluation of road roughness for taking into account human factors.

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