Doctoral Thesis

Efficient Road Roughness Monitoring using Mobile Profiler and GIS in Establishing Pavement Management System

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Abstract

The International Roughness Index (IRI) has become one of the major road roughness indexes that most commonly used by the road management authorities and researchers throughout the world since the World Bank has developed it in 1986.

In recent years, road administrator of Hokkaido prefecture in Japan and Xinjiang region in China are especially requested to create a visual map of road network to monitor road surface conditions and asked to conduct pavement management on their own road ways more quantitatively. In order to respond these requirements, the purpose of the study mainly focuses on solving the pavement monitoring issues.

Therefore, during the last three years of doctoral research works, measurement, analysis, evaluation and comparison study of road roughness conditions and ride quality (RQ) affected by the roughness are dealt with, in core cities of Hokkaido and two countries. In this case, efficient mobile road profiler (MRP) developed by Kitami Institute of Technology (KIT), was used together with ArcGIS and mathematical processing software.

Along with the development of Response-type road roughness measuring systems (RTRRMS), many countries have developed their own road profiling devices in measuring the longitudinal profile or IRI on their roadway sections. KIT developed a new, cost-effective, time-stable, and user-friendly compact mobile road profiler (MRP) to address the demand known as "System with Two Accelerometers for Measuring Profile, Enabling Real-time data collection" (STAMPER). The new system configured with two conventional small accelerometers, a global positioning system (GPS) sensor, an amplifier and a personal computer.

Since 1995 to the present, Xinjiang Expressway in China has been built for the total mileage of 4,300 kilometers, in recent years local road agencies required to establish a suitable PMS for regional weather conditions regarding road users saving for the future. In order to respond these demands, authors have carried out road roughness measurement in August 2016 at one of the trunk expressway in Xinjiang with the total

mileage of 874 km, which was initiated at the beginning of the 21st century.

On the other hand, in Japan, road networks have been sufficiently developed from stand point of road network. From 2013 to present, we have conducted road roughness survey on the municipal road of the different cities, and different road classes, road directions, wheel paths and various conditions of the road roughness in Hokkaido prefecture for carrying out a comparison study.

GIS technology is considered for implementation for many infrastructure planning and management systems, owing to its superior spatial data handling capabilities. In this study, we used GIS to carry out the spatial evaluation for deteriorated pavement areas based on collected roughness data.

In conclusions, new findings in this paper are summarized as follows:

- STAMPER has proven a significant advantage by enabling road surface profile measurement in real time without a special vehicle.
- It is recognized that visualization using ArcGIS by combining Japan Digital Road Map (DRM) to evaluate and show road conditions of different cities considering seasonal changes is a powerful tool to make decision of establish of the municipal PMS.
- Survey results of the road surface conditions show that RQ analysis according to the ISO 2631 standard represents the different levels of RMS (root mean square) value of vertical acceleration data, which is far from"Uncomfortable" or "extremely uncomfortable," it means that ride quality at the measuring locations is acceptable for passengers.
- In accordance with the national highway evaluation standard "JTGF801-2012" of China and testing results of IRI threshold standardized by Nippon Expressway Company Limited (NEXCO), there is significant relationship between the IRI and pavement serviceability rating (PSR). The survey results conducted in both countries' expressway proved that level of classification on the roughness was closely common to the both countries.

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CHAPTER *1*

Introduction

1.1 Background and purpose

The concept of road surface or pavement is, using a kind of durable material laid down on an area to support vehicular or foot traffic, such as a road or walkway. In the past, many countries extensively used cobblestone and granite setts on their roadways. According to the road construction history in recent years, permeable paving methods are initiated to be used for low-impact roadways and walkways. Road surface divided into asphalt, concrete and composite pavement. Asphalt pavement is known for its durability and resilience since the 1920s, and it made up of stone, sand, additives and liquid asphalt. Concrete pavement created by using a concrete mix of portland cement, coarse aggregate, sand and water. Composite pavement is the combined result of the portland cement concrete sublayer with asphalt, and it mostly used to rehabilitation construction of the existing roadways rather than in new construction.

Pavement roughness or smoothness is defined as the deviation of the vertical amount of the road surface, and it is one of the major technical indicators of the pavement conditions to evaluate the ride quality (RQ) of new and rehabilitated pavements. Pavement roughness is closely related to traffic safety, comfort, economy, and it also has a direct impact to carrying capacity and life cycle of the pavement. Uneven road surfaces will increase running resistance, and decrease the life cycle of mechanical parts and tire wear, fuel consumption and directly increase running costs of the vehicle.

Road roughness is induced by vehicle vibrations that will cause additional traffic bumps, affecting driving comfort and safety. Frequent vibration will increase impact force to the pavement, and it also accelerates the damage as well as reduces life-cycle of the pavement. Since the introduction of international roughness index (IRI) in 1986[1], it has become one of the indexes most commonly used in the world for evaluating and managing roadway systems. The IRI is the index which represents the surface conditions of a highway section, and it is obtained from measured longitudinal road profiles. The IRI is calculated by using a quarter-car vehicle mathematical model, whose response is accumulated to yield a roughness index with units of slope (in/mi, m/km, etc.).[2]

Pavement management system (PMS) 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 [3]. 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[4]. Based on monitoring road surface conditions of municipal roads, this strategy has motivated local road administrators to develop and improve their PMS to provide a better ride environment.

On the other hand, in China, the ministry of communications highway research institute introduced a basic framework of information management system (IMS) of the road surface. The IMS consists of the database of performance evaluation, performance prediction and maintenance decision on the pavement.

During the development of pavement maintenance system, the ministry of communications highway research institute, Tong Ji University and other scientific research units established highway pavement maintenance system in 1991. It is named Highway Information Management System (HIMS) [5], which demonstrated that China's road management had reached a new level. In case of Xinjiang, the government officially began to invest in expressway development from 1995 to the present. Xinjiang Expressway has been built for total mileage of 4,500 kilometers. However, PMS is not implemented for the entire area and required suitable PMS taking into account the weather conditions and from standpoint of road users saving for the future.

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 into four general types: response-type road roughness measuring systems (RTRRMS), direct profile measurements, indirect profile measurements, and subjective panel rating [1, 6]. Most highway agencies collect IRI data using a laser sensor or a high-speed profiler. This equipment measures surface profiles at regular traffic speeds and provides excellent results for use in network analysis for PMS. However, because these devices are mounted on a full-size van, an automobile, or a trailer, they are difficult to use on roadways at short intervals [7]. Also, these devices are rather expensive and delicate. In order to satisfy these requirements, Kitami Institute of Technology (KIT) provided a low-cost road profile measuring system. The profiler consists of two small accelerometers setting up to a vehicle suspension system, while conventional high-speed profilers which use laser sensors [8]. 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 [9]. This study focuses on a method for providing basic information about road roughness and IRI on different classes of roadways in different two countries, which may assist and improve the implementation of PMS not only for expressways but also for municipal roads.

1.2 Concept of the road surface characteristics

For the particular nature of the road surface, the difference of the basic features and derived features is necessary to understand. There is the concept of the pavement characteristics in figure 1-1 [10], which involves the basic characteristics formed by geometric shape, evenness, textures and others. As to such as the evenness of the basic characteristics, there are individual relationships with the drive dynamics effectiveness, drainage qualities, skid resistance, reflection properties, tire noise and rolling resistance of the derived characteristics.

As important issue for the final evaluation of these characteristics, there is a significant relationship with the traffic safety, riding comfort, environment protection, energy saving, pavement protection and vehicle protection. We are concerned here with the evenness. As shown in the above figure, it is possible to confirm that, it has the link with the evenness a lot, and also evaluation elements of the road users is most.

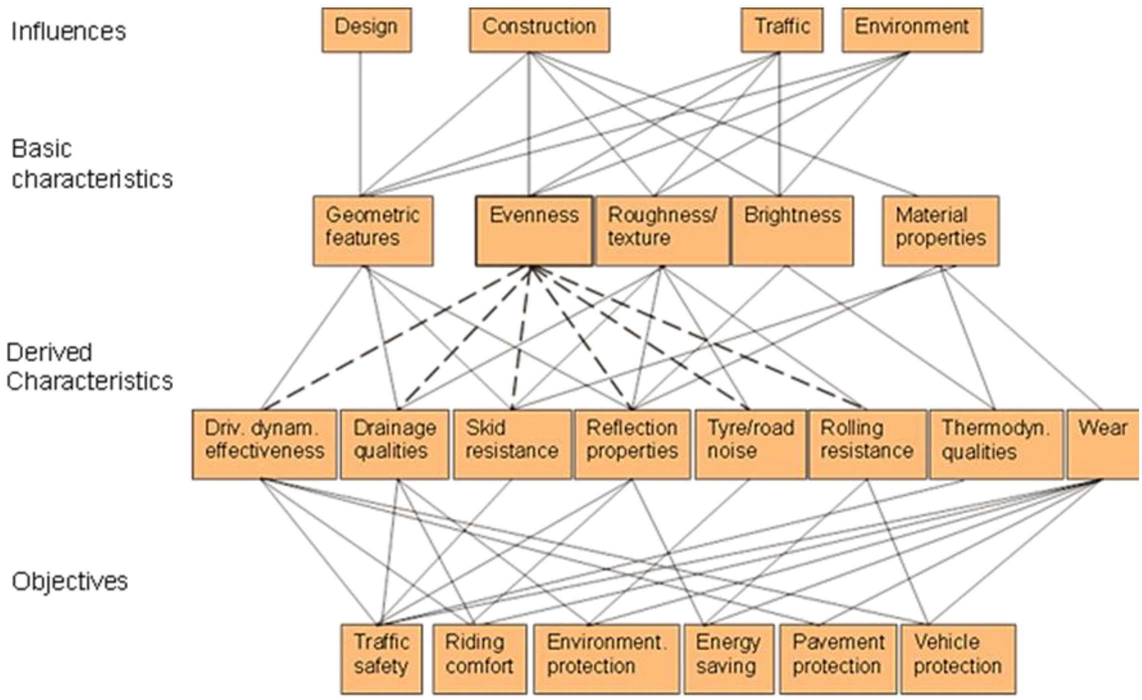

Figure 1-1 Concept of the surface characteristics [10]

1.3 Historical back ground of the road survey device

According to the latest scientific explanation, surveying is the determination of the terrestrial or three-dimensional position of points and the distances and angles between them. These points are always seated on the surface of the Earth, and they are usually used to establish land maps and boundaries for ownership, locations like corners of a building or the surface location of subsurface features, or other purposes required by government or civil law.

There are many devices for measuring road roughness in use throughout the world. The most basic concept of the road survey or surface roughness measurement is explained that it is the kind of technique, which is held by using a sort of survey device to measure the surface conditions between the two points. According to the Sayers [6] explanation about road roughness measuring devices, they are grouped into four generic classes based on the profile measurement or the IRI measurement.

Table 1-1 Classification of the profiler and its characteristics [6]

Equipment Class	Class Characteristics
Class 1: Precision profiles	(**1**) Requires precision measurement of road profiles and computation of the IRI at highest accuracy. (**2**) 2 % accuracy over 320 m. (**3**) IRI repeatability of roughly 0.3 m/km on paved roads & 0.5 m/km on all road
Class 2: Non-precision Profiles	Requires measurement of road profiles and computation of the IRI but not capable of Class 1 accuracy
Class 3: IRI Estimates from Correlations	(**1**)Includes all response type devices and not necessary measure road profile. (**2**) Devices are calibrated by correlating outputs to know IRI values on specific road sections.
Class 4: Visual inspection of IRI	Roughness measure is not reproducible or stable with time, and IRI only estimated by subjective rating.

1.3.1 Class 1: Precision Rod & Level device

The rod and level as shown in figure 1-2, are traditional surveying tools, the level provides the elevation reference, the readings from the road providing the height relative to the reference, and a tape measure locates the individual elevation. Most people call the rod and level method as "static" because the instruments are not moving when the elevation measures are taken. Although the static equipment is familiar to most engineers, for conducting measurement by rod and level tools, it is necessary to pay attention to take elevation measure at close intervals of a foot or less and the specific height action needs be accurate to 0.5mm or less.

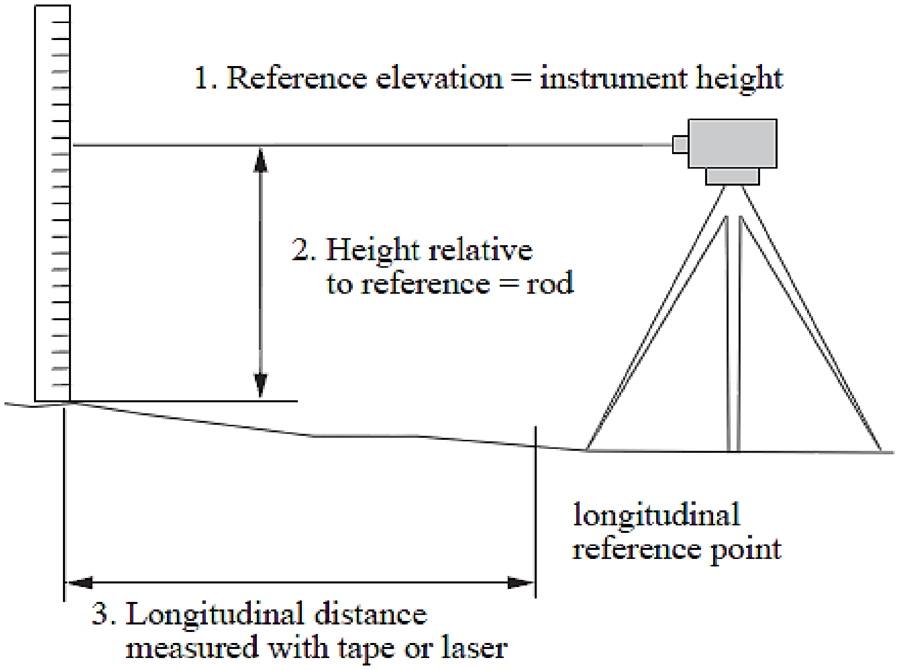

Figure 1-2 Road & Level [2]

1.3.2 The other static device

There is another profiling device as shown in figure 1-3, that conform to the requirements for Class 1 devices and usually used to measure reference profiles on calibration sections, which is called the Dipstick.

The Dipstick is the road roughness measurement device which is “walked” along the line being profiled. The device contains a precision inclinometer that measures the height of the two support feet at the base of the instrument [2]. These feet can be spaced 20 to 500 mm apart. The Dipstick is moved by leaning all of the device weight onto the front foot, and then pivoting the rear foot around the front foot by 180 degrees. When the instrument has stabilized, the change in elevation is automatically recorded and a "beep" is sounded. The longitudinal distance is determined by multiplying the number of measures made with the known spacing between the contact feet [2]. The Dipstick can record at approximately 200 m in per hour.

Figure 1-3 Road profiling device “Dipstick”

1.3.3 Class 2: High-speed road profiling devices

According to the Sayers explanations[6], high-speed profile devices as shown in figure 1-4, are capable of measuring a precision profile of one or more wheel paths while moving at speeds more than of 100 km/h. The first high speed profiling device developed in 1960[2]. Since then, significant advances in precision measurement technology have significantly aided the design of high speed profilers, and recently these devices are used for road surveillance in many parts of the world. High-speed profiling devices are also called to as Inertial Profilers, due to the use of accelerometers to determine an inertial reference which provides the instantaneous height of the measurement base at all times when the vehicle is moving which always provides the instant height of the measurement base at all times when the vehicle is in motion.

Figure 1-4 High-speed profiling devices

The high speed profiling devices have some advantages. These are: It is capable of measuring the surface profile very accurately. In addition, it uses the IRI transform with a fixed computer algorithm, the processing constants still exist unchanged, and therefore the measured IRI is consistent over time.

According to the stability and accuracy of IRI values obtained from a proven high speed profiler, these IRI values can be used to track the deterioration of network sections from one year to the next. It is often able to measure both longitudinal and lateral profiles while providing roughness and rut assessment simultaneously. Some of them can also

provide a high-definition video of pavement surface during the surveying.
Like some other devices in Class 1, it also has disadvantages; these are: It is not always successful in profiling gravel roads, because of its laser height sensors. One of the primary disadvantages of these devices is, relatively expensive than response type devices – few network agencies can afford to purchase and maintain their profilers. While the manufacturer calibrates high-speed profilers, a large number of verification test and control procedures are still not followed; the results of these devices are usually much less than results of the calibrated response type device. In addition, these validation procedures are expensive and require road network owners to spend more time and money on the upfront investment. The operation and control procedures of the high-speed profiling devices are rather complex, and it requires road administrators devote more time to understand and participate in the validation and inspection procedures.

1.3.4 Class 3: Response type road profiling devices

Response type road profiling devices are the first type of device used to measure and obtain road roughness. These types of devices almost always consist of an accelerometer installed in a vehicle or trailer to record the up-and-down movement of the suspension system, which is called the suspension stroke. These types of device were appeared at the beginning of 1920, and are still in widespread use.
Response type road devices belong to Class 3, which has a full name of response type road roughness measuring systems (RTRRMSs) as shown in figure 1-5. In order to estimate roughness index IRI, which has a first implementing correlation equations with other variables, and these systems can collect IRI data of long pavement sections quickly than the other devices of Class 1 and Class 2[11, 12]. Almost, most of the RTRRMSs still have a common problem, which is the speed of the investigation. It is necessary for these systems to update a constant survey speed or to keep the rate within a certain range [13-14].
There are also some advantages of the response type road roughness device such as Response type road profiler has been widely used throughout the world for many years, and the engineers from all over the world are well acquainted with the operation and output of these types of devices. In general, the output of these types of devices is

known to be consistent with the engineer's roughness and road condition assessment.
Response type road roughness devices are relatively inexpensive. A financial cost of response type systems is less than a 1/10th cost of a high-speed profilometer.
Although, these types devices demand frequent maintenance of operation, after the once calibration it always remains valid for a long time, the maintenance cost of the equipment is inexpensive. The calibration process of response type devices is quite easy and cheap to perform once calibration sections have been set out and measured.
One of the most significant advantages of the response type devices, it can survey on gravel roads but inertial profilometer cannot do.
Although, these types of devices have so many advantages, it also has some disadvantages same as Class 1 and 2; these are: The accuracy and repeatability of response type road profiler are more lower than that the type of Class 1 profiling device. Moreover, the annual deterioration of IRI on a highway section is constantly smaller than the measurement error of response type devices, which is because of the lack of high precision, and also because of errors inherent in the calibration to correlate with IRI. It means that response type devices cannot track the deterioration of a road network annually in general.
The transformation process IRI value in response type devices, it is entirely dependent on the suspension system of the vehicle. The output of these type devices tends to shift over time and not stable. Because of these types of devices require calibration at least once in a year. As one of the most disadvantages of these type devices, it can only measure road roughness. But, there are some modern high speed surveying devices, which do not only measure the lateral and longitudinal profile but also obtain high-definition photographs or videos of the road surface at the same time and real time, and it also convenient for decision makers.

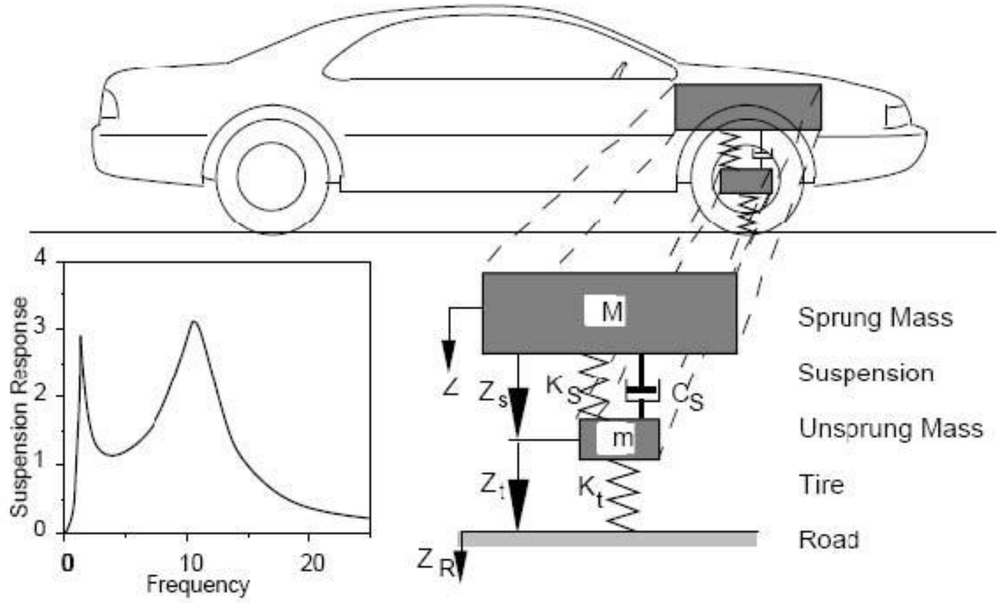

Figure 1-5 RTRRMS with its algorithm [2]

1.3.5 Class 4: Visual inspection of IRI

Because of the current road roughness measurement options, Class 4 measurements methods are not widely regarded as being suitable for estimation of the road roughness at the network level. Therefore, the use of this approach has a limit with only very professional workers in this career. The advantage of this method is, almost with zero price and only work with eyes and intuition. But it also has most significant disadvantages that, no accuracy, no stable data and not enough explanation to answer why.

1.4 **New road roughness device "Compact road mobile profilometer"**

The conventional profilers are not used to collect profile data frequently (every day or week) because data collections need 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 rapidly and become easy to operate, but the response-type profilers are still difficult to keep the 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 implementable 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 as shown in figure 1-6. A small GPS sensor can be placed at any corner of a vehicle's front panel to obtain traveling speed and measurement location.

(a) Accelerometer (b) GPS sensor (c) Transducer and computer

Figure 1-6 System instrumentation

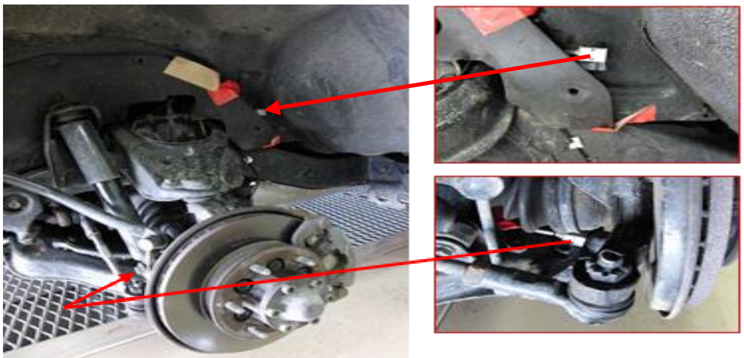

Figure 1-7 Two accelerometers installed on a suspension system

Two small accelerometers are mounted on the sprung and unsprung masses of the suspension system of survey vehicles and road profile is calculated by back-calculation method with the correcting vehicle speed, as shown in figure1-7. The significant information of the two primary signal transducers is also indicated in Table 1-2.

Table 1-2 Main specifications of accelerometers

	AS－10HB（Sprung）	AS20－HB（Unspring）
Rating capacity	98.07m/ s^2（10G）	196.1m/ s^2（20G）
Response frequency range	0～560Hz	0～650Hz
Rated output	563μV/V（1125×10^{-6} Distortion）	562μV/V（1124×10^{-6} Distortion）
Nonlinearity	Within (1.00%RO)	Within (1.00%RO)
Calibration coefficients	0.01778G/1μV/V 0.008889G/1×10^{-6}	0.03558 G/1μV/V 0.01779 G/1×10^{-6}
Resistance	Input 120.1Ω Output 142.3Ω	Input 120.9Ω Output 120.9Ω

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. This system can be installed in any automobiles in the market place as shown in figure 1-8. Therefore, as to facilitate to monitoring road conditions for road administrators of local governments, the overview of system structure as shown in figure 1-9. The primary information of the survey vehicle "BIGHORN" will be described in Table 1-3.

Figure 1-8 Survey vehicles: Isuzu Motors Limited (Ltd.) BIGHORN

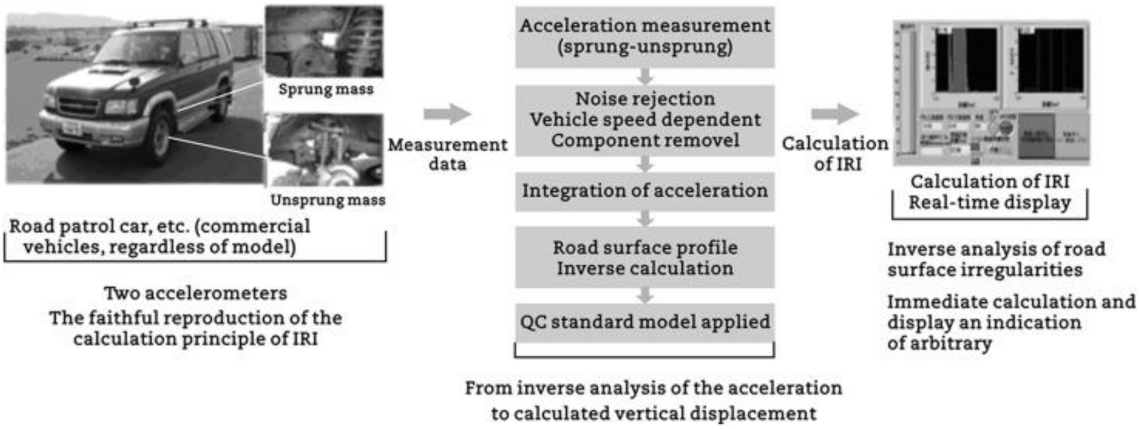

Figure 1-9 Overview of the compact road mobile profiler (MPM)

Table 1-3 Main specifications of BIGHORN

Engine	**3.0-liter intercooled turbo direct injection diesel DOHC16 valve**
Transmission	4A/T
Vehicle weight (Kg)	2170
Length (mm)	4750
Width (mm)	1745
Height (mm)	1840
Front suspension	Lotus tuning double wishbone torsion bar spring independent suspension
Rear suspension	Lotus Tuning four-link coil spring axle suspension
Shock absorber type before and after	Lotus tuning gas-filled double-acting hydraulic cylinder
Tire (front and back)	245/60R16

1.4.1 Computing IRI using the compact mobile profiler in pavement monitoring

Regarding 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 Figure 1-10 that contains the vibration parameter of the measured QC model

2) Convert the horizontal distance interval x_0 to the horizontal distance range at the vehicle speed of 80 km/h. Then, add this to the equation of motion (b) in Figure 1-10, 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'.

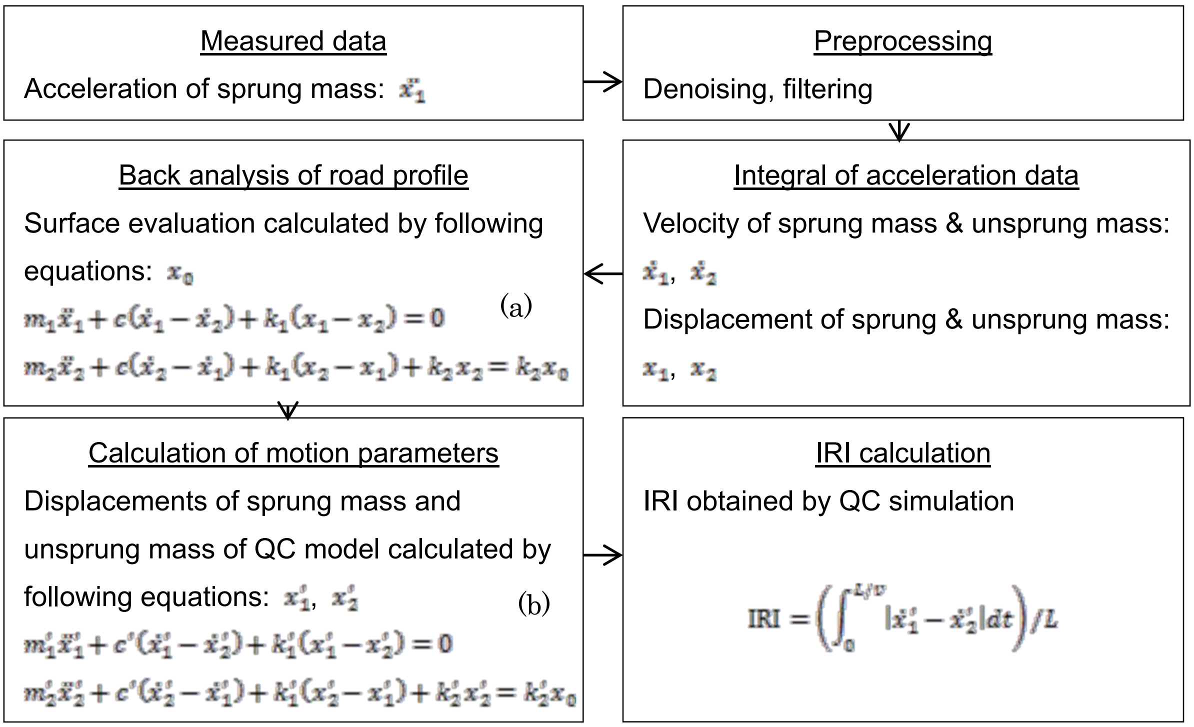

Figure 1-10 Steps of IRI calculation.

1.5 Special road roughness evaluation tool "KITDS"

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 associated with revision of a road traffic act for a period in Japan[15].

DS examines various topics, such as safety training at a driving school [16, 17], car design and development [18], road-sign design [19], evaluation for physiology of the human body [20], ITS [21] and so on.

In the past, the road data were mainly 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 [22]. The prototype of KITDS was based on a conventional DS used to assess traffic safety for driver training.

Since then, KITDS acquired many advanced functions, such as the evaluation of road surface characteristic data and vehicle motion data in the real world. 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 taking account of human factors. Figure 1-12 shows the overview of KITDS.

Figure 1-11 A view of the KIDS in the Experiment

1.6 **Composition of the research work**

I would like to write down each chapter of my thesis according to the following contents.

Chapter 1, mainly explain the research background, purpose, concept of the surface characteristics, and it also includes some of the introduction to the developing history of road roughness profiling devices and its advantages and disadvantages. The new compact road mobile profiler and one of the particular road monitoring devices called “STAMPER” and “Driving Simulator” will also be explained, which is developed by Kitami Institute of Technology.

Chapter 2, explains some of the different road roughness indices, such as international roughness index (IRI) and its use. It will also give some explanation about the other roughness indices, which has been in use in two countries, and its calculation process.

Chapter 3, introduces some of the key software, which was used to spatial analysis of road roughness Index IRI, it will also introduce the other software in order to calculate and analyze the other road roughness indices.

Chapter 4, shows one of the research works, and it’s conducting process, which is named: Measuring and evaluating of road roughness conditions with a compact road profiler and ArcGIS.

Chapter 5, shows the comparison and evaluation study with its methodology, and going to explain about comfortability of ride quality in different two countries.

Chapter 6, summarizes the thesis with its conclusions and references.

CHAPTER *2*

Basic Information of Roughness Indices

The definition of the roughness is the variation in surface elevation that induces vibrations in traversing vehicles and historically has been long recognized as an important measure of road performance [23]. There are many evaluation indices of road surface are in use in different countries. Such as, international roughness index (IRI), the standard deviation of longitudinal roughness (σ), pavement condition index (PCI) and pavement serviceability index (PSI). Because these indices have direct relationships with the ride quality of road surface. The basic definition of the ride quality index (RQI) refers the protection degree of offered vehicle occupants from uneven elements in a road surface.

2.1 **Development history of international roughness index "IRI"**

The international roughness index (IRI) was the result of the international road roughness experiment (IRRE), which was held in Brazil , and it was conducted by research teams composed of many countries in the world such as; Brazil, England, France, the United States, and Belgium. The main purpose of IRRE is to find the best practice methods, which are suitable for the different types of road roughness measuring devices now in use. At the same time, it was also planned to produce a means for comparing roughness data obtained by different procedures and instruments, because the methods used to characterize road roughness are not equivalent [6].

To obtain correct IRI, they have divided the measurement equipment into two categories. Firstly they used; surface profiling methods, they used both manual quasi-static methods and high-speed profilometers to measure the longitudinal elevation profile of the road surface and then analyzed to obtain one or more roughness indices in the IRRE. Secondly, they used; Seven Response-Type Road Roughness Measuring Systems (RTRRMSs), five of them consist with roadmeters which are installed in ordinary passenger cars, the other two are self-contained roadmeter / trailer units. Each RTRRMS conduct repeated measures on all of the sites at different speeds. The roughness data obtained by the result of the vehicle motions in traveling over the road surface. The results of the collected data, which is achieved by all types of RTRRMSs by using same tests speed show that the correlation between the measured roughness data onto each of them gives a high degree of correlation, and all of them matched to a single roughness scale without compromising their accuracy.

On the other hand, the results of the profile data, which is obtained by using different profilometric methods, showed that some data could produce excellent results but not all of them. In addition, several types of the profile-based roughness indices also showed good correlation with the roughness data measured from the RTRRMSs. Lastly, they proposed a single roughness index, which is called International Roughness Index (IRI). As it has been proved that, the IRI is a measurable index by using all kind of road roughness measuring devices which have applied in the IRRE, and it also showed that, it is almost compatible with all types of roughness measurement devices used worldwide[6].

According to the IRRE, IRI has several strong points than other roughness indices. Which is summarized that it does not change with time (time stable), it is compatible with manual methods for obtaining road profile (transportable). It is the reflects of the road conditions, and it has significant effects on vehicle operating costs, ride quality, and safety (relevant) and it can show the same results obtained from the different survey equipment on the same road sections (valid).

2.1.1 Distribution range of IRI

The IRI summarizes the road roughness qualities that impact vehicle response. It is most appropriate when a roughness measure is desired that relates to overall vehicle operating cost, overall ride quality, dynamic wheel loads (that is, damage to the road from heavy trucks and braking and cornering safety limits available to passenger cars), and overall surface condition. The following Figure 2-1 shows IRI ranges represented by different classes of road.

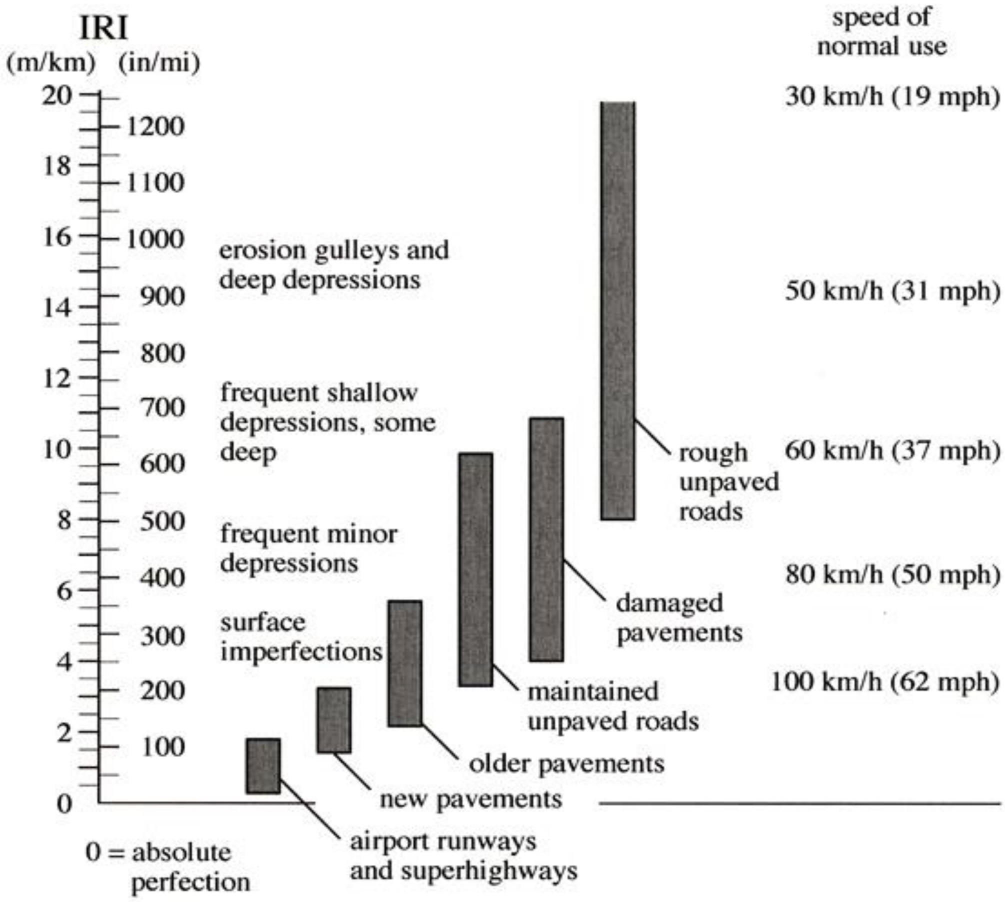

Figure 2-1 IRI scale [2]

2.1.2 IRI obtained from quarter-car

Since the development of IRI in 1986s [1, 6], it has become a well-recognized standard for the measurement of road roughness.

The main advantages of the IRI are being stable over time and transfer able throughout the world. The IRI is an index defined by applying the algorithm proposed by Sayers [24] 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 Figure2-2[25]. 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.

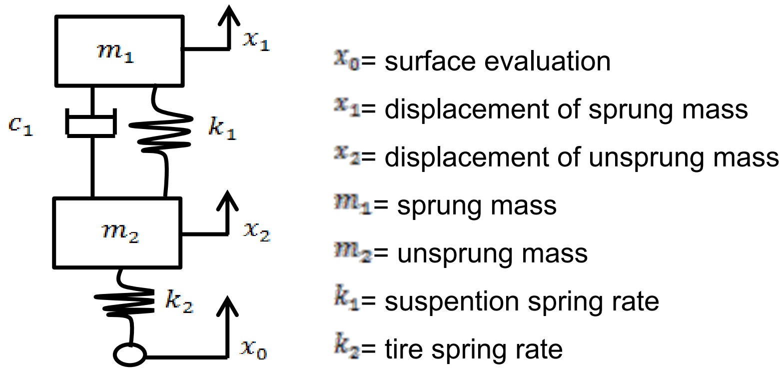

Figure 2-2 Quarter-car model [25]

During the simulation, the quarter car system runs over the longitudinal profile, measured in the field at a constant speed of 80 kilometers per hour. The roughness of this surface induces dynamic excitation to the quarter car system, generating different vertical speeds ($\dot{z}_s$&$\dot{z}_u$) or accelerations ($\ddot{z}_s$& $\ddot{z}_u$) in the sprung and unsprung masses. As a result, a relative movement is produced between the chassis and the axle of the ideal vehicle. The IRI value for a given section length (100 m) is computed according to following equation 2-1.

$$IRI = \frac{\int_0^{L/v} |\dot{z}_s - \dot{z}_u| \, dt}{L} \qquad \text{(Eq. 2-1)}$$

Where;

L = Traveling distance (m).

ν = Vehicle speed (m/s).
$\dot{z}_s$ = vertical speed of the sprung mass.
$\dot{z}_u$ = vertical speed of the unspring mass.
dt = time increment.

2.2 **The standard deviation of longitudinal roughness (σ)**

Since 1960, in case of quality control after the pavement construction in Japan, there is one more statistical roughness index, which is primarily obtained from the "standard deviation of the longitudinal profile taken along with the imaginary line" under the wheel paths, by the unit named "evenness"[26]. It is a static scale to evaluate road surface roughness regarding standard deviation of slope variance. The scale is measured by a 3-meter profilometer. But this seems inappropriate to explain causation of many kinds of pavement performance based on their demand. There are other reasons in the interval of data to calculate the index is 1.5m.

2.3 **Pavement condition index (PCI)**

Several numbers of pavement condition indices such as pavement condition index (PCI) are obtained and used to pavement management evaluation throughout the world. PCI is the basic results of the subjective rating of the number of pavement distresses, which has ranged from 0 to 100. Zero represents the poor/failed pavements and one hundred being excellent. In addition to distress data, the specialized equipment also obtains ride quality information at the same time. In the past decade, some researchers in the USA conducted some interesting study to find the correlation of the IRI-PCI for evaluating their pavement smoothness and ride quality. One of them is, from the period of 1991 through 2000, introduced Park et al. [27] using data from nine states and provinces in the Northern America established a power relationship between PCI and IRI. The IRI-PCI data, which is used in this study, was afforded from the DataPave® program for highways in the several regions; those are Delaware, Maryland, New Jersey, New York, Vermont, Virginia, Ontario, Quebec and Prince Edward Island. The equation of the power correlations between the IRI-PCI showed in equation 2-2.

$$log(PCI) = 2 - 0.436log(IRI) \qquad \text{(Eq.2-2)}$$

On the other hand, in 2012 some researchers from Iran [28], estimated PCI values based on different types of pavement distress and critical levels of them by using two optimization techniques: Artificial Neural Networks (ANN) and genetic programming (GP). They collected from more than 1,250 km of highway sections in Iran and then developed mathematical models based on PCI. They used a feed forward ANN with the network for trained they adopted the back propagation method. In addition, they used root-mean square error (RMSE) fitness function for the GP approach. Lastly he concluded that, the ANN- and GP-based projected values were determined to be in good agreement with the field-measured PCI values. The reported R2, RSME and mean absolute error (MAE) for the ANN-based models were respectively 0.9986, 0.99, and 0.49, whereas they were equal to 0.9898, 2.63, and 1.79 respectively for the GP-based model.

In 2015, Stephen et al. established a model that PCI from IRI by the functional classification and by the pavement type in the District of Columbia, based on the two years of surface roughness data [29]. The results of this study obtained based on the mean IRI and PCI values by using validation methods of the regression model. Lastly, they got the following equation 2-3 of the regression model.

$$PCI = A\ (IRI) + k + \varepsilon \qquad \text{(Eq. 2-3)}$$

Where;

PCI = dependent variable with the constants of A and k.

IRI = independent variable with the associated error of ε.

2.4 **Pavement serviceability index (PSI)**

Since the development of the Present Serviceability Index (PSI) from AASHO road test [29], it has become one of the well-established indexes that assist in evaluating the ride quality. Pavement Serviceability represents the level of services that pavement structures offer road users. This indicator first appeared as a rating made by the users on the state of the road, particularly the road's surface. This score is represented by a subjective index called Present Serviceability Rating (PSR) and may be replaced by an objective index called PSI. PSI is the definition of the pavement serviceability, which is obtained from individual observation of the road users. PSI is defined as " The judgment of an observer as to the current ability of the pavement to serve the traffic it is meant to serve" [30]. To produce the original AASHO Road Test PSR scores, observers rode around the test tracks and rated their ride quality using the quantitative scale shown in figure 2-3. The range of this subjective scale is, from 0 (essentially impassable) to 5 (excellent). Although PSR is based on passenger sensation of the expermental section, it mainly reports the road roughness because surface roughness largely affects the comfortability of the traveling sections of a highway.

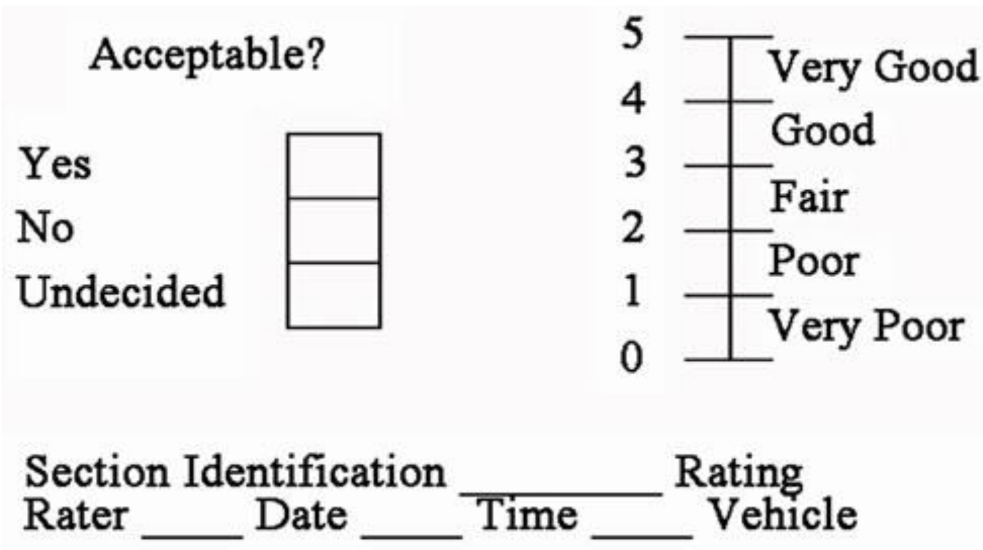

Figure 2-3 Individual present serviceability rating form [2]

2.5 **Root Mean-Square (R. M. S.)**

In profile analysis, root-mean-square is a definition of solve every problem came from vibration signal, by squaring.
Root-mean-square is identical standard deviation if there is no offset in the acceleration signal. The unit of r. m. s. of acceleration is m/s^2.

Mathematically, r. m. s. can be expressed as following equation 2-4.

$$a_{w\ r\ .m\ .s.} = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt} \qquad \text{(Eq. 2-4)}$$

Where:
$a_{w\ r\ .m\ .s.}$= frequency-weighted r .m .s. acceleration
T= measurement duration
$a_w(t)$= frequency weighted acceleration at time t.

2.6 **Crest Factor (CF)**

The crest factor is a dimensionless quantity defined as the ratio of the peak acceleration to r .m .s. The lowest possible crest factor is 1, which occurs for a square wave; a sine wave has a crest factor of 1.4. Gaussian random vibration has a crest factor of 1.7. If any of these signals contained a single shock, then the crest factor would increase, but the r. m. s. might not be substantially affected.
Therefore CF is useful in assessing the applicability of r .m .s. averaging.
CF can be expressed as following equation 2-5:

$$CF = \frac{\max(a_w(t))}{r.m.s.(a_w)} \qquad \text{(Eq. 2-5)}$$

Where:
a_w= frequency-weighted acceleration.

2.7 **Power Spectral Density (PSD)**

Power Spectral Density (PSD) is a function of frequency; it mainly deals with the statistical representation of the importance of various wave numbers. In other words, PSD shows the strength of the variations (energy) as a function of frequency.
It represents at which frequency variations are strong and at which frequency variations are weak. The unit of PSD is energy (variance) per frequency (width) and it possible to obtain energy within a specific frequency range by integrating PSD within that frequency range. Regarding ride quality evaluation, the uneven road surface, since those show irregular shape with a change in amplitude and different wavelengths are large, in this case, PSD can perform to evaluate rough road surface at a frequency band easily.
PSD is calculated by following equation 2-6;

$$G_z(v) = G_0[1 + (v_0/v)^2]/(2\pi v)^2 \quad \text{(Eq. 2-6)}$$

Where;
$G_z(v)$= Power spectrum density (m^2/cycle/m)
v= Pulse number (cycle/m)
G_0= Uneven parameter (uneven level)
v_0= Cutoff wave number

CHAPTER *3*

Analyzing Software of The Roughness Indices

According to the present development situation of the informative management Technology, there are so many advanced software or systems have been into traffic engineering careers, such as Auto CAD, GIS, ProVAL and the others and this software still solved some difficult problems of the engineers. The focus point in the thesis is to assist in the establishment of an optimal PMS, in the process of introducing a PMS, this argument used some advanced software to carry out analyzing surface condition and evaluating it on the network level. The following steps will present the application of this software in road surface evaluation.

3.1 **Utilizing GIS together with DRM**

The digital road map (DRM) database is the standard national digital road map database supported by Japan DRM Association [31]. Since then, it plays a key role in various systems for road management and vehicle navigation systems to link road network and geographical information.

GIS is a computerized spatial data management system, in this study which is mainly used for the accumulating, storage, retrieval, analysis and display of road roughness condition at the network level, together with the DRM to visualize the survey results linking land-use and road classification of the local cities in Hokkaido prefecture.

3.1.1 DRM database in pavement monitoring

DRM database has been initially introduced for the primary purpose of developing 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 components of pavement management such as road administrators, lane widths, and locations of road structures. Therefore, it contributes to visualize the surface roughness condition. The database is composed of nodes and links in road networks as shown in Figure 3-1.

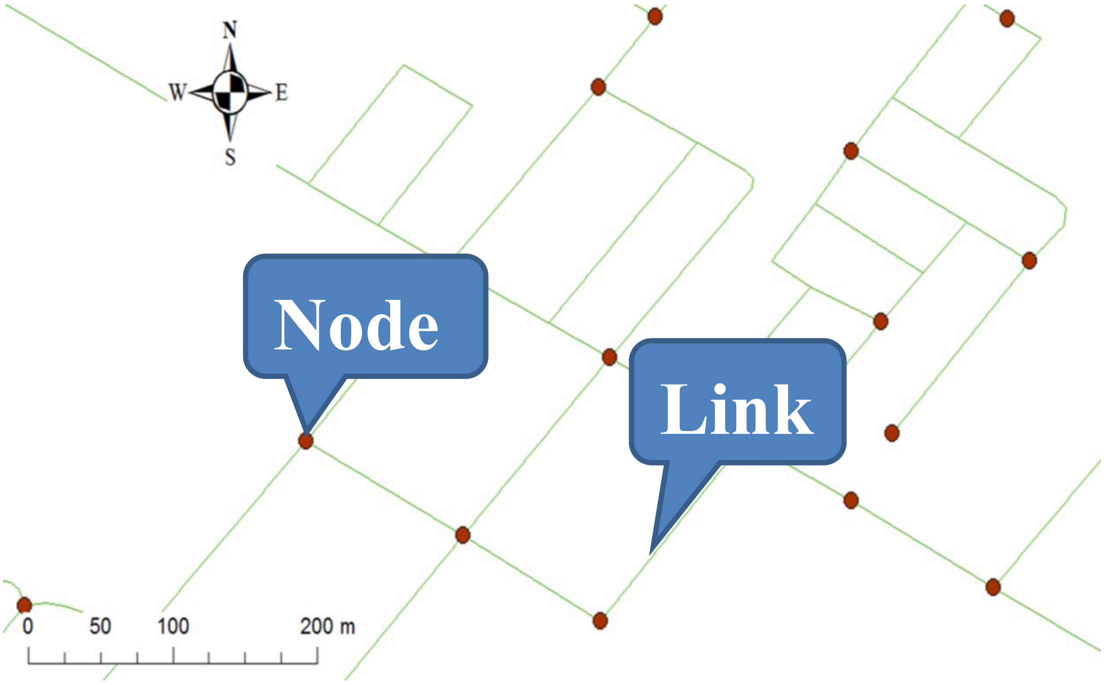

Figure 3-1 Representation of the road network in DRM Database

3.1.2 Spatial data management system "GIS"

The ArcGIS is commercially based well-known GIS (Geographic Information System). A GIS is computerized database management system which is used for, accumulating and compiling geographic data, analyzing and storing mapped information, sharing and discovering geographical information and managing geographic information in a spatial database [32].

GIS includes two different broad types of information, georeferenced spatial data and attributes data. Geo-referenced spatial data define objects that have an orientation and relationship in two or three-dimensional space. Attributes related to a street section, it might include its width, number of lanes, construction history, road surface condition and traffic volumes. A topological relationship between the spatially geo-referenced geometric entities represented by point, line or polygon, which will associate with a location of somewhere on the surface of the earth should be maintained. Traditionally, topological relationships include adjacency such as "what adjoins what, containment it means that, what encloses what, and proximity shows how close something is to something else" [33].

The system also provides an infrastructure for making maps and geographic information available throughout an organization, across a community, and openly on the Web.

Following figure 3-2, 3-3 and 3-4 are examples of the ArcGIS features, which shows the road categories, lane width, and each road administration, respectively, for urban areas in Hokkaido population more than 100,000. In these figures, the road categories are classified based on the following criterion.

Notes for road category in Figure 3-2:

Expressway is not included in national highways

Major local roads mean arterial prefectural highway specified by the Road Act, the Minister of Land, Infrastructure, Transport and Tourism (MLIT).

Prefectural road means an ordinal prefectural highway, which does not include exceptional roads.

Another road: Municipal roads or road exempt from the Road Act.

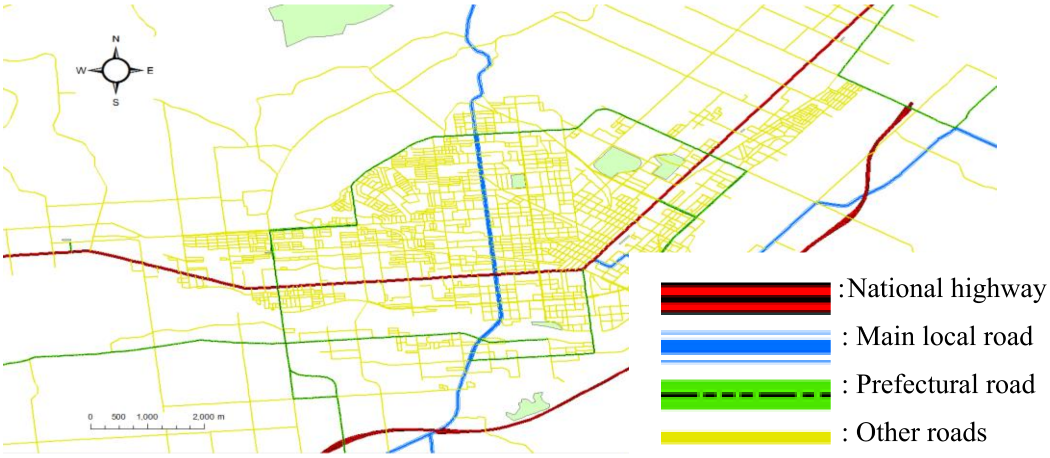

Figure 3-2 Road classification

Notes of road width in figure 3-3

Width is more than 13.0 m.

Width is between 5.5 and 13.0 m.

Width is between than 3.0–5.5 m.

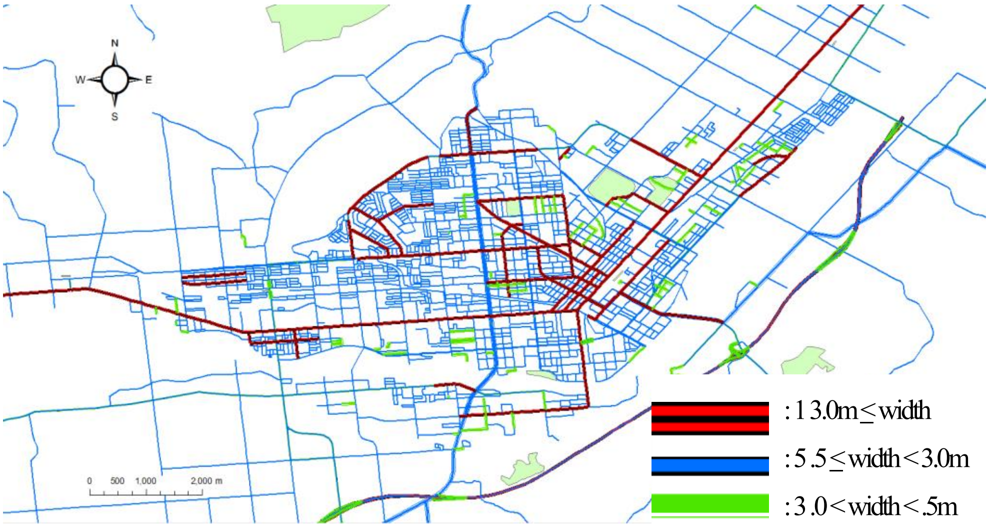

Figure 3-3 Road width

Notes of classifications of road administrators in figure 3-4
National highway government.
Prefectural highway government.
Another city, town and village highway governments.

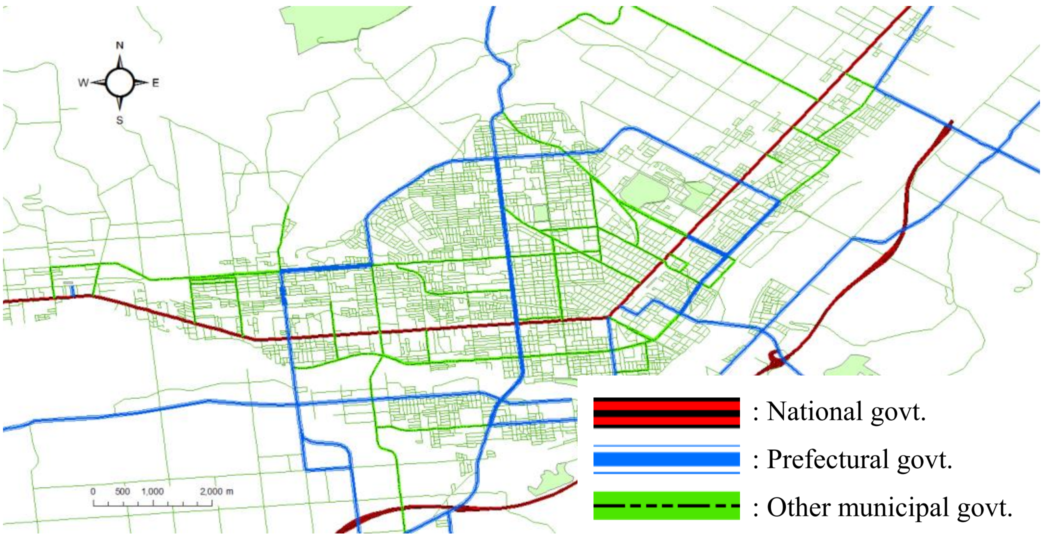

Figure 3-4 Road administration

3.2 **Profile viewing and analysis software "ProVAL"**

ProVAL (Profile Viewing and AnaLysis) is an engineering software application that allows users to view and analyze pavement profiles in many different ways [34]. It is easy to use and powerful yet to perform many kinds of profile analyses. ProVAL is a product, sponsored by the US department of transportation, Federal HighWay Administration (FHWA) and the Long-Term Pavement Performance program (LTPP).
ProVAL can import road profile data from various format files and can save them in the standard pavement profile format file. It can also save the complete analyzing results of the projects, which can also preserve user's information and analyze the inputs. It also has one more feature that, after the data analysis is performed, it can print a report based on the original road profile data and the results of any analysis, which has been done with this software. According to its advantages, it has been adopted by many agencies around the world.
The following figure 3-5 is one of the evaluating results based on the road roughness condition.

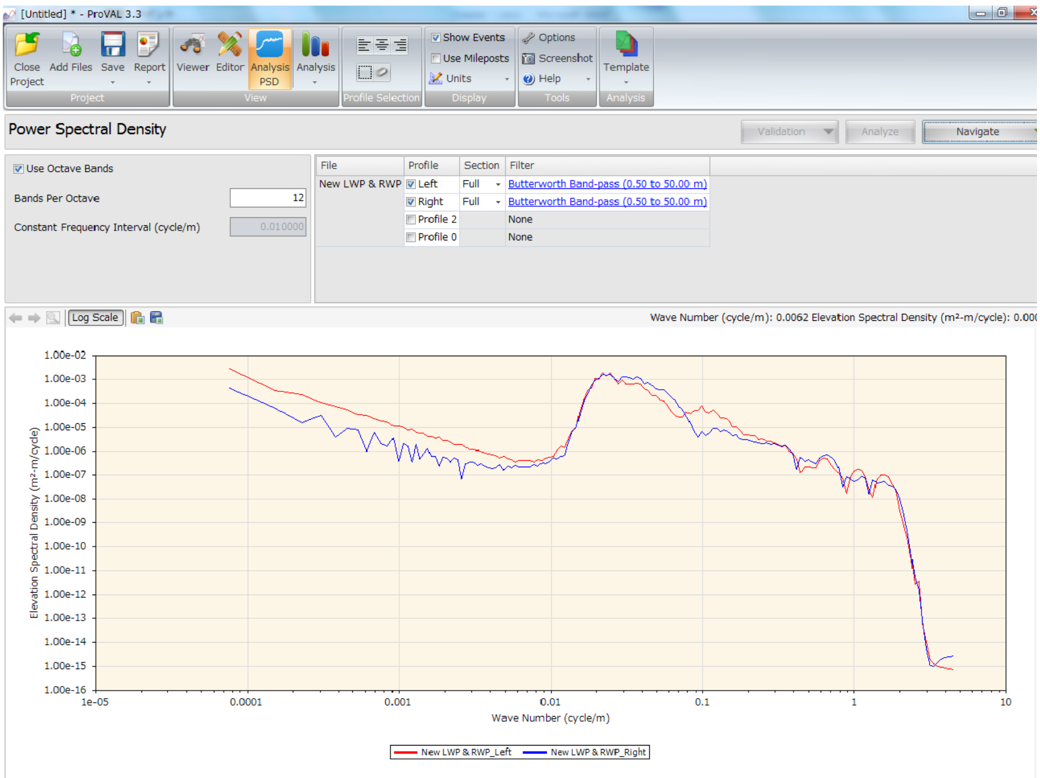

Figure 3-5 One of the examples PSD result by ProVAL

CHAPTER *4*

Measuring and Evaluating Road Roughness Conditions with a Compact Road Profiler and ArcGIS

4.1 **Abstract**

With a broad 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 road conditions. To fulfill these requirements, the author studied as follows. Firstly, this study carried out by using a new compact road profiler "STAMPER" 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 research work 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, it will present the measurement results of IRI in two different cities during different seasons by using GIS to compare the road conditions. According to the results clarified on various statistical characteristics of road profiles, this study recommends that it is necessary to establish pavement management system (PMS) in consideration of road class, the network of local city, and evaluation and management of road conditions in winter quantitatively. Lastly, we have measured and evaluated ride quality by assessing differences between the inner wheel path (IWP) and outer wheel path (OWP) of the vehicle taking into account the previously mentioned profilers and the driving simulator, which is called KITDS. Results show that information from both wheel paths contributes to improving current monitoring process regarding pavement surface, and expects to construct a high level of PMS for road administration in the future.

4.2 **Introduction**

There are some pavement condition indices, and they are used to establish a pavement management system, one of the most commonly used is IRI, and it is closely related to the road user's safety and comfortability on a highway section. In the other word, smooth road surface can afford drivers or users a very comfortable riding environment. A lot of researchers have studied about IRI which is a major factor that, it is the result of the real road surface conditions, and it is a well-established index that can assist to the developing of the pavement management system.

According to the such a significant relationship among the IRI, ride quality of a pavement section and pavement management system, this study focuses on a method for providing fundamental information about IRI on municipal roads, by using a low-cost road profile measuring system. As it can be obtained IRI data directly from the road surface in real time with the high-accuracy, this feature may assist and improve the implementation of PMS in municipalities.

The overall objectives of this study are as follows:

1) To introduce the results of the road roughness conditions of the municipal roads in different cities during different seasons by using a new compact road profiler.
2) To present the survey results linking land-use and road classification by using GIS together with the DRM database.
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, KITDS and the ISO standard 2631 are applied[35].

4.3 Applications of electronic road map and GIS on road monitoring

As it is mentioned about the implementation of the GIS in infrastructure planning and management systems in above section, in this study, the author utilizes its superior spatial data handling capabilities of GIS together with the DRM database. Measurement results of the IRI obtained by the STAMPER have been shown in this section.

During the November 2011 and March 2013 in Kitami city, and November 2012 in Kushiro city [36] with the total survey length of 89.3km, 81.1km and 56.2km respectively as shown in figure 4-1. Both of two cities have populations of over 100 thousand and are one of core cities in Hokkaido with the daily traffic volume of 16,000 and 17,000 vehicle/day as shown table 4-1. 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 figure 4-2 and 4-3, 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. Criteria for IRI classification depend on the management objectives and road category.

Table 4-1 Traffic volume of two cities

		Ratio of each types vehicle			
Cities	Traffic volume (vehicle/day)	Mid-size vehicles	Truck	Light-truck	Bus
Kitami	16000	74.0	9.0	16.0	1.0
Kushiro	17000	80.0	5.0	14.0	1.0

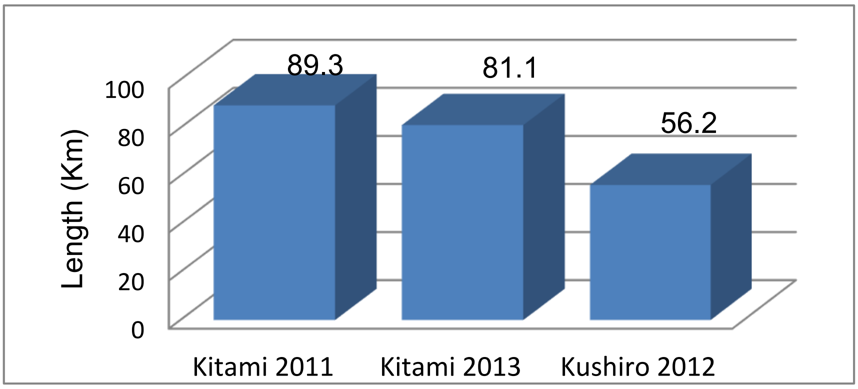

Figure 4-1 Total survey length

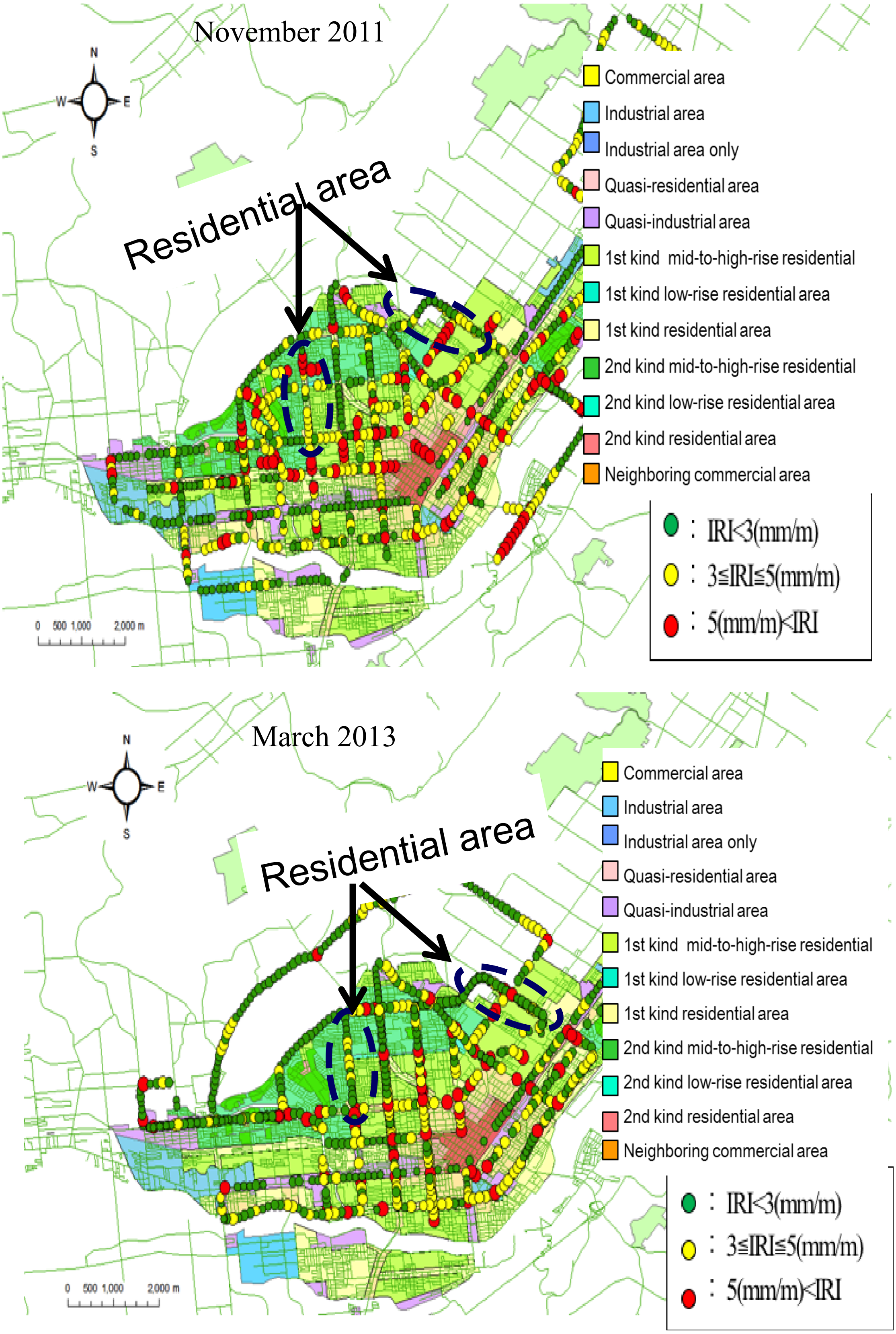

Figure 4-2 IRI based on the digital road map and GIS examples of Kitami city

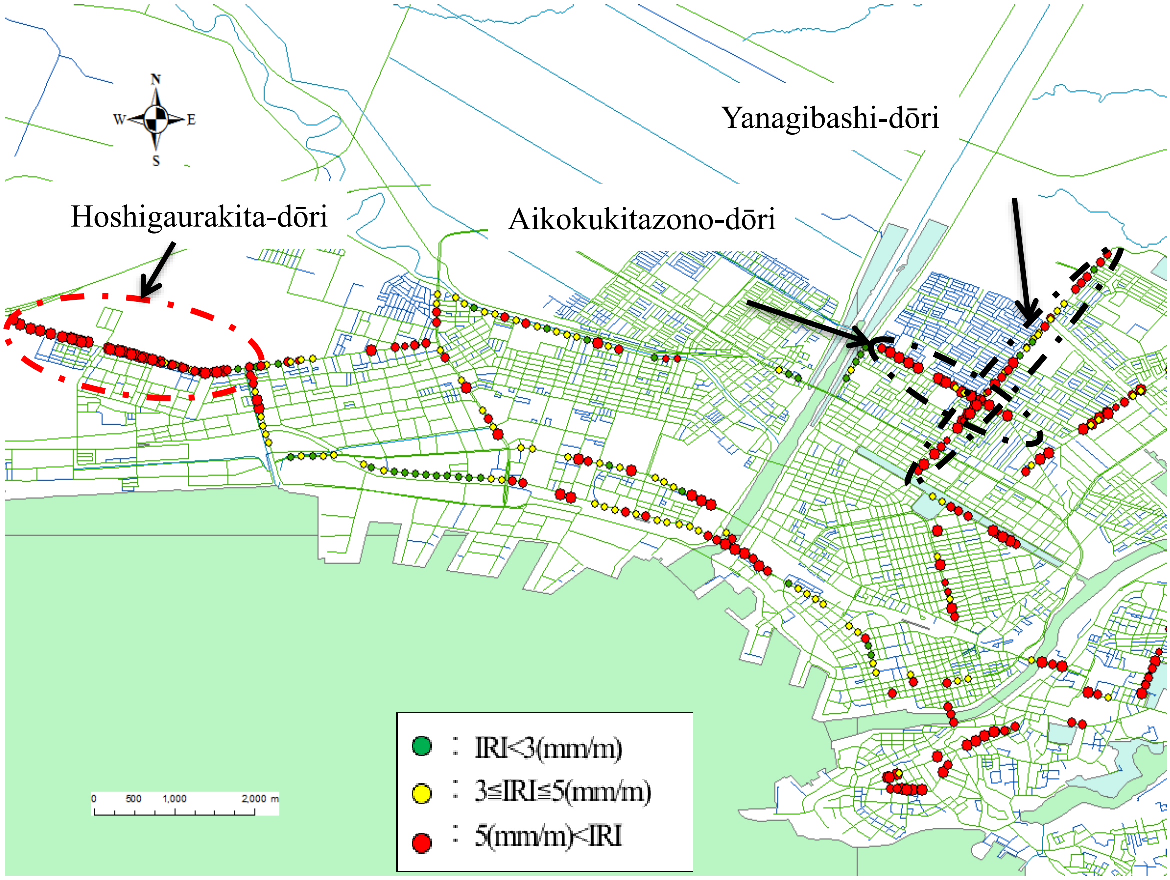

Figure 4-3 IRI based on the digital road map and GIS example map of Kushiro city

4.4 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 figure 4-4 and Figure 4-5. In order to calculate histograms and cumulative curves, IRI data is used for each 100-m section of the road.

The figure covers that; National highways 95, major local roads 83, prefectural roads 177 and other roads (municipal roads mainly) 542 in 2011. National highways 91, major local roads 64, prefectural roads 208 and other roads 461 in 2013 in Kitami city. On the other hand national highways 164, major local roads 41, prefectural roads 17 and other roads 217 in Kushiro city in 2012. Concerning the four different road classes in Kitami city, the surface conditions of the national highway and prefectural road in 2013 are better than those in 2011. Major road situations are not that different. On the other hand, conditions of other roads are deteriorating year by year. Particular note is that no IRI data less than 5 m/km are observed for national highways. In Kitami city, 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 Kitami and Kushiro city based on the network IRI as shown in figure 4-6 has demonstrated that the road evenness of the Kitami city is better than that of Kushiro city in general.

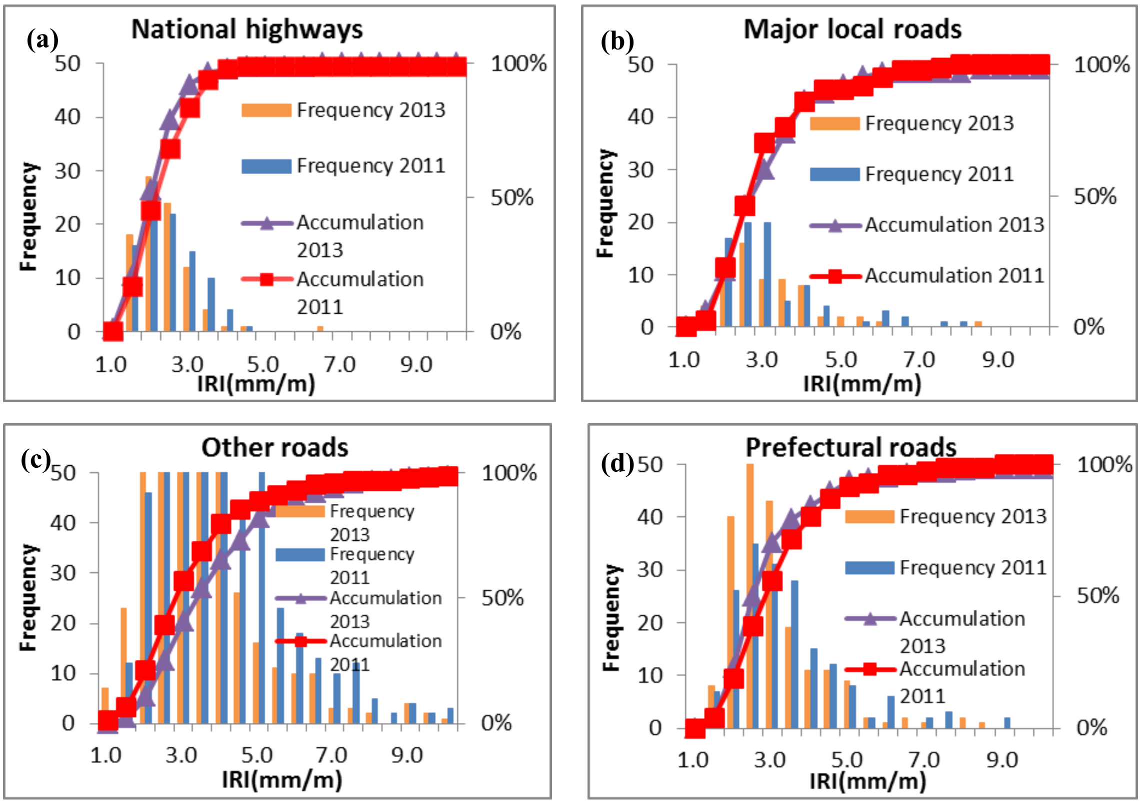

Figure 4-4 Histogram and cumulative curve of IRI in 2011 and 2013 (Kitami)

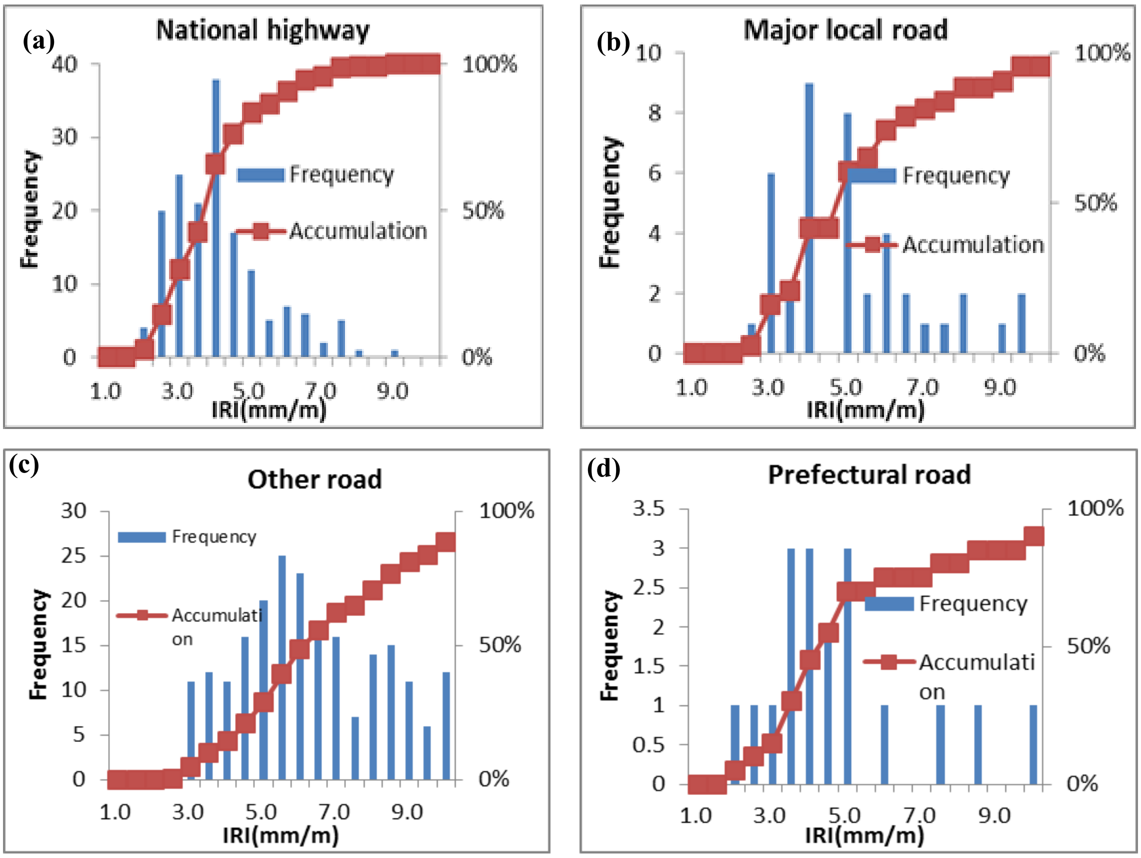

Figure 4-5 Histogram and cumulative curve of IRI in 2012 (Kushiro)

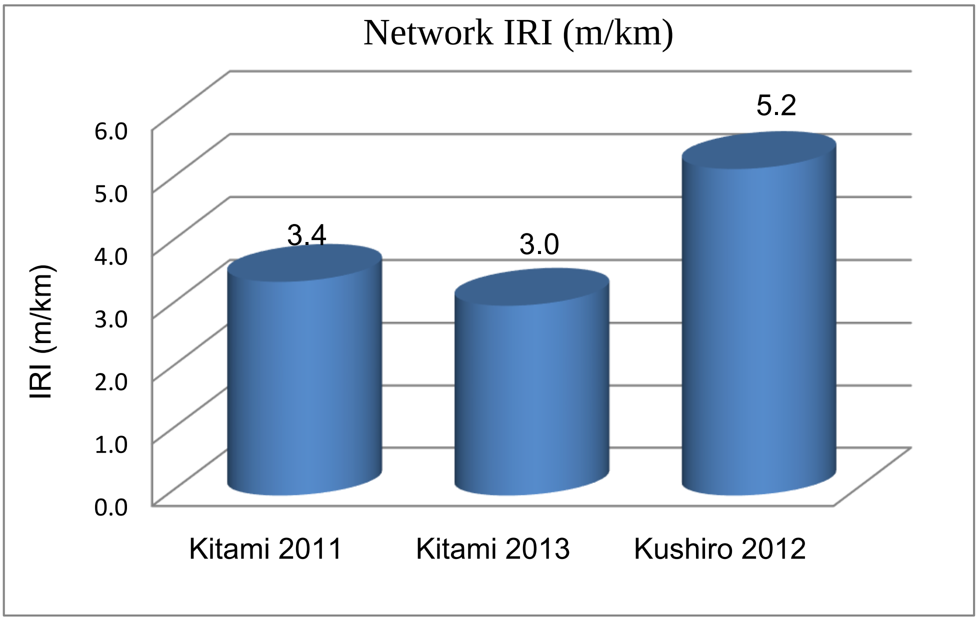

Figure 4-6 Network IRI of two cities

4.5 **Visualization of measuring results by ArcGIS in different seasons**

In order to respond to the strategy from MLIT, improvement of traffic safety and flow in the 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. Figure 4-7 and Figure 4-8 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 [4]. Figure 4-7 shows an example of IRI road map detailing a southbound (SB) direction in comparison with road surfaces in different seasons. Figure 4-8 shows those for northbound (NB). Clearly, dry road conditions are better than those of snow roads, as seen in both figures.

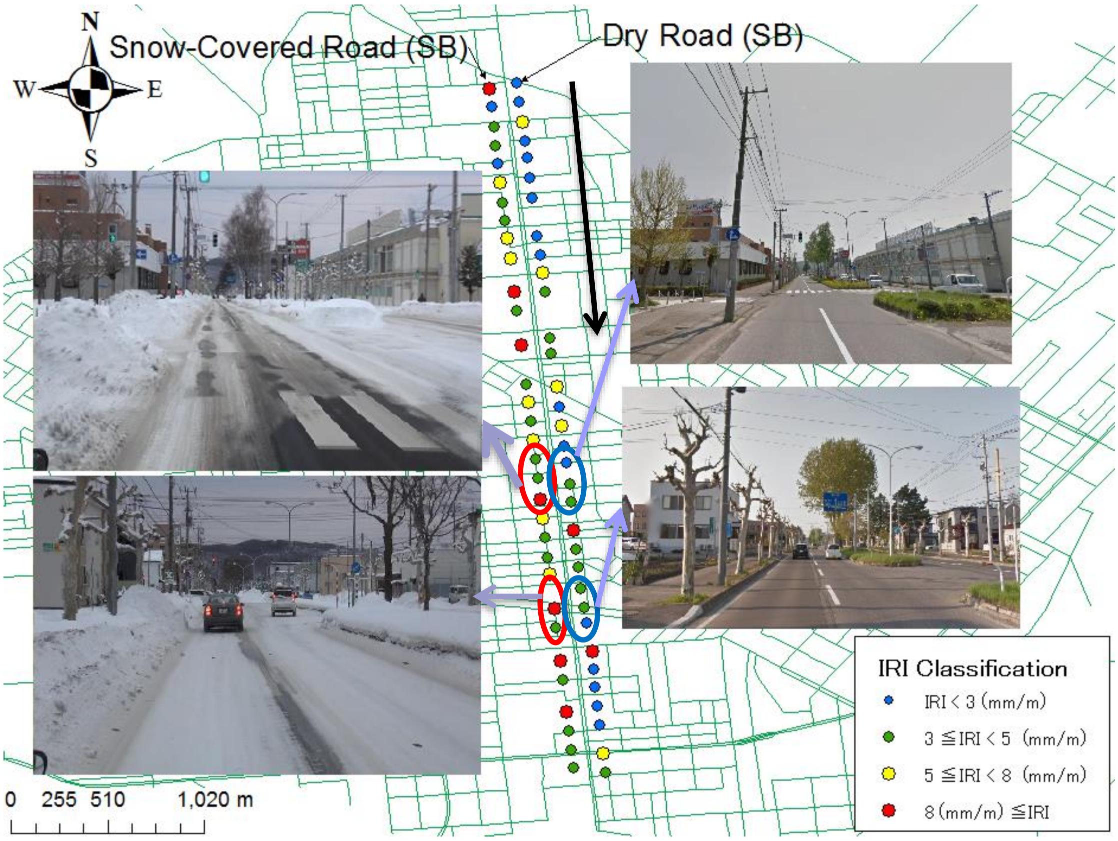

Figure 4-7 Seasonal change of road roughness condition (SB)

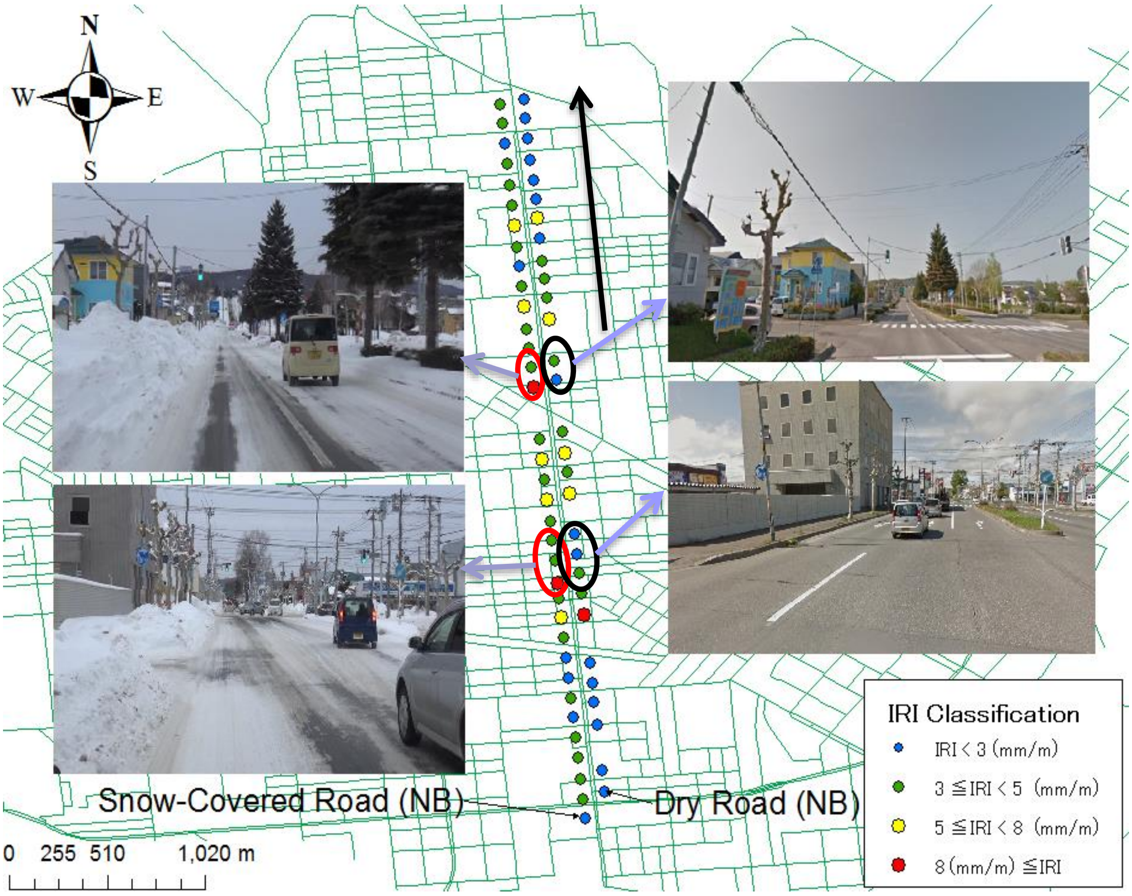

Figure 4-8 Seasonal change of road roughness condition (NB)

4.5.1 Statistical results

Figure 4-9 shows results from the histogram and cumulative curve, obtained from municipal roads using the same IRI data for each 100 m interval. Each figure also shows the seasonal changes of road conditions. According to the histogram and cumulative distribution function curve (CDF) 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.

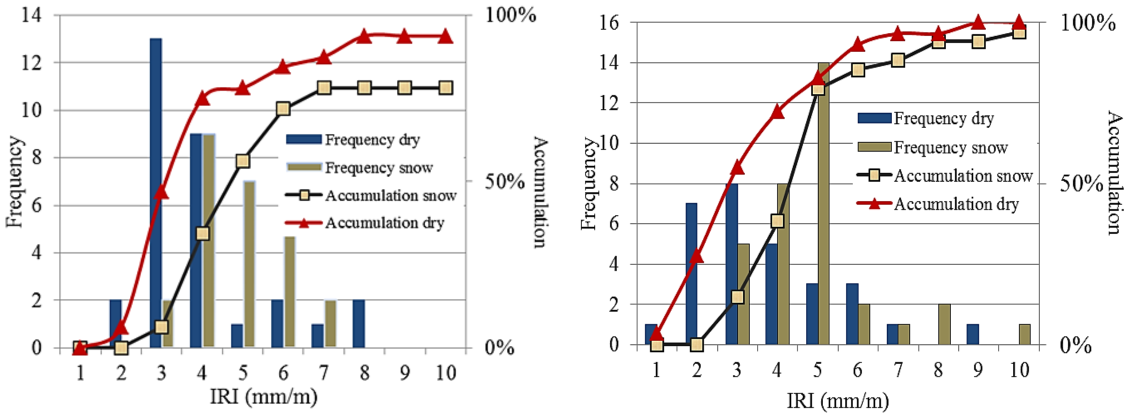

Figure 4-9 Results of roughness condition south bound and north bound

4.6 **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. The functional state 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 to determine the best rehabilitation strategies.

According to the development history of IRI, it proved that IRI is a reasonable index in pavement smoothness monitoring or road surface evaluation. From these explanations about the IRI, it is full enough to say that, the lower the calculated IRI; the smoother the pavement will ride, the higher the IRI; the rougher the pavement will ride. The units and calculation algorithm of IRI are presented in equation 2-1 in Chapter 2.

4.6.1 Analyzing the ride quality on an route line

In May 2014, we carried out a pavement roughness survey work by using two compact road profilers at the speed of 70 km/h; the road roughness data were obtained on 7800-m road sections of a high-standard highway during the golden season of the local area in Hokkaido. 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. Figure 4-10 is the representation of surveying location.

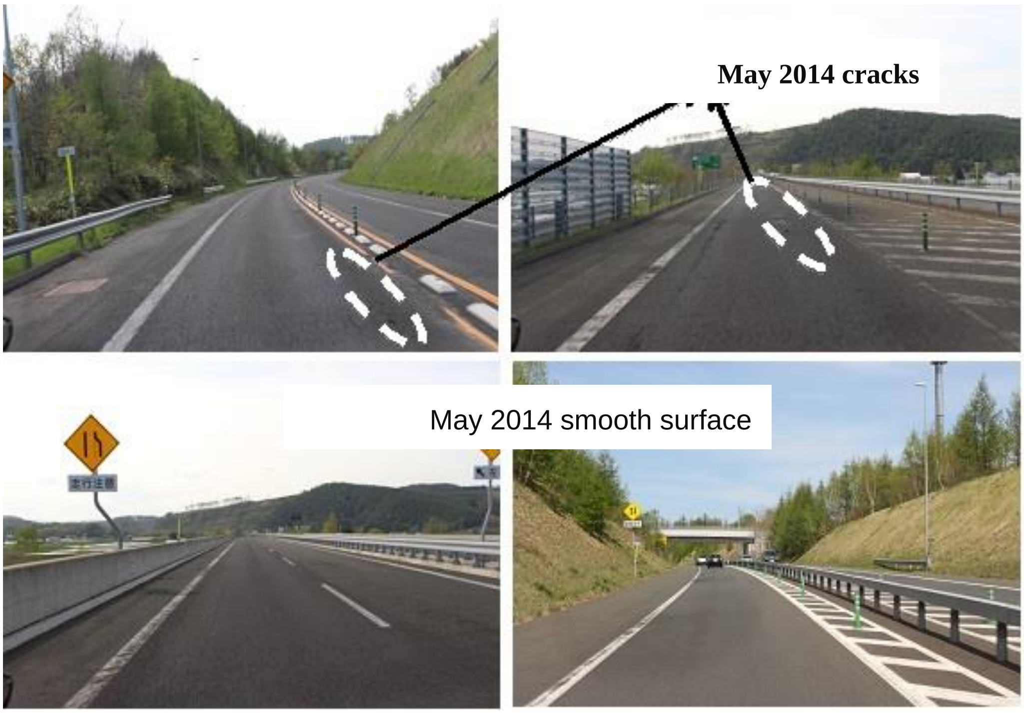

Figure 4-10 Surface conditions of the measurement location

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 Limited (NEXCO) introduced a maintenance standard for the expressway in Japan. Especially, IRI value over 3.5 m/km signifies the need to rebuild while the IRI less than 3.5 m/km is acceptable.

Figure 4-11 is a summary of the targeted section of the high-standard highway in the local city, and it shows that the most smooth and rough sections are used to evaluate and compare the ride quality by NEXCO road maintenance standard.

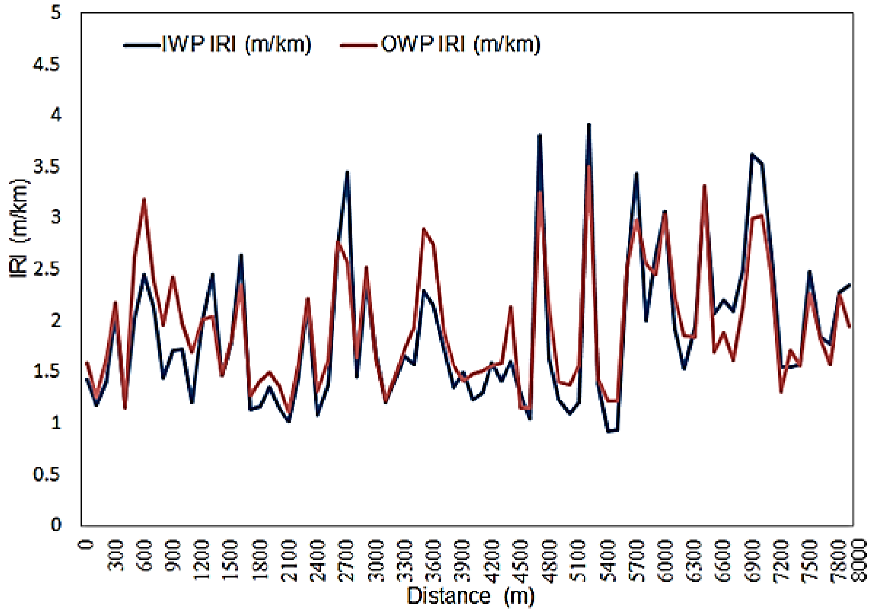

Figure 4-11 Road roughness conditions of both wheel paths

Fig. 4-12 shows the results of IRI on the smooth section. Figure 4-12(a)–(d) shows that the IRI range is less than the maintenance standard. However, the comparison results between the inner and outer wheel paths indicate that the inner wheel path is better than those of outer wheel path.

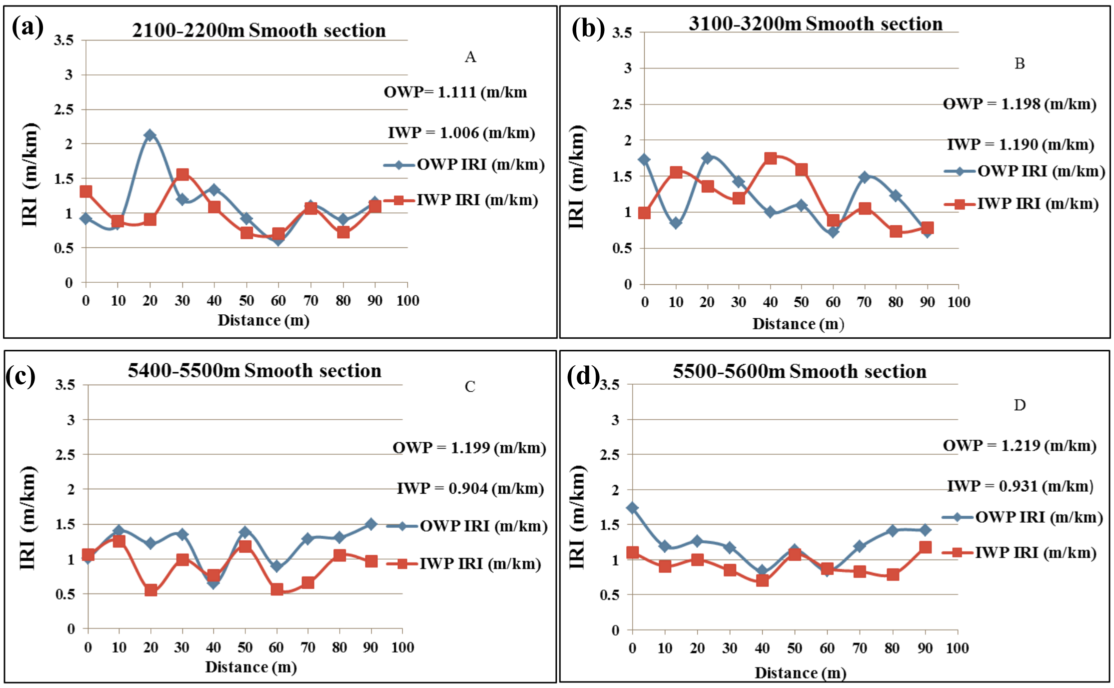

Figure 4-12 Ride quality conditions for smooth sections

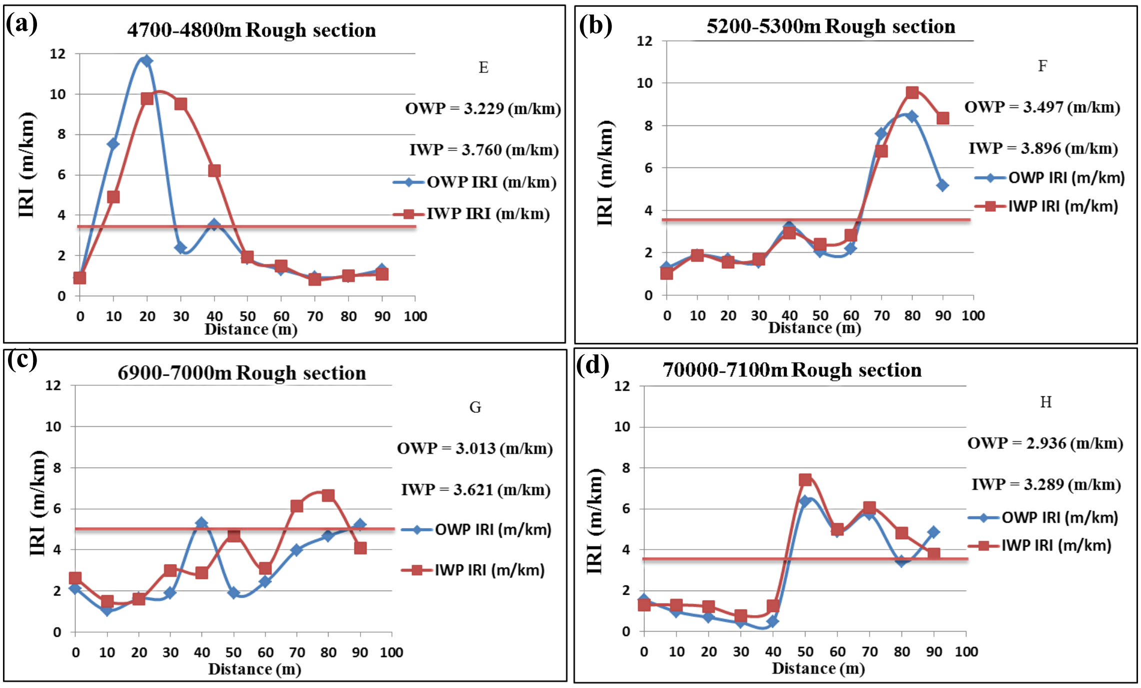

Figure 4-13 Ride quality conditions for rough sections

Figure 4-13 presents the IRI results on the rough section. Figure 4-13 (a)–(d) show that the majority of IRI range is over the maintenance standard. Road administrators should rebuild construction and improve the ride quality on these sections. Also, 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.

4.6.2 Ride quality evaluation

Along with the development of the several types of research about the ride quality evaluation based on the surface roughness data, some interesting studies were carried out to investigate the influence of pavement roughness on driver response. These are, road surface evaluation based on the brainwaves of passengers [37, 38], evaluation of the driving comfort by using frequency-weighted r.m.s. based on vehicle acceleration, and it provided an excellent relationship between IRI and vibration acceleration [39]. In the past decade, there are two more important topics, which are, (1) using a driving simulator to evaluate the road surface roughness, and studied the quantitative evaluation of ride comfort [40], and (2) using driving simulator and physiological signal to evaluate the ride quality [41].

As introduced in the previous chapter 1, KITDS is possible to evaluate and study a different kind of topics, such as evaluation of comfortability of the drivers based on the physiological signal. To genuinly 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 profilometers. To evaluate and compare the RQ between both wheel paths, KITDS are used to obtain vertical acceleration data, and Root Mean Square (RMS) and Crest Factor (CF) are introduced to identify the ride quality completely. The algorithms and explanations of the RMS and CF expressed previous chapter 2. Figure 4-14 shows the correct positions and sensitive ranges of the acceleration data as highest, middle and lowest level, respectively. And the different results of these three levels of RMS and CF are shown in Table 4-2.

ISO 2631 standard [42] is mainly used to for assess ride quality levels by weighted R.M.S. acceleration.

The range of the RMS for evaluating comfort is categorized in Table 4-3.

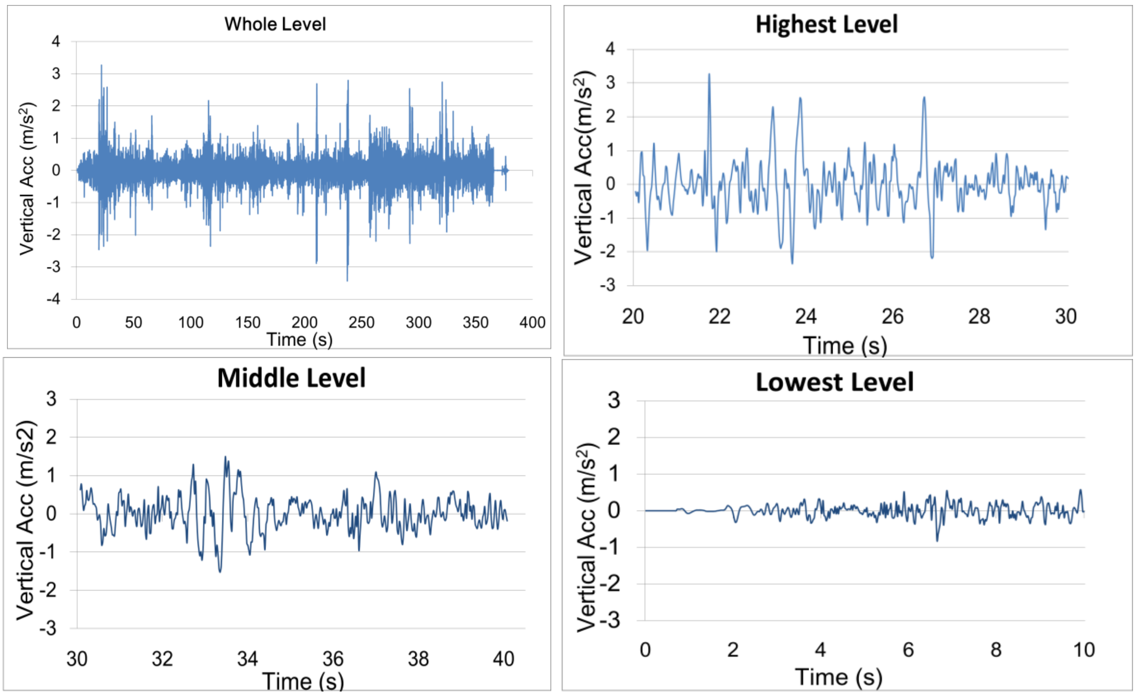

Figure 4-14 Vertical acceleration data obtained from DS

Table 4-2 Results of RMS and CF

	R.M.S (m/s^2)	Peak Acceleration(m/s^2)	CF
Highest	0.74	3.25	4.39
Middle	0.46	1.5	3.28
Lowest	0.17	-0.81	-4.76

Table 4-3 Categories of ISO 2631-1 standard

Comfortable	$\leq$0.315 (m/s^2)
a little uncomfortable	0.315~0.63 (m/s^2)
fairly uncomfortable	0.5~1 (m/s^2)
uncomfortable	0.8~1.6 (m/s^2)
very uncomfortable	1.25~2.5 (m/s^2)
Extremely uncomfortable	$\geq$ 2 (m/s^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 it.

CHAPTER 5

Comparison Study of Two Countries Expressway Based on Its Acceptable IRI Thresholds

5.1 **Abstract**

Road roughness constitutes the main feature of the pavement surface that defines user comfort, and it has a great impact on the safety, drivability, and passenger comfort of vehicles. On the expressway, an influence caused by road roughness will significantly affect not only comfortability of the passenger but also the life cycle cost of road structures. This study highlights the correlations associated with the evaluation and implementation of the International Roughness Index (IRI) and Present Serviceability Index (PSI) on the expressways of two countries. The national standard in China for IRI thresholds for expressways range from 2 mm/m to 3.2 mm/m indicating "acceptable" road sections, and IRI less than 2 mm/m are considered to be "good" road sections. On the other hand, standard categories of IRI in Japan's expressways from 1mm/m to 3.5 mm/m suggested "acceptable" road segments and less than 1mm/m recommend being "good" road segments

The following case studies are conducted to find out the confidence on IRI thresholds in two countries.

Firstly, conducting road roughness survey and collect IRI data in two countries expressway by using own surface profile equipment, categorize IRI data based on the national standard of both countries. Secondly, divide it into several sections, in this case, we separate each 2 km as one segment, then calculate the average and standard deviations of each sampling units. Thirdly, calculate PSI based on the correlation equation between the IRI-PSI established by AASHO for motorways. Lastly, confirmed the road surface and its ride quality conditions by using vertical acceleration data based on the ISO 2631-1[42] standard obtained by survey vehicle.

The calculated PSI value of each sampled sections shows that the correlation between the IRI-PSI quite fit with each other, in this case it is possible to initially identify that, the given thresholds of IRI from both countries is acceptable. Furthermore evaluation of the ride quality based on the ISO 2631-1 standard also shows, the ride quality of those sections almost seated in "Comfortable" level, in that case, it is entirely possible to mention, the road surface conditions and it is ride quality is good and the both countries thresholds are acceptable.

5.2 Introduction

Expressway pavement requires a massive investment of public funds for construction and subsequent maintenance purpose. These pavements are one of the main for essential economic activities such as transporting goods and persons not only in industrialized societies but also in developing countries. The increase of traffic volume has subjected these pavements to more loads than the past and has affected these pavement structures which are either approaching or have exhausted their life cycle design. Due to the deterioration of the road surface, many local road management agencies have gradually shifted their emphasis from a construction of new pavements to maintenance and rehabilitation “M&R” of existing roadways. Because of the complex behavior of pavements, it 's hard to manage old road networks. Also, most agencies are now forced to make the fiscal simplicity of the increasingly severe budget constraints, it lead to a reduction of maintenance activities. In the past few decades, many research topics have been the focus on the development of pavement management systems (PMS) by many agencies for their roadways. The major role of these systems is assisting decision-makers to find “M&R” strategies for maintaining expressway's road surface in a serviceable condition over a specified period in the most cost-effective manner [43]. According to the preferences of the relevant organizations concerned, PMS may take various forms; however, all PMSs have some requisite elements or functions, for their operation. These essential functions are network inventory, pavement condition evaluation, pavement performance prediction and planning methods. A PMS can assist to life cycle cost analysis “LCCA” for various alternatives and decision-makers about the timing of applying the best alternative. It can provide a systematic, consistent method for selecting "M&R" needs and determining priorities and the optimal time of repair by predicting future pavement conditions [44]. Figure 5-1 shows the Life cycle curve of a pavement, and it can contribute to make "M&R" decision for road administrator

As mentioned above, since the establishment of the International Roughness Index (IRI) in the early 1990's, it has become one of the most important indicators for assessing highway surface around the world. The national road Administration of both countries has strongly required all provinces and prefecture to report IRI values annually in order to serves to the Highway performance monitoring and maintenance program. IRI is the results of the standardized measure of the reaction of a vehicle to roadway profile and road roughness that is expressed in "m/km or inches per mile." A higher IRI value represents the rougher road, and a lower IRI value represents the smoother road. The

Ministry of Transportation of China and Nippon Expressway Company Limited (NEXCO) in Japan has provided thresholds for roadway smoothness based on which pavement rehabilitation decisions are necessarily made, among other elements. Some local road agencies [45] are in the process of establishing IRI thresholds based on the verification of Pavement overlay design.

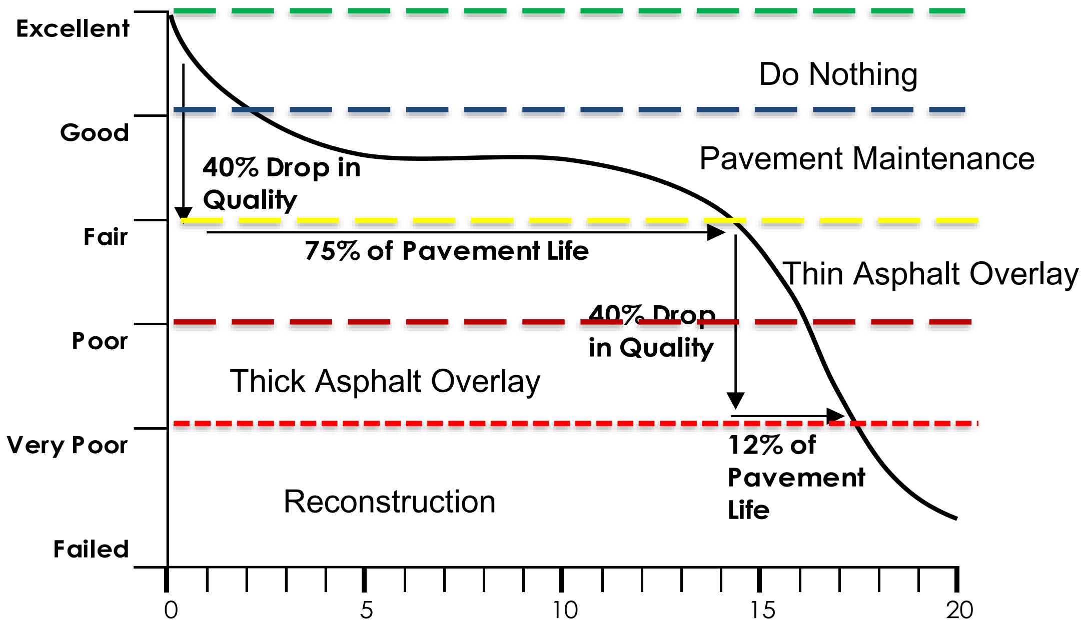

Figure 5-1 Pavement Life Curve

5.3 **Pavement Management in China**

Road mileage in China reached 4,463,900 kilometers by the end of 2014, 4.8 times the road mileage three decades ago. Among the different types of roads, China's expressway system has been expanding quickly since 1990. Nationwide, the total mileage increased from 400 kilometers in 1990 to approximately 111,900 kilometers in 2014. The well connected expressway network was made possible by the National Trunk Highway Development Program initiated under the Government's Ninth Five-Year Plan (1996– 2000). Its stated objectives were to connect all provincial capitals and cities with a registered urban population of greater than 500,000 on a single expressway network and to construct routes between targeted centers and the border in border provinces as part of the Asian Highway Network [46]. According to the original plan, the network was to be completed by the year 2020, but it was actually completed in 2007. One reason for the early completion was that the highway construction became part of the stimulus package to cope with the Asian Financial Crisis [47]. Regional growth differences are even more pronounced regarding the length of expressways. Expressway mileages increased from 3,163 to 36,102 kilometers between 1997 and 2013. In comparison, the expressway length in the western provinces increased from 358 to 33,843 kilometers; this growth can likely be attributed to China's Western Development Program, which was initiated in the late 1990s.

From 1950 to the present, total length of different level of roads in Xinjiang have been built for total length of 178,300 kilometers. It includes 4316 km of expressway, 1302 km of high-standard highway, 14482 km of national highway, 29,560 km of provincial roads and 128,567 km of other road as shown figure 5-2 and 5-3 [48].

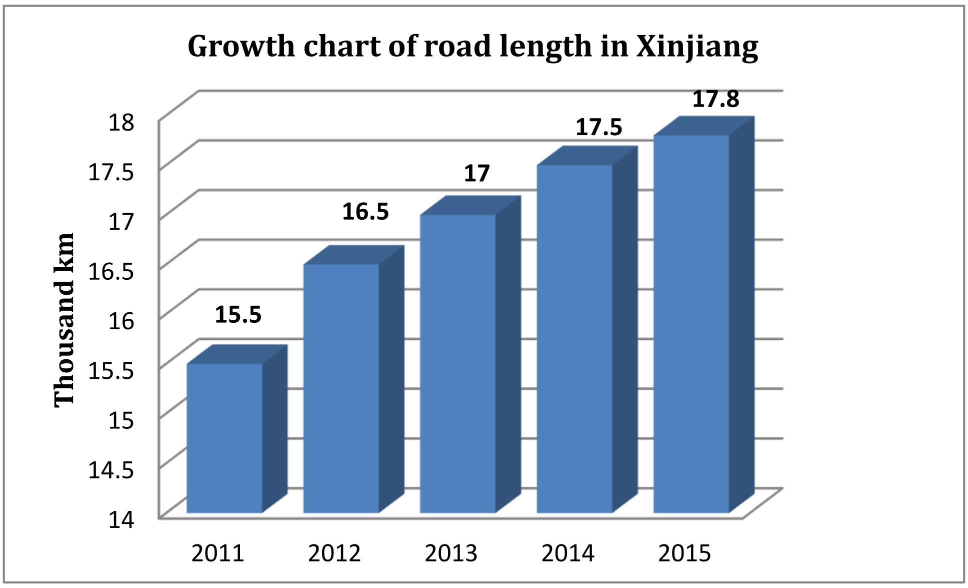

Figure 5-2 Growth chart of road length in Xinjiang

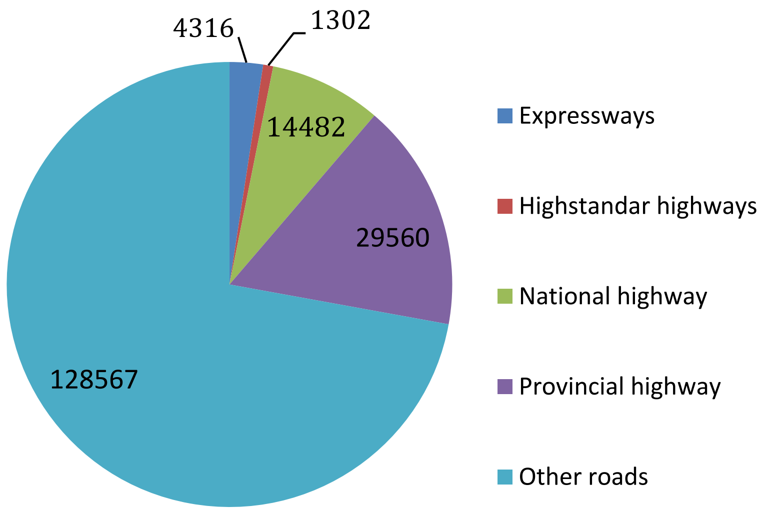

Figure 5-3 Total length of each roadway in Xinjiang

The Xinjiang region has paved pavement and simple paved road mileage of 113455 km, an increase of 7078 km over the previous year; accounting for 63.6% of the total highway mileage, three percentage points higher than the previous year. Each type of road mileage is: there is paved pavement mileage of 39488 kilometers, 3685 kilometers increase over the previous year. Among them, the asphalt concrete pavement of 38,973 km, 3,672 km increase over the previous year. Cement concrete pavement of 515 km, 13 km increase over the previous year. Simple pavement 73,967 km, 3,392 km increase over the previous year. Unpaved roads 64,808 kilometers, 4,282 kilometers less than the previous year[48]. Table 5-1 shows paved condition of the road surface with different material.

Table 5-1 Paved condition of road surface with different material

Year	Total	Asphalt concrete	Cement concrete	Simple pavement
2014	106378	35301	502	70575
2015	113455	38973	515	73967
Growth(%)	6.7	10.4	2.5	4.8

The China pavement management system (CPMS) is the product of one of the Government of China's national key research projects conducted between 1986 and 1990. Thereafter, the Ministry of Communications set out to implement the CPMS for managing road maintenance throughout the country by the year 2000. The first phase, to

1996, saw its introduction to 174,000 km of trunk roads in 14 provinces.

This resulted in a significant improvement in the management of road maintenance by presenting investment alternatives to provincial engineers in a coherent fashion. The CPMS comprises three components: a comprehensive database, a network level maintenance management system and a project level maintenance management system [49]. Figure 5-4 and 5-5 shows the flow chart of expressway maintenance information system and repair plan of the CPMS with its standard for the "M&R" as shown in table 5-2. Note, MIS is the short name of "Management Information System"

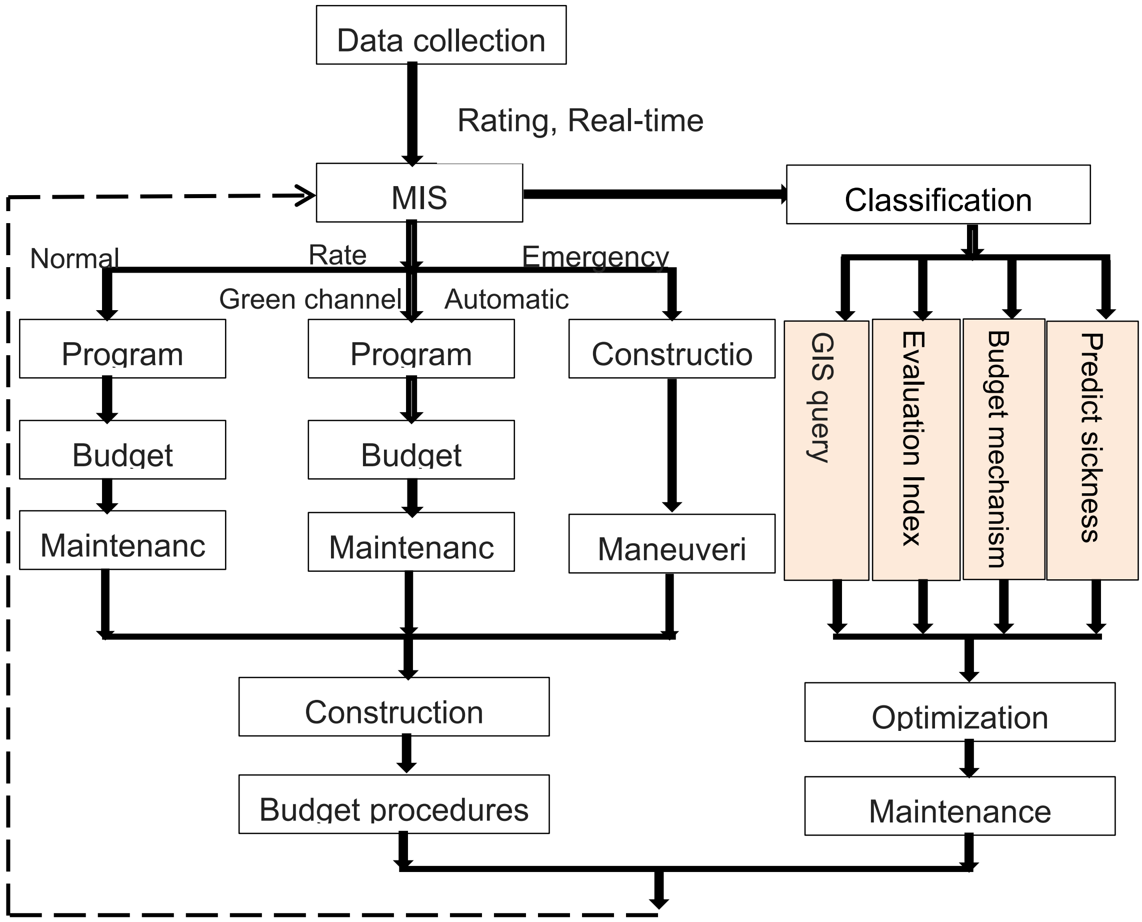

Figure 5-4 Flow chart of maintenance information system of the CPMS [49]

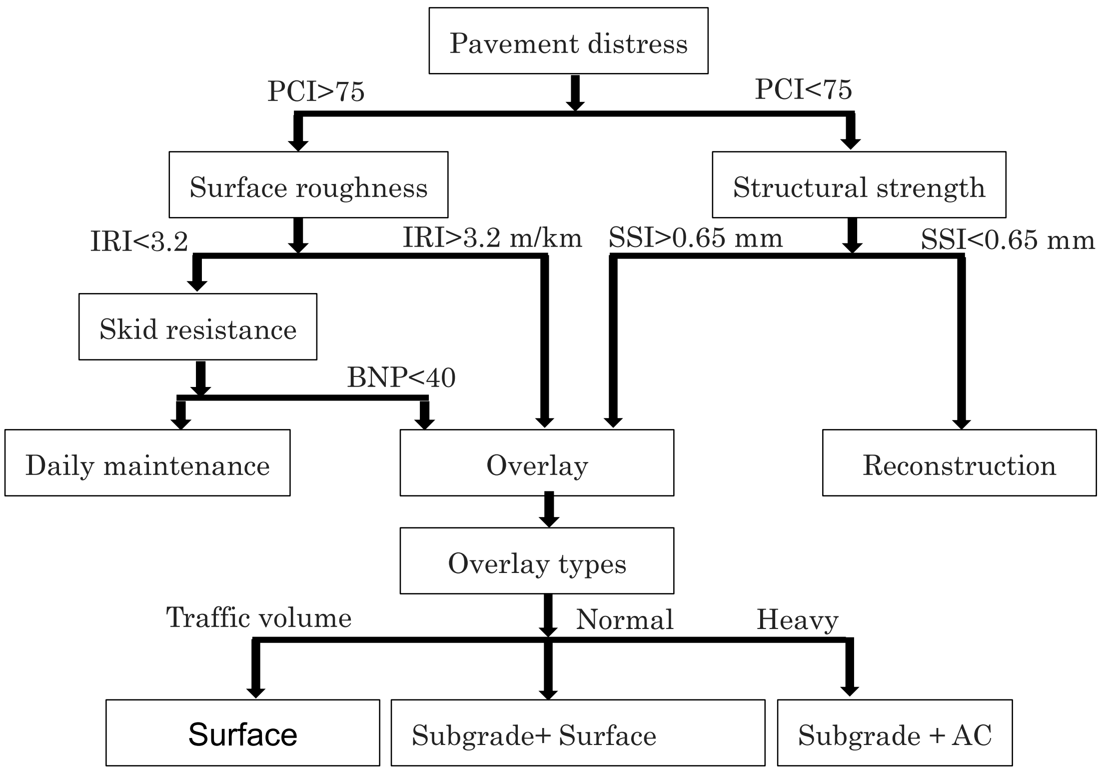

Figure 5-5 Flow chart of repair plan [49]

Table 5-2 "M&R" standards for expressway in China

Evaluation indices	Excellent	Good	Fair	Poor	Very poor
PCI	100~86	95~76	75~60	60~40	<40
SSI	>1.2	1.2~1.0	0.8~1.0	0.6~0.8	<0.6
RQI	≥8.5	≥7.0~<8.5	≥5.5~<7.0	≥4.0~<5.5	<4.0
SFC	≥0.5	≥0.4~<0.5	≥0.3~<0.4	≥0.2~<0.3	<0.2

5.4 Pavement Management in Japan

In Japan, roads are classified and categorized by "The Road Act" as national expressway, national highways, prefectural roads and municipal road. According to the significant information from the MLIT, The total actual length of roads is 1,203,777km as of April 2008[50]. The categories and administrators of these roads are shown in Table 5-3, and figure 5-6.

Table 5-3 Actual lengths of roads by category and respective administrators [50]

Category		Length (km)	Administrator
National expressways			Expressway companies (Public)
National highways	Designated	22,786.6	Ministry of Land, Infrastructure, Transport and Tourism (MLIT)
	Non-designated	31,949.3	Prefectures, Government-ordinance-designated cities
Prefectural roads		129,392.9	
Municipal roads		1,012,087.8	Government-ordinance-designated cities, towns, villages

Figure 5-6 Actual length of roads by category [50]

Ministry of Land, Infrastructure, Transport and Tourism of Japan has developed pavement management system called “MLIT-PMS” to make maintenance and rehabilitation decision by utilizing of the limited budget [51]. MLIT-PMS consists of pavement data bank and repair planning system. Figure 5-7 and 5-8 are the basic flow of the MLIT-PMS and its repair plan.

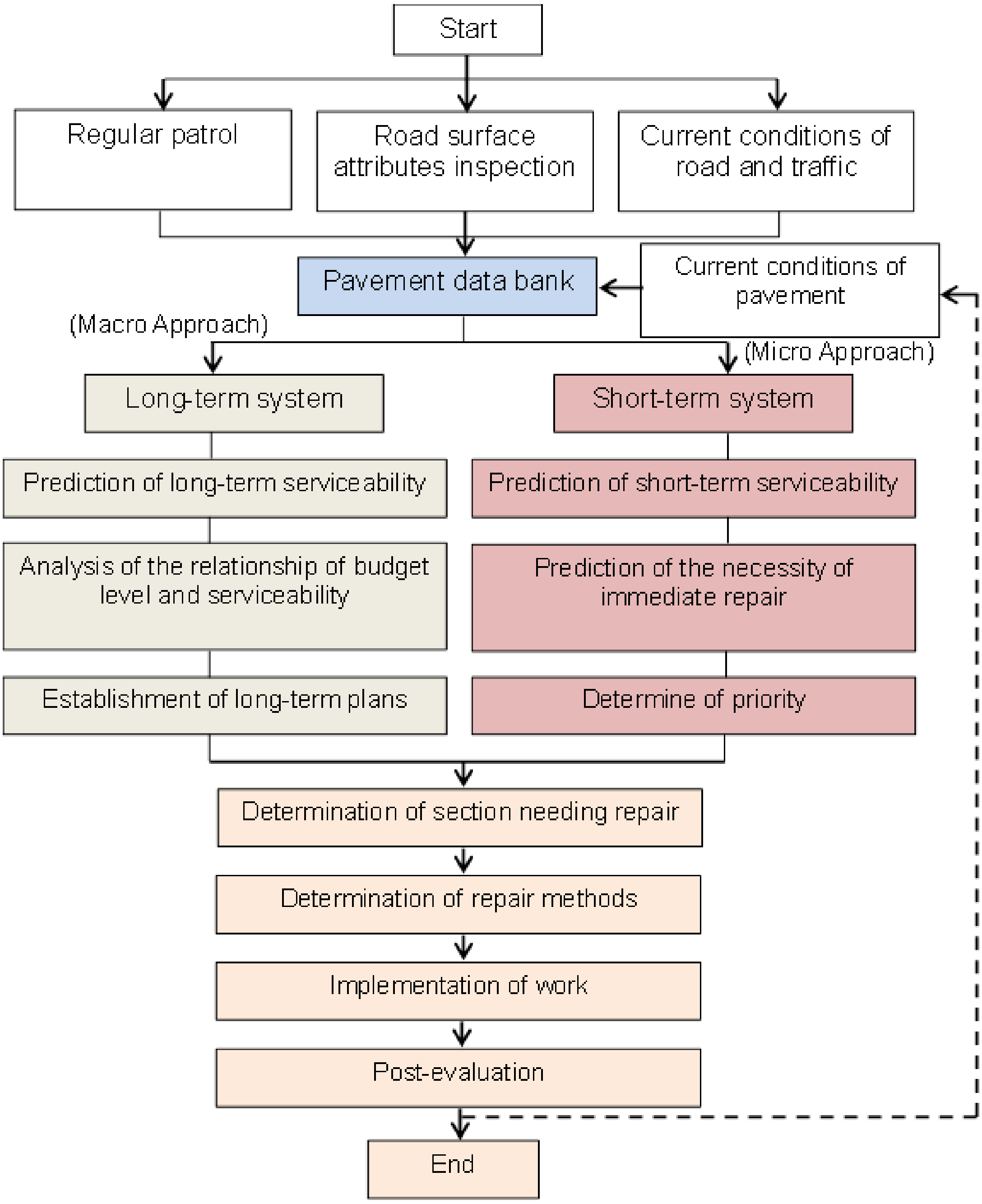

Figure 5-7 Basic flow chart of pavement management [51]

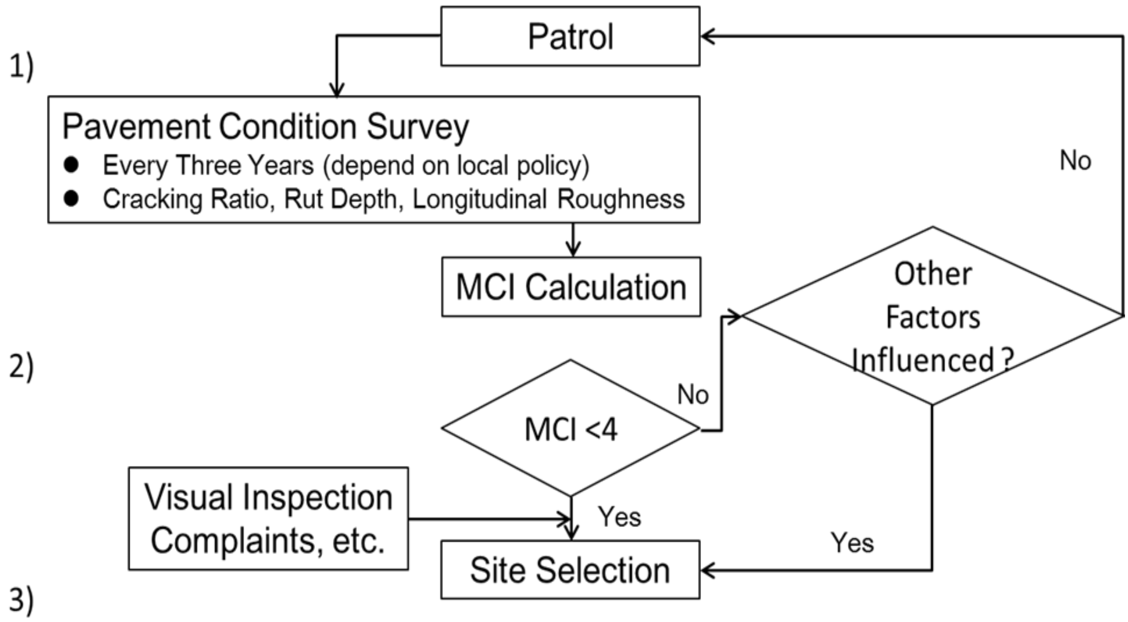

Figure 5-8 Flow chart of repair plan [51]

Collected data by road surface attribute inspection with automated pavement surface measuring devices are stored in pavement data bank. Collection data is cracking ratio C (%), rutting depth D (mm) and roughness σ (mm). The data collection interval for those indices is each 100m. In order to make a better decision, MCI (Maintenance Control Index) is necessary to calculate. MCI calculated from these data as synthesis evaluation index.

$$MCI = 10 - 1.48 \cdot C^{0.3} - 0.29 \cdot D^{0.7} - 0.47\sigma^{0.2} \quad \text{(Eq. 5-1)}$$

5.5 **Objectives**

According to the importance of IRI thresholds in pavement monitoring, this study aimed at using the limits of IRI which was obtained by the two countries road administrations, then giving a reliable proof that is this efficient or not by using the correlation equations of IRI and PSR.
Regarding further more evaluation of the surface roughness, I conducted the research study to evaluate the ride quality of measured locations by using RMS method based vertical acceleration data of survey vehicle, and ISO 2631-1 standard [42].

5.6 **Literature review**

Road pavement smoothness or roughness can be expressed regarding surface irregularities that affect the ride quality. Since the establishment of IRI in the late 1970s by IRRE, it has become an internationally accepted parameter to monitor roadway smoothness and irregularities [6]. Many research works [1, 52] have shown that smooth roads, as a whole, costs highway agencies less over the life cycle of the pavement. Thereby decreasing the overall cost of maintaining the roadway in addition to user operating costs, delay costs, and fuel consumption. IRI is measurement results of the specific surface monitoring vehicles with computer technology to obtained pavement roughness. These vehicles record the displacement of the vehicle chassis, which is located on the front or rear axle, usually regarding irregularities meter per kilometer [1, 36]. IRI values represent the profile slope of the road surface by combining with a reference elevation, height about the reference, and longitudinal distance.
Except for IRI, there is one more index named PSR; it can also distinguish the smoothness and roughness of road surface. The PSR depends on a human subjective evaluation of ride quality on a particular road segment. The American Association of State Highway Officials (AASHO) establish this fact in 1962. PSR is mainly working with the panel rating that asks inspector vs. examiner who ride motor cars over the selected pavement sections, and rate it based on of its scale from 5 (excellent) to the 0 (impassable to ride). The federal highway administration (FHWA) conducted several studies and established smoothness index for their highway networks through automation “IRI” can be correlated with the subjective ride experience or evaluation of

road users "PSR" [52]. Road surface roughness is a primary indicator of the ride quality and can produce emphasize in the pavement structure that could reveal origin untimely pavement fatigue and accelerated pavement deterioration. Pavement roughness indices, together with other pavement measurements, can indicate pavement surface deformation. Pavement distress, whether originating from above or below, undermines pavement drainage and thereby potentially compromise highway safety, resulting in a deterioration of the pavement roughness index value. As a consequence, studies suggest that the extent of pavement distress could be correlated with pavement roughness indices, including IRI. Road surface roughness is a primary indicator of the ride quality and can produce emphasize in the pavement structure that could explain origin untimely pavement fatigue and accelerated pavement deterioration. Pavement roughness indices, together with other pavement measurements, can indicate of pavement surface deformation. Pavement distress, whether originating from above or below, undermines pavement drainage and thereby potentially compromise highway safety, resulting in a deterioration of the pavement roughness index value. As a consequence, studies suggest that the extent of pavement distress could be correlated with pavement roughness indices, including IRI.

The Ministry of Transportation in China recommends thresholds of IRI that, the IRI between the "2-3.2 m/km" for acceptable ride quality, if it is over than 3.2 is not acceptable in the 2012 highway design and surface evaluation plan for the expressways [53]. Table 5-4 shows the thresholds of IRI for China's expressway.

On the other hand, NEXCO introduced the new IRI thresholds for the expressway in Japan, that is, the IRI between the "1-3.5 m/km" is acceptable for the ride, if IRI over than 3.5 is not acceptable. The thresholds of IRI for Japan's expressway has also expressed in Table 5-4.

Table 5-4 IRI thresholds for both countries expressway

Ride Quality terms	IRI Threshold in China (m/km)	IRI Threshold in Japan (m/km)
Good	IRI $\leq$ 2	IRI $\leq$ 1
Acceptable	2 < IRI $\leq$ 3.2	1< IRI $\leq$ 3.5
Poor	IRI>3.2	IRI>3.5

In a case of objective evaluation of the pavement roughness, some interesting studies were performed to investigate the influence of pavement roughness on driver response in both countries. In 2002, some of the researchers in Japan examined the influence of road steps on the brainwaves of passengers [37, 38]. In 2001, Fukuyama studied about the evaluation method of driving comfort using frequency-weighted r.m.s. acceleration and demonstrated that there is a good relationship between IRI and vibration acceleration [39]. In 2008, Tateki evaluated the riding quality based on the road roughness conditions by using special surface evaluation equipment "DS" [40].

On the other hand, some of the Chinese researchers also studied some interesting topics. In 2010, Wang studied about the influence of IRI on a driver's physiological reaction by using HRV parameters [54]. In 2011, Zhang studied about a topic named; investigating the relationship between pavement roughness and heart-rate variability by road driving test, in this study he successfully evaluated the effects of pavement roughness on the driving comfort of a driver by using HRV and RMS method [55].

5.7 **Data collection sites**

In order to study the influence of pavement roughness to the riding comfort of the vehicle, in this study, several road sections with different pavement roughness are selected and IRI tests are performed on these road sections at speed between 80km/h to 120 km/h in both countries. In the survey, we used a profiler developed by Kitami Institute of Technology named "STAMPER" with the driver who has more than five years driving experience.

Moreover, the test part selected in Xinjiang is the key expressway with the daily traffic volume of 2859 vehicle/day, and that it does not only link the south and north part of Xinjiang but also links it with the inner China. The duration of the whole measured section is about 900km for both south and north directions. Following figure 5-9 and 5-10 shows the total traffic volume of the different levels of Xinjiang's highway in 2015 and daily traffic volume of the road roughness survey location.

Figure 5-11 shows the roughness measuring sites on August 17th, 18th and 19th in Xinjiang Figure (a) is the survey location of the first day, and figure (b), (c) represents the survey location on the second day and (d) is the site of third day roughness measurement.

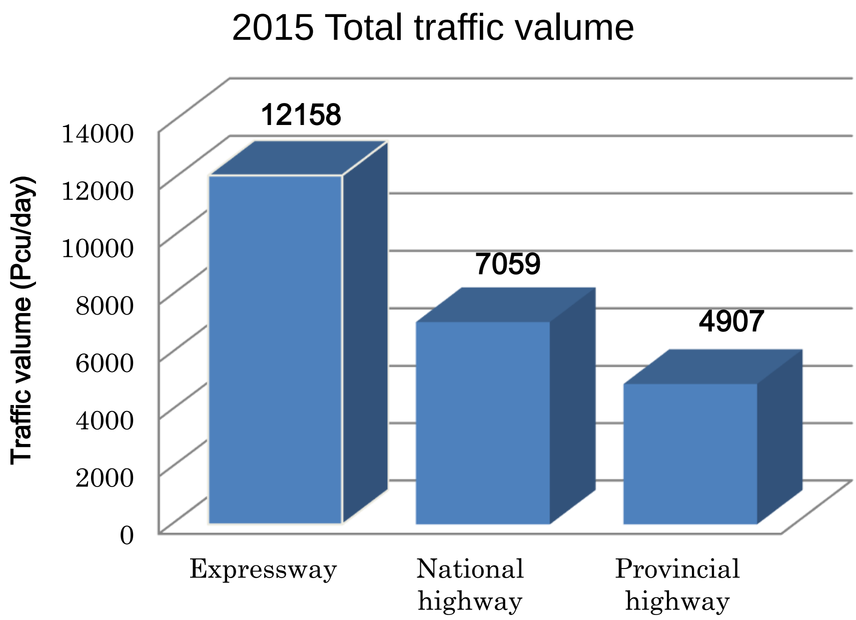

Figure 5-9 Total traffic volume of Xinjiang highways in 2015

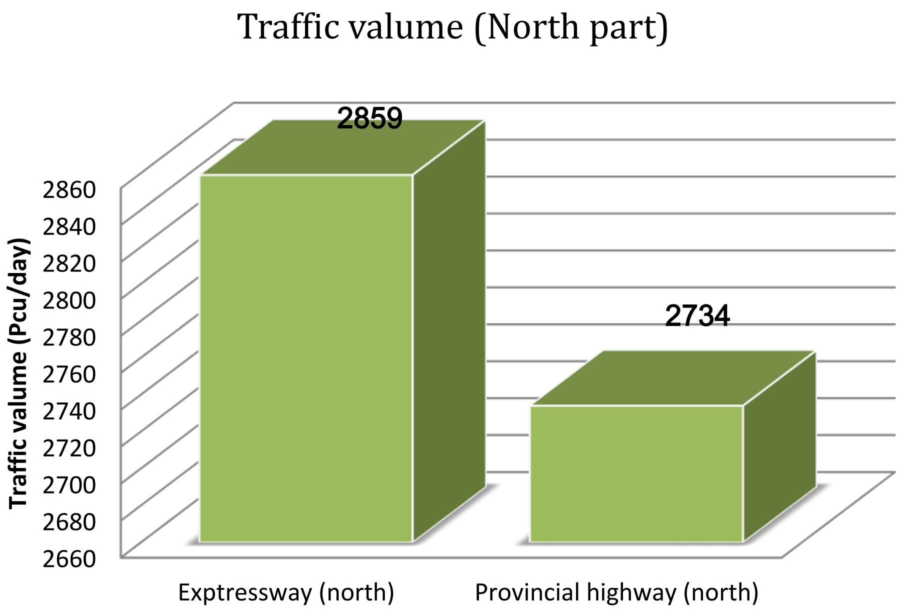

Figure 5-10 Traffic volume of the north part of Xinjiang expressway in 2015

Figure 5-11 Overview of the test section in Xinjiang

On the other hand, we have measured IRI of the expressway in Hokkaido prefecture of Japan in Jan 22th and 24th. The survey was conducted by using the same equipment at which we held in Xinjiang, and IRI data collected for each 100m interval, the sections selected for road roughness survey are, those of the trunk expressways in Hokkaido. Pavement roughness test conducted for around the 262km on targeted motorways. Figure 5-12 shows the daily traffic volume of measurement locations in Hokkaido with different types of vehicle as of 2016, and it will contribute to knowledge about the relation between the surface deterioration and traffic volume. Figure 5-13 is the road roughness survey locations of the Hokkaido, the subfigures (a) and (b) show the surface conditions of first-day road roughness collection, and subfigures (c) and (d) are the view of the road surface of second-day surface monitoring.

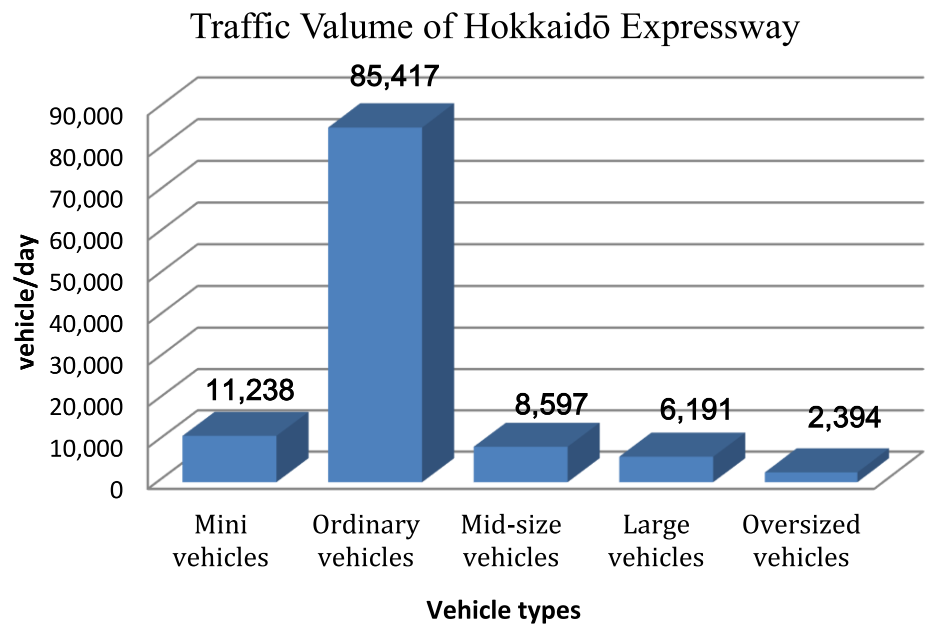

Figure 5-12 Traffic volume of Hokkaido expressway

Figure 5-13 Overview of the survey location in Hokkaido

5.8 **Research methodology**

In order to prove the established IRI threshold from both countries, this study conducted pavement smoothness monitoring in two countries, respectively. Then selected more than 50 road segments in each countries expressway, after then using the correlation equation obtained from MnDOT and AASHO scale calculated the PSI of each sampled road sections, to find the out the relationship between the two different indices by using simple regression analysis. Based on the results of regression models, acceptable IRI values were obtained at a 95% confidence interval together with the average value of the thresholds for both countries, respectively.

The correlation equation [56] of IRI- PSI obtained by MnDOT for bituminous has been shown equation 5-1.

$$PSR = 5.697 - (2.104\sqrt{IRI}\ ) \qquad \text{(Eq. 5-1)}$$

Furthermore, this study evaluated the ride quality based on the vertical acceleration data together with the ISO 26-31 standard, obtained by two active sensors mounted at the suspension system of the survey vehicle. The results of r.m.s. calculated based on the acceleration data.

The results contribute that it is efficiently comfortable and no more r. m. s. data out of acceptable range. Figure 5-14 shows the average IRI value of the three days roughness measurement in Xinjiang and two days of Hokkaido side, and figure 5-15 shows the average PSI value of them.

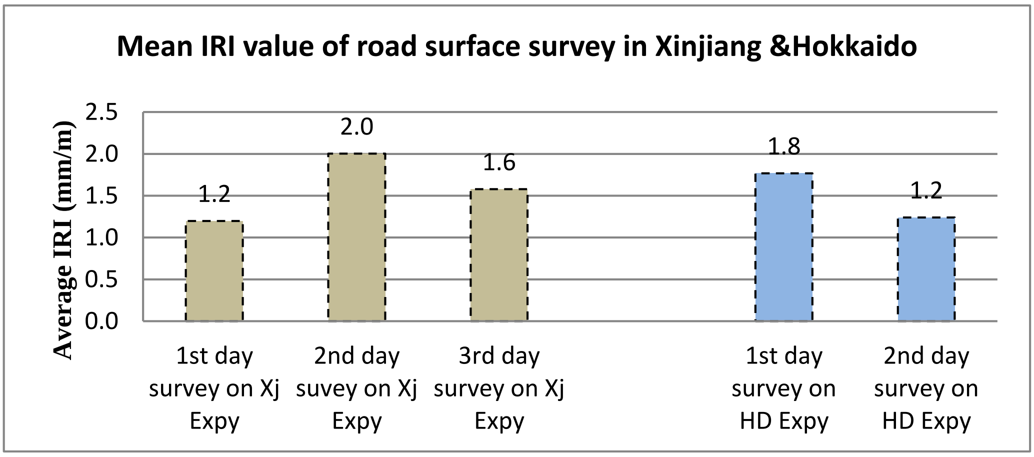

Figure 5-14 Overview of the IRI at both sides

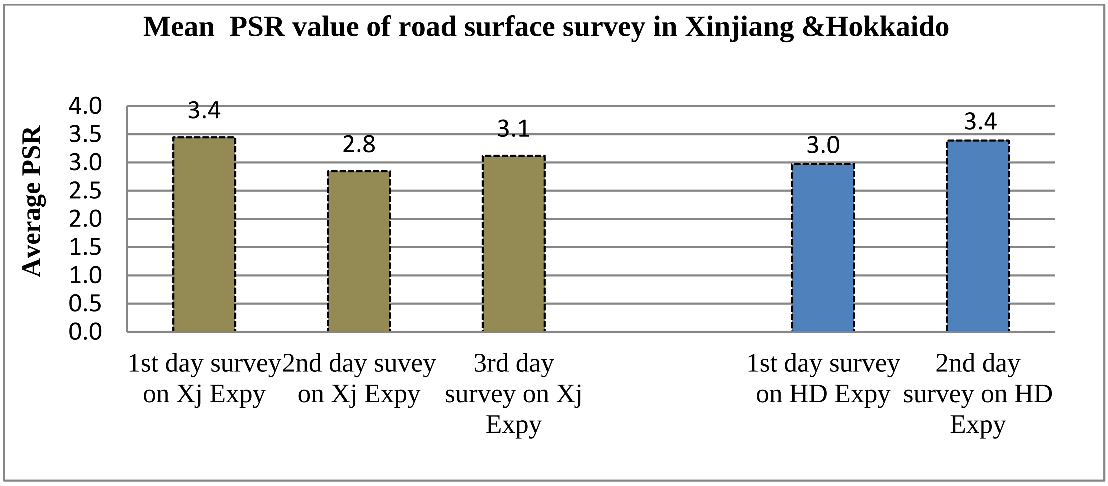

Figure 5-15 Overview of the PSI at both sides

According to the IRI thresholds obtained by both countries and the PSI scale of AASHO, the figures show that the mean values of IRI are within or smaller than acceptable range which corresponds that PSI values are over 3. It means that most of an expressway in two countries are doing maintenance work very well and the serviceability of measured locations are good. Table 5-5 shows the results of the measurement in both countries, and it represents the mean IRI and PSI with its standard deviations. According to the table, it is possible to say that, the standard deviations of each mean IRI is not significantly different from the average value and it should be considered within the allowance range.

Table 5-5 Mean IRI and PSI with deviations

Classification	Mean IRI (mm/m)	IRI St.dev (mm/m)	Mean PSR	PSR St.dev
1st day survey in Xj Expy	1.2	0.6	3.4	0.6
2nd day survey in Xj Expy	2.0	1.4	2.8	0.9
3rd day survey in Xj Expy	1.6	0.8	3.1	0.6
1st day survey in HD Expy	1.8	0.9	3.0	0.6
2nd day survey in HD Expy	1.2	0.5	3.4	0.4

5.8.1 Statistical analysis

As explained in above section, the data analysis was performed for each country. The calculated ratings of the PSR were correlated to the IRI values using regression analysis methods. Figure 5-16 and 5-17 show the actual conditions of IRI in both countries, respectively. After the calculation of the correlation has done, the figure 5-18 and 5-19 were achieved.

Figure 5-16 shows that the selected surface conditions of the expressway in Xinjiang mostly fall within the acceptable or less than acceptable range. However, regarding few points show, the road surface conditions were situated out of acceptable ranges, to identify the actual surface condition of these points, in the next section we are going to visualize the real surface condition with the live photos by using GIS. In the case of figure 5-17, it shows that the road surface conditions of the selected sections of the Hokkaido Expressway, perfectly fall within the acceptable range or less than it. However, some points have possibility falling to the unacceptable criterion, in this case, we used same methods for the selected segments of Hokkaido Expressway showed the actual conditions of the road surface.

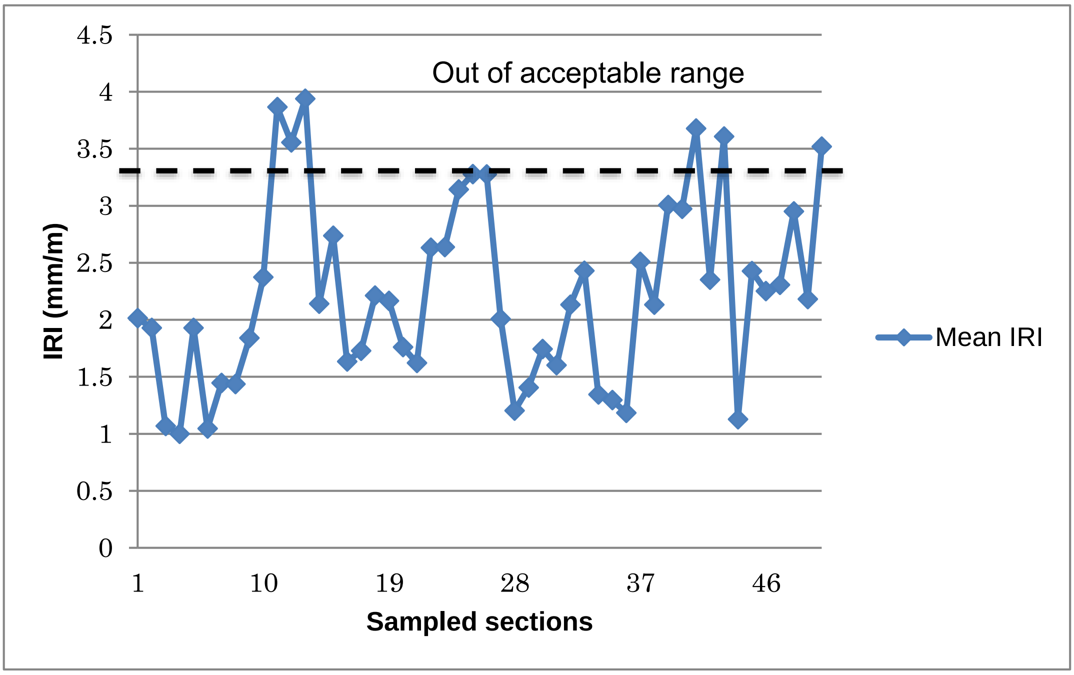

Figure 5-16 IRI of each sampled sections in Xinjiang

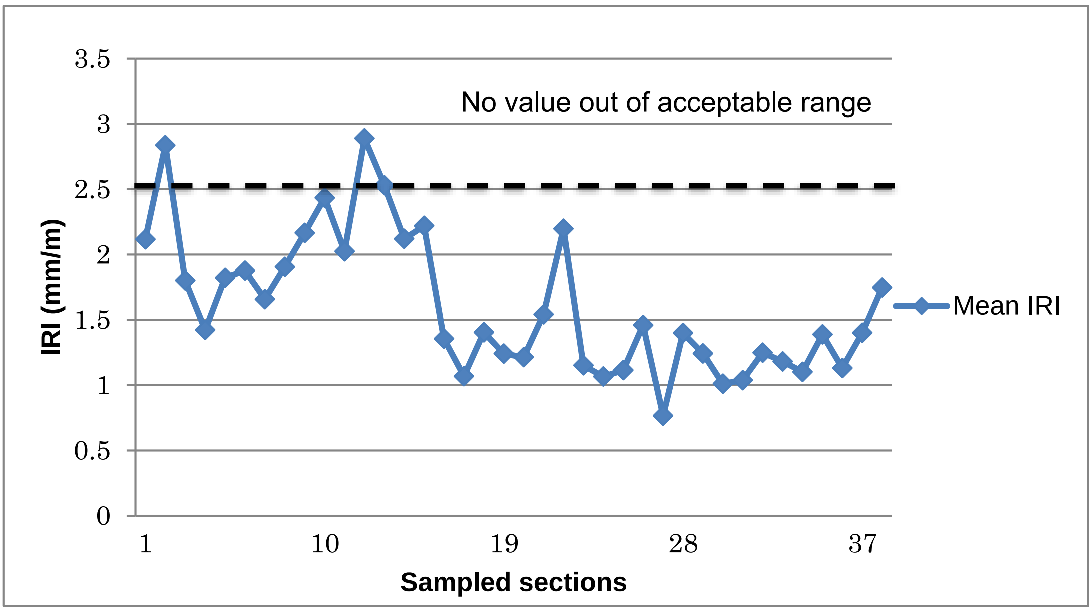

Figure 5-17 IRI of each sampled sections in Hokkaido

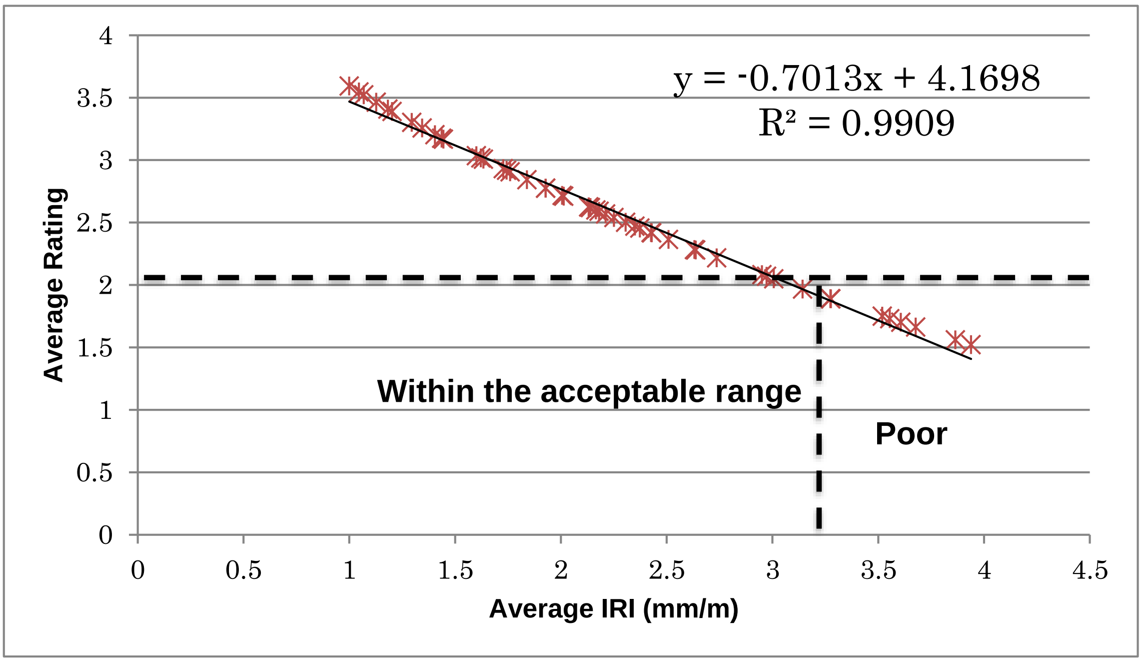

Figure 5-18 Linear correlation of IRI-PSI in Xinjiang expressway

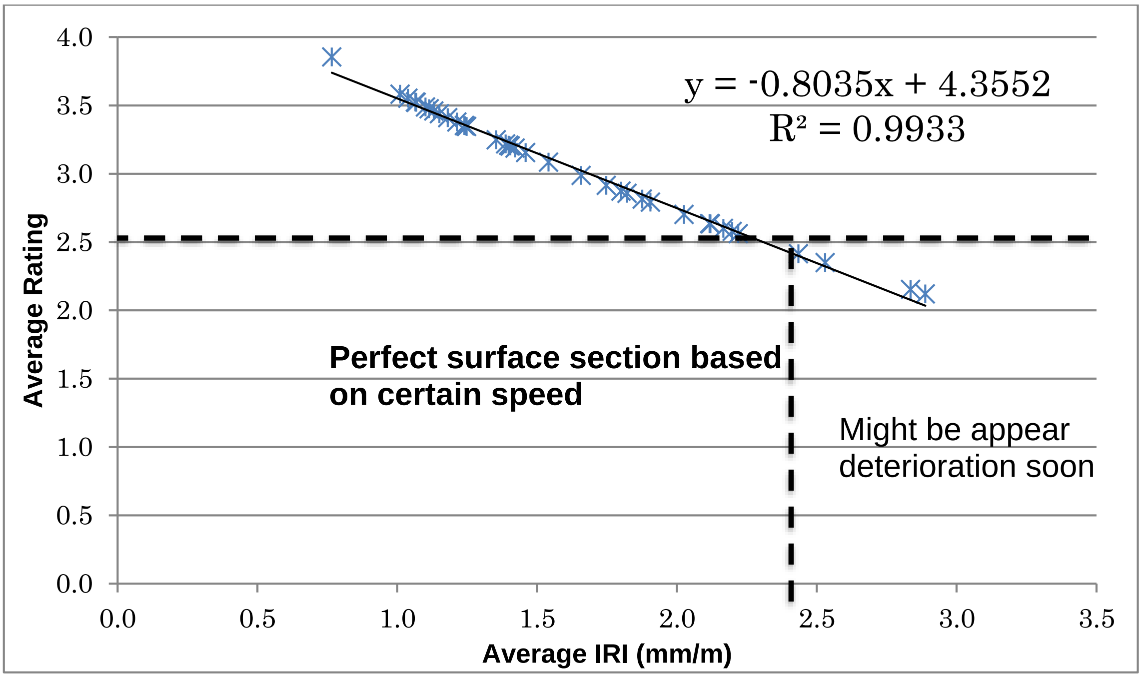

Figure 5-19 Linear correlation of IRI-PSI in Hokkaido expressway

For further determination of those critical sections, it shows that there is really out of acceptable range, or it has an individual risk to be going to deterioration. In this case, I used correlation analysis method between the two independent indices IRI-PSI by using the correlation equation of PSI with the 95% of confidence and 5% level of significance. The results of correlation analysis between the IRI-PSI show that the linear relationship of two indices are quite fit with each other, and it also shows the same points of IRI value that falls acceptable range. The results have proven that it might have the risk to appear pavement deterioration. In this study, the R^2 value of each side also reported within the correlation figures.

5.9 **Visualization of critical pavement sections by using GIS**

For the visualization of the IRI data on a spatial environment, this study employed special software for visualizing measured IRI data as an attribute in a GIS. GIS has been recognized as a useful tool in the operating process PMSs, and some researchers used it to provide a rational categorization threshold representing the conditions of the IRI on different classes of the highway network in their country.

In order to be able to yield the IRI data on the GIS maps, it requires paying attention to the roughness tabular data showing the testing location GPS coordinates as East, and North. The IRI classification was based on a particular criterion which determined a range of IRI values for each class. Also, the range of classification values was beyond the highest roughness IRI value in our survey data. The following figures are the mapping results of the IRI in the target sections. Which might be assisting to the road administrator quickly find out the reasons of surface deterioration. Hopefully, have some contributes to developing PMS in measured location. Figure 5-20 to 5-25 show the whole measurement duration in three days with some critical sections picked up from it, and road surface conditions represented with different colors. The red color means that the ride quality of this section is out of acceptable range or road surface is going to be poor. The reason of the surface deterioration comes mostly from changeable weather conditions with the high elevation of survey location. Figure 5-26 to 5-29 represent the road surface conditions of the Hokkaido high standard highway and expressway. Judging from the real situations of these roadways, it is entirely possible to say that, the road administration of Hokkaido area kept their surface in very well condition even in winter season. It is hard to compare the road surface conditions of two countries expressway, because the surface measurement in both countries conducted in different two seasons, but even it is in different seasons, the results shows that, selected road surface of Hokkaido Expressway is better than those of Xinjiang.

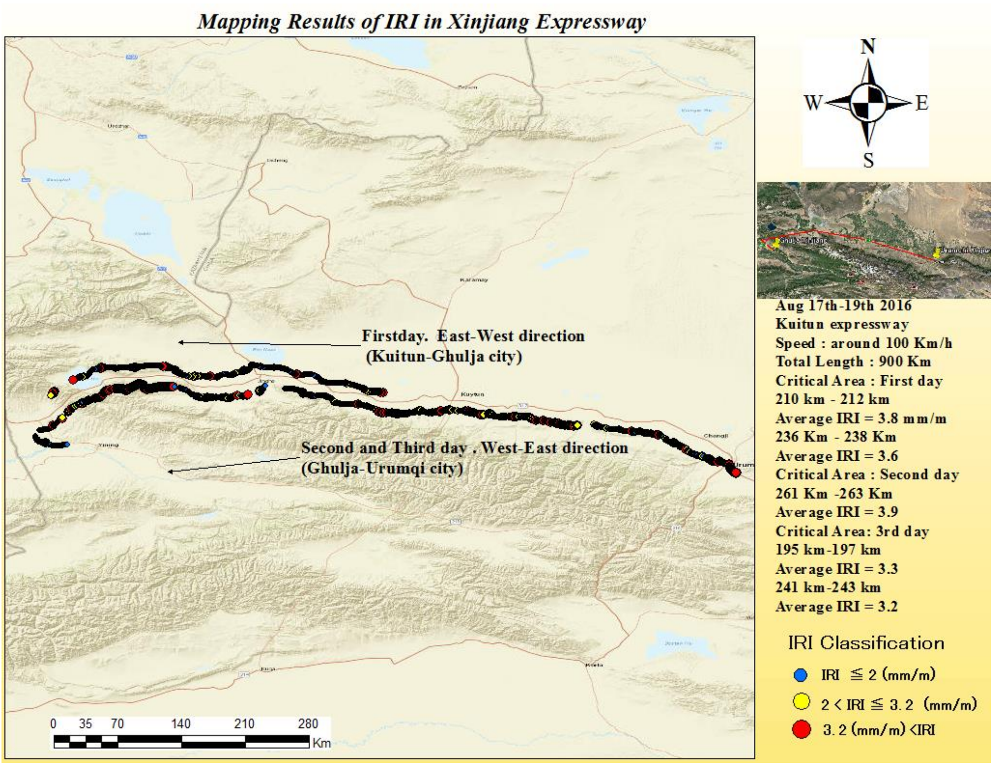

Figure 5-20 Mapping result of whole measuring duration in Xinjiang

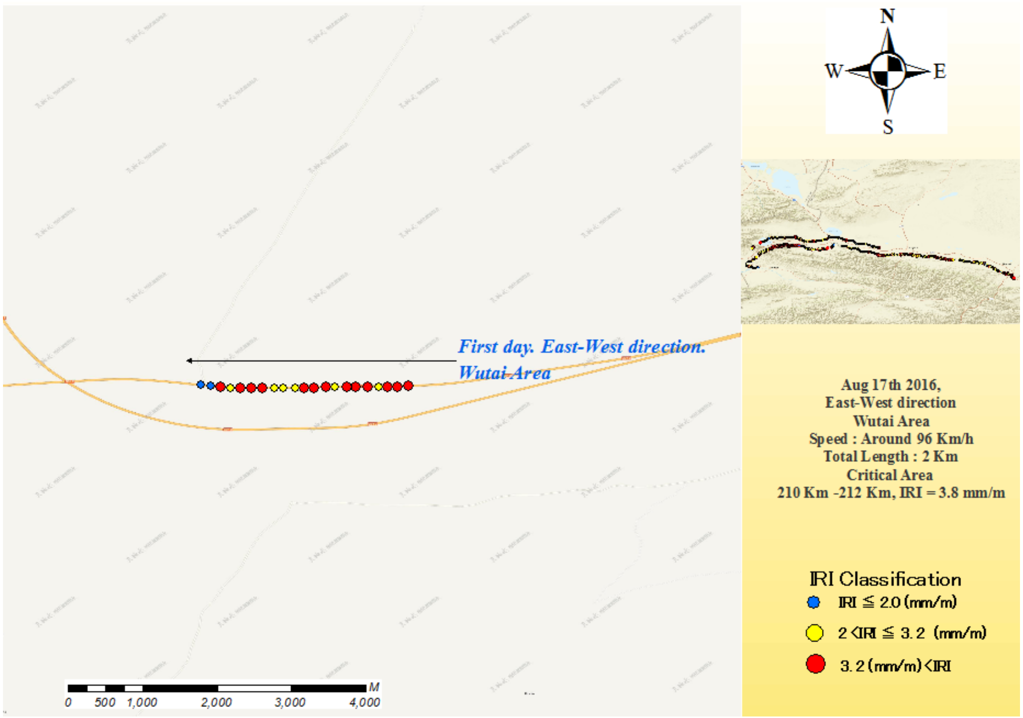

Figure 5-21 Mapping result of first critical section in Xinjiang

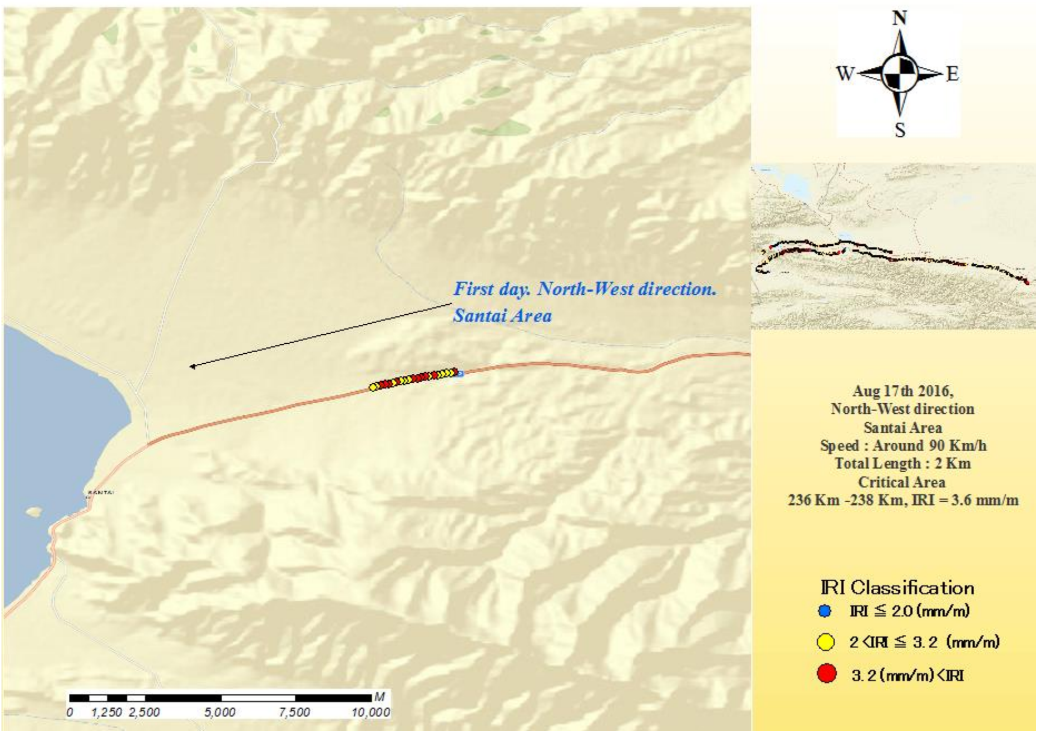

Figure 5-22 Mapping result of second critical section in Xinjiang

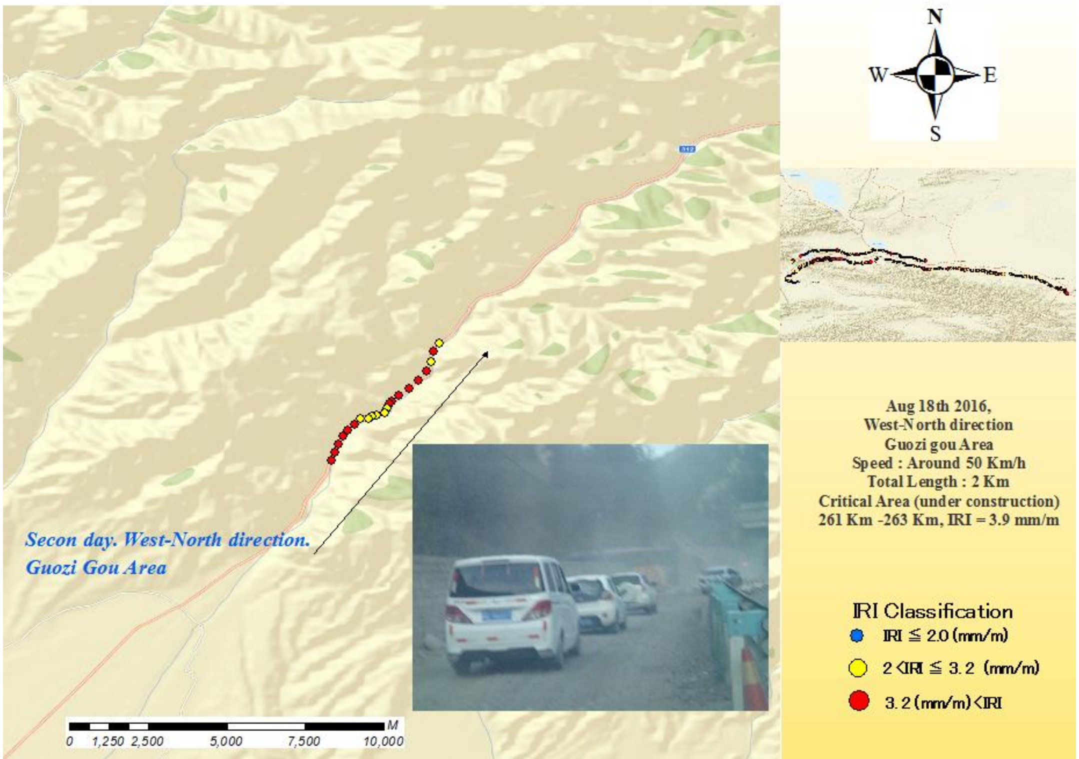

Figure 5-23 Mapping result of third critical section in Xinjiang

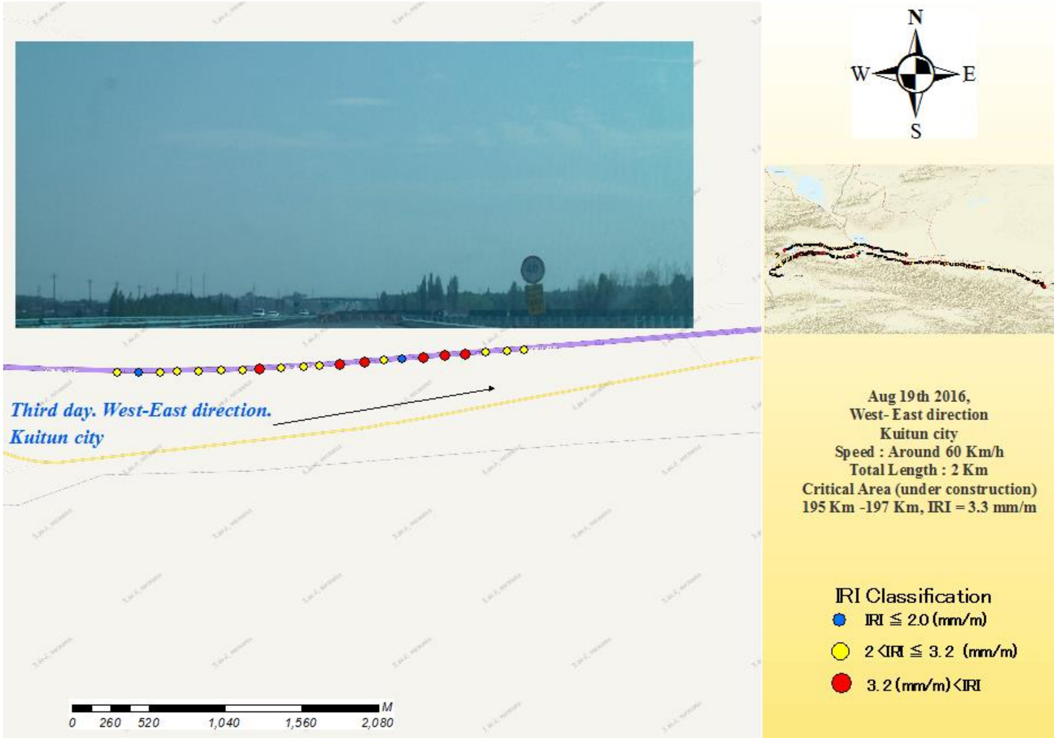

Figure 5-24 Mapping result of forth critical section in Xinjiang

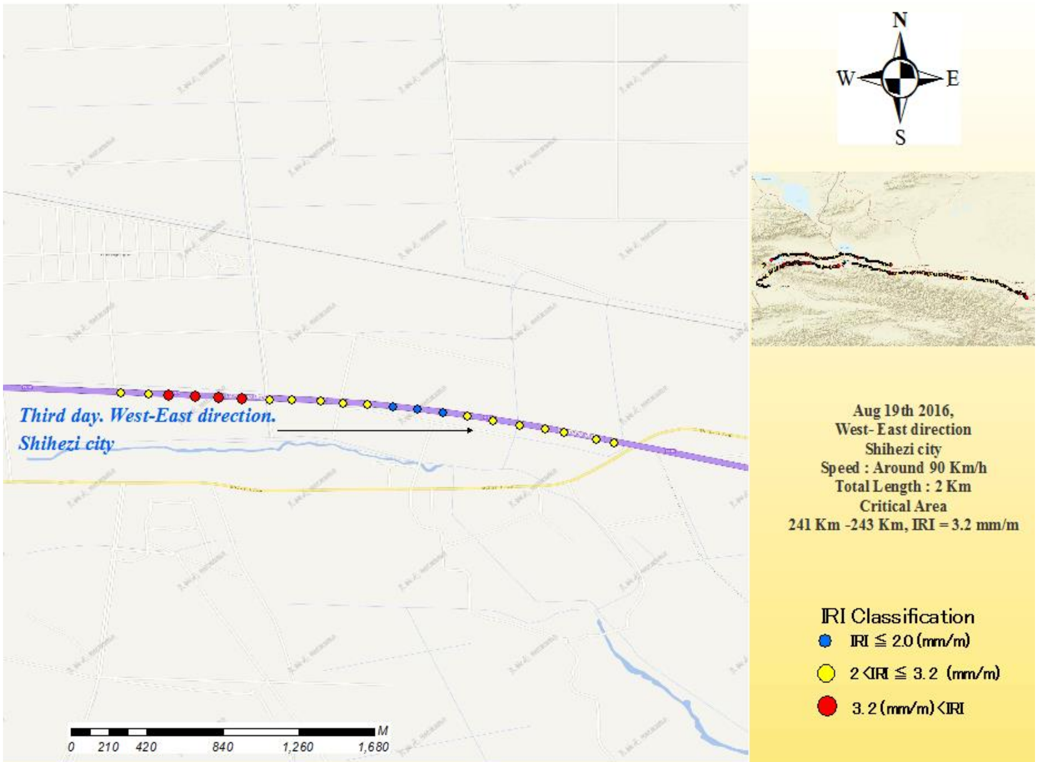

Figure 5-25 Mapping result of fifth critical section in Xinjiang

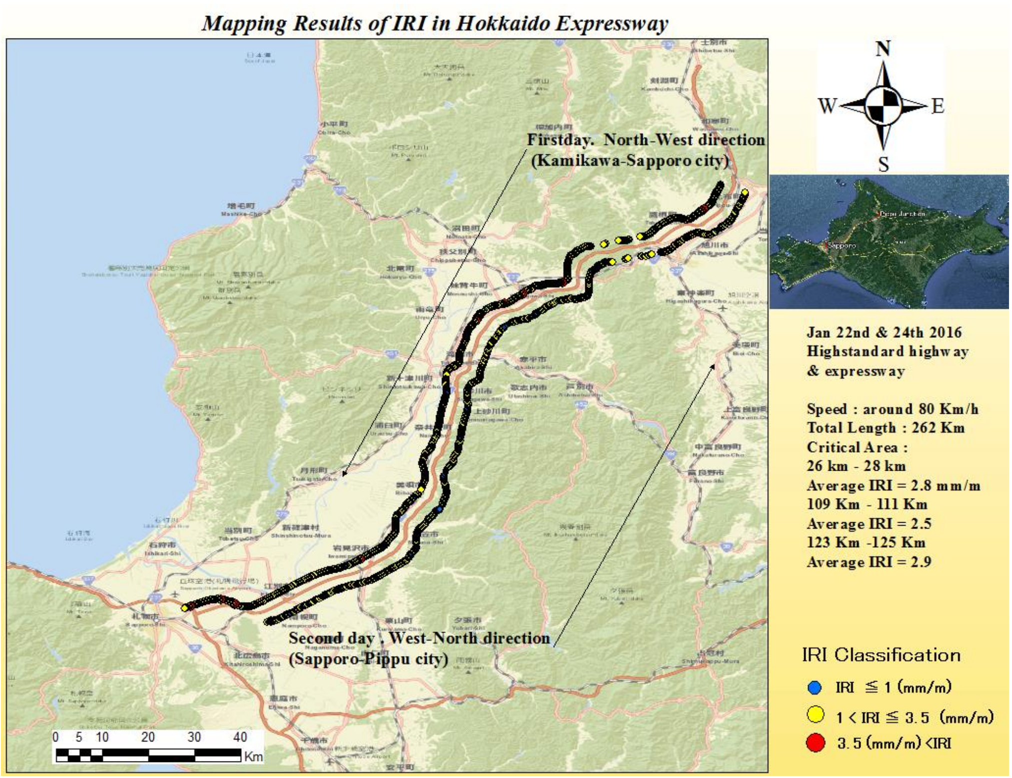

Figure 5-26 Mapping result of the whole duration in Hokkado

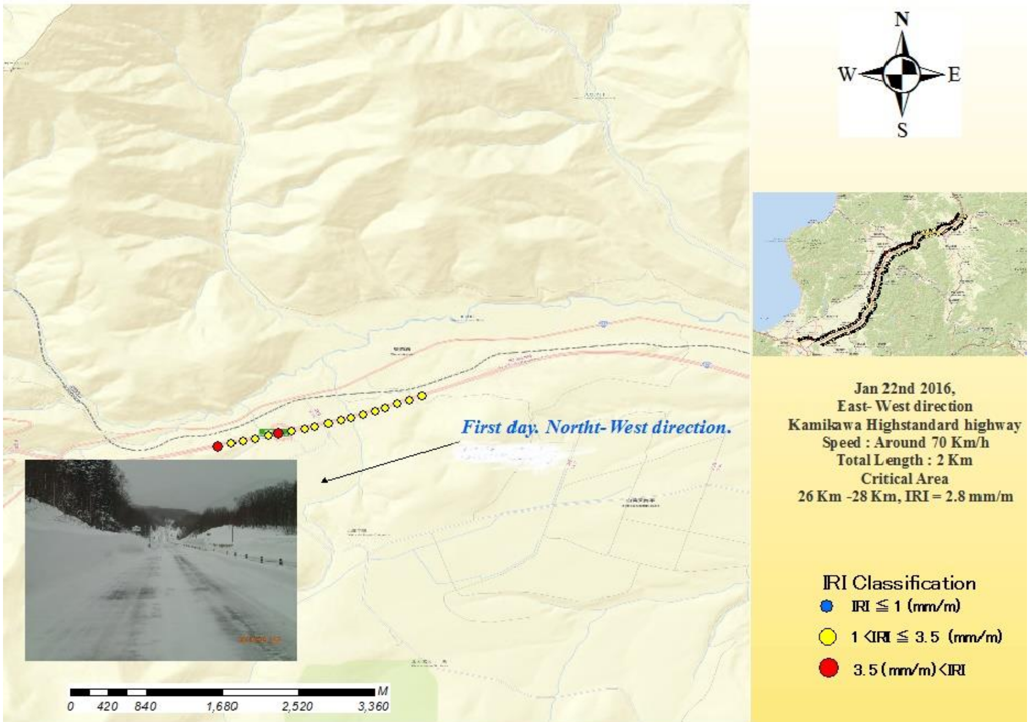

Figure 5-27 Mapping result of first critical section in Hokkaido

Figure 5-28 Mapping result of second critical section in Hokkaido

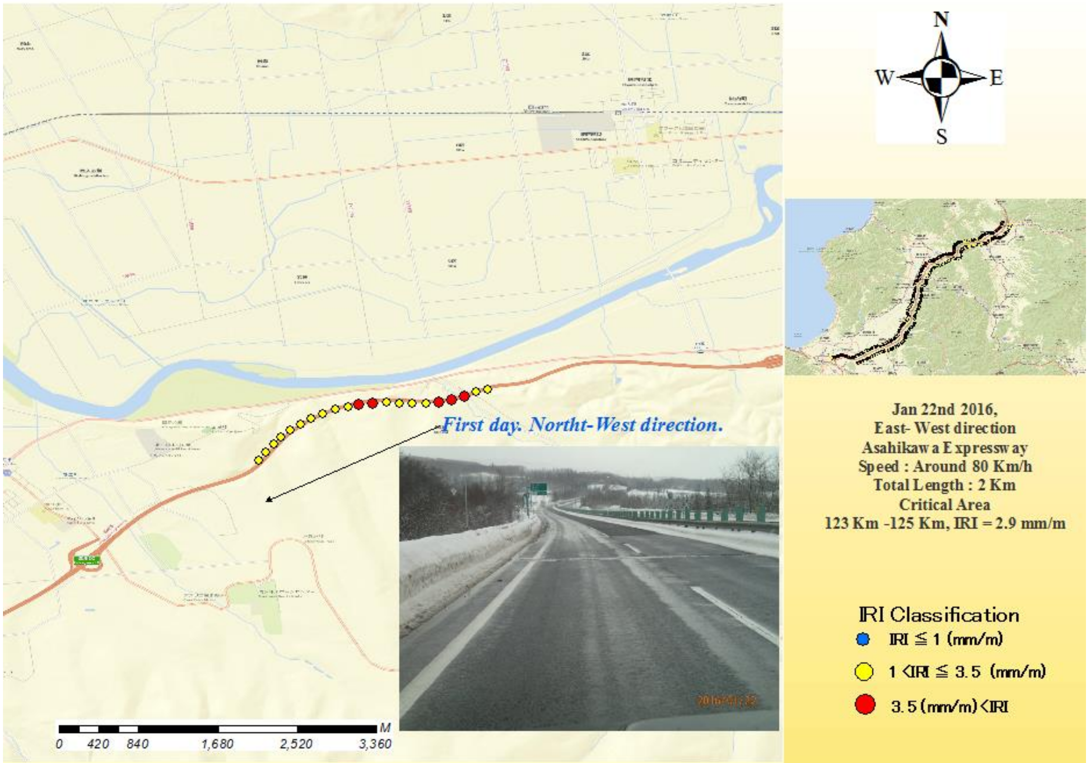

Figure 5-29 Mapping result of third critical section in Hokkaido

5.9.1 IRI clarified by using histogram and cumulative curve

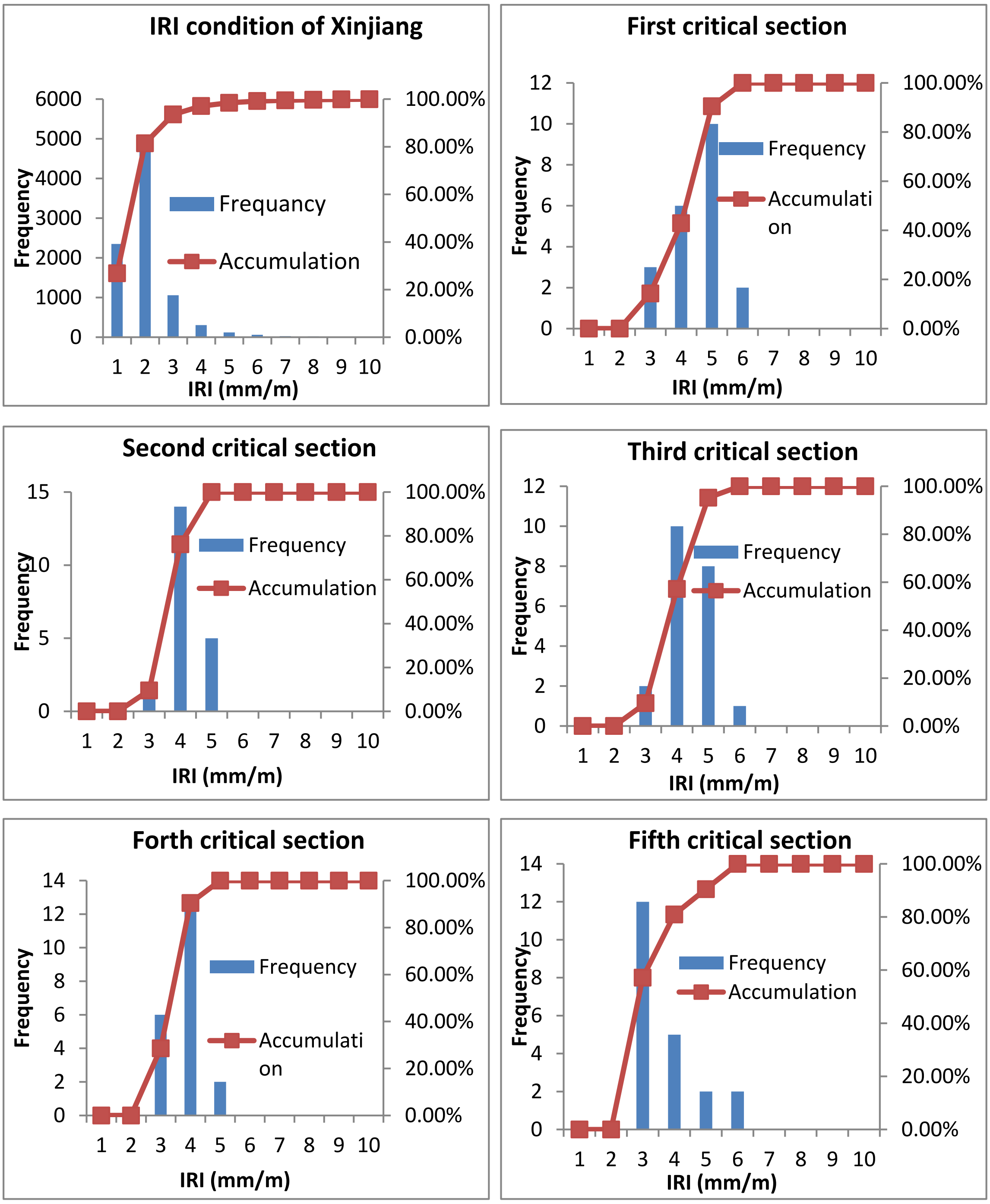

Figure 5-30 Frequency distribution of IRI for Xinjiang Expressway

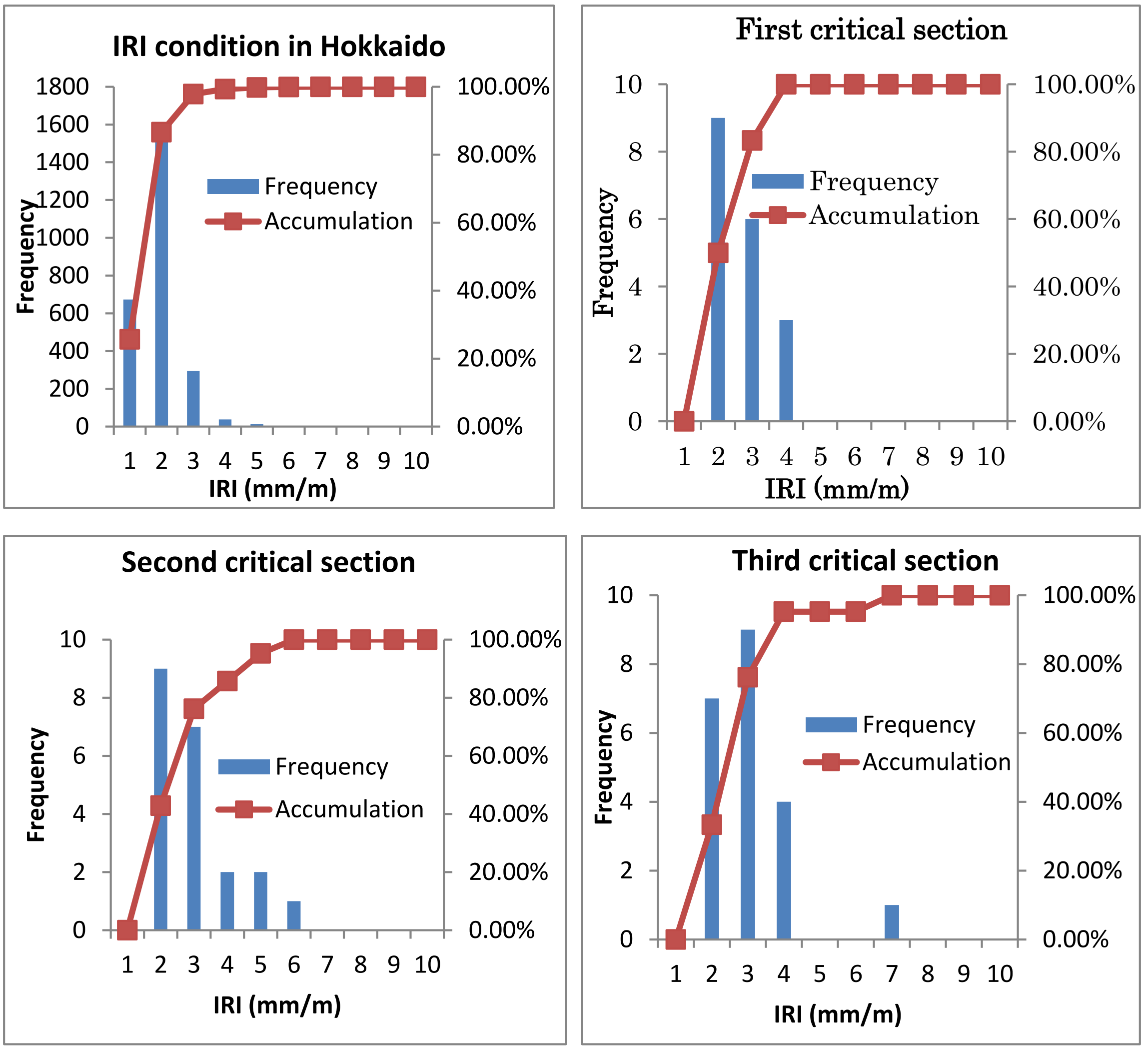

Figure 5-31 Frequency distribution of IRI for Hokkaido Expressway

The IRI conditions of both countries are clarified by histogram and cumulative curve as shown in Figure 5-30 and 5-31. In order to calculate histograms and cumulative curves, I used IRI data for each 100-meter section of the road sections.

From these results as to the situation of different two countries, it is cleared that the evenness results of 80% IRI data less than less or equal to 2 mm/m are observed for Xinjiang Expressway. On the other hand, 87% of the data less or equal to 2 mm/m of IRI value for Hokkaido Expressway. Judging from the comparative study of road conditions between different two countries has found that the evenness of the Hokkaido is better than that of Xinjiang expressway in general.

5.9.2 Ride quality evaluation in Xinjiang

The International Organization for Standardization has developed ISO 2631-1 in 1997s; the ISO 2631-1 suggested to the evaluation of the comfortability of the road users as shown in the previous chapter. As will be noted from table 5-6, the most of the frequency-weighted r.m.s. acceleration fall in the range from 0.59 m/s^2 to 0.96 m/s^2; it might cause the driver feels uncomfortable. Table 5-7 shows the acceleration range based on the frequency-weighted r.m.s. from 0.30 m/s^2 to 0.69 m/s^2; it means that, the level of ride quality in these sections fall "little uncomfortable" or "fairly uncomfortable" levels. Figure 5-32 and 5-33 shows frequency band of evaluated sections in different two days and travel speeds.

Table 5-6 Test results of r. m. s. and CF at the first-day survey

Time (s)	RMS (m/s^2)	Peak Acceleration (m/s^2)	CF
0-0.1	0.11	1.41	13.04
20.4-20.5	0.88	1.57	1.78
40.2-40.3	0.53	0.92	1.74
60.5-60.6	0.96	1.21	1.25
94.2-94.3	0.59	2.64	4.47
104-104.1	0.75	0.98	1.29
120-120.1	0.24	1.45	6.03
171.1-171.2	0.61	1.35	2.21
277.4-277.5	0.86	1.87	2.17
311.3-311.4	0.39	1.65	4.25

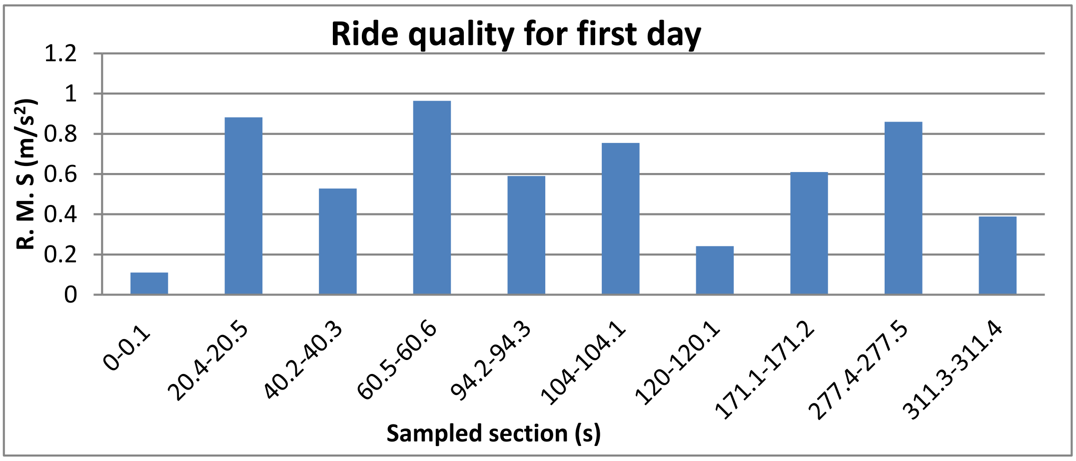

Figure 5-32 Evaluation result of Ride quality in Xinjiang

Table 5-7 Test results of r. m. s. and CF at the second-day survey

Time (s)	RMS (m/s^2)	Peak Acceleration (m/s^2)	CF
0-0.1	0.58	0.86	1.48
12.5-12.6	0.30	0.70	2.29
30.6-30.7	1.16	1.34	1.16
55.3-55.4	0.48	0.71	1.47
90.6-90.7	0.81	1.87	2.32
137.7-137.8	0.65	0.83	1.28
181.6-181.7	0.69	0.91	1.31
210.8-210.9	0.52	0.40	0.76
321.6-321.7	0.69	1.55	2.24
408.3-408.4	0.26	1.63	6.16

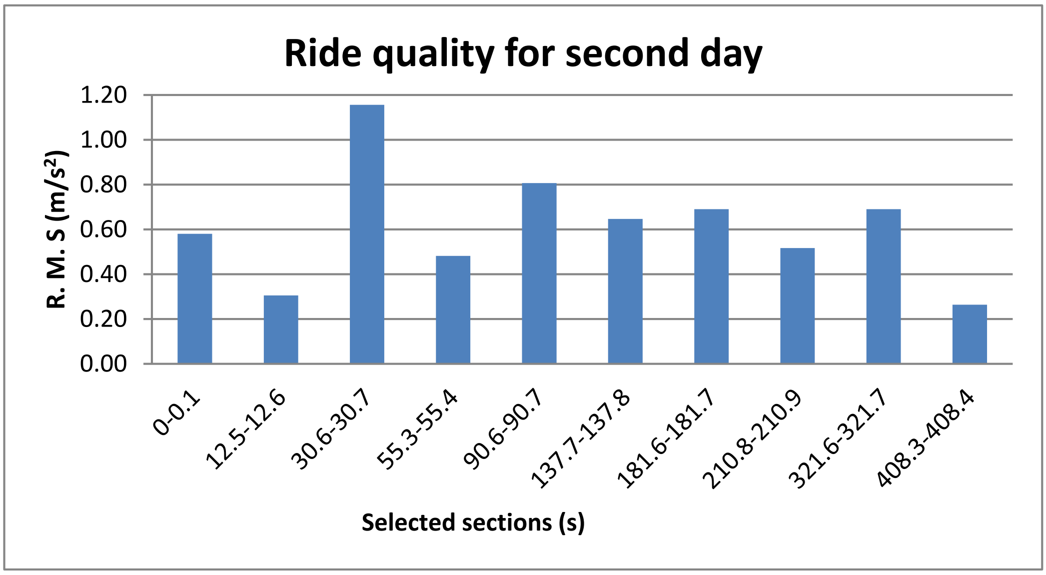

Figure 5-33 Evaluation result of Ride quality in Xinjiang

CHAPTER *6*

Conclusions

6.1 **Overall summary**

The pavement condition of the arterial roads network of two countries was analyzed using data obtained from field studies such as road roughness, road profile and vehicle acceleration. The acceleration analysis by ISO standard is a conventional approach to confirm the driving comfort because it always considers the effects of road roughness to the passenger's ride quality. 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. This study provides basic information about the road surface conditions of various road classes and seasons by using a mobile profilometer and advanced monitoring systems such as STAMPER, DRM database, and ArcGIS. The authors have demonstrated the variability of IRI by using a frequency distribution function to enhance the credibility of this study from data collection to analysis.
From the purpose of this study, the IRI measurement as a 10-m and 100-m intervals 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 a high standard highway to evaluate ride quality.

6.1.1 Summary Key Points

Definition of efficiency;
Efficiency signifies a level of performance that describes a process that uses the lowest amount of inputs to create the greatest amount of outputs. Efficiency relates to the use of all inputs in producing any given output, including personal time and energy. Efficiency is a measurable concept that can be determined by determining the ratio of useful output to total input. It minimizes the waste of resources such as physical

materials, energy and time, while successfully achieving the desired output.

Confidence of efficient road surface monitoring in this study;

- The significant advantages of compact mobile profilometer (MPM) to measuring road roughness;
  - Cost-effective and hybrid monitoring:

    MPM can enabling road surface profile measurement by using two small accelerometers without a particular vehicle and in real time.

    It is also possible to acquire road profiles not only single wheel path but also for both wheel-paths, IRI and acceleration data at one time.

- Visualization of IRI by using DRM database with GIS
  - DRM database with GIS 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.
  - DRM data with GIS strongly expected that application of the results of this study can contribute to monitoring the road roughness and identification of the road distress conditions to establish the sophistication of the PMS.

- Ride quality evaluation by using KITDS
  - KITDS has distinct 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.

- Lessons from comparison studies
  - Between two cities;

    The situation of different four road classes in two cities has demonstrated that, the evenness of the Kitami city is better than that of Kushiro city in general. The most significant reason of the pavement deterioration in Kushiro city is, it has quite long road construction history and daily traffic volume is bigger than the Kitami city at the road surface measuring locations in Kushiro city.

- Between two countries

  The comparison results of two countries Expressway contribute; establishment of efficient simple PMS for the local expressway in Xinjiang and Hokkaido will increase the life cycle of road pavement and decrease the costs of the annual maintenance or reconstruction.

  On the other hand, although the surface roughness measurement carried out in winter season on one of the main expressways in Hokkaido prefecture, the results show us not only the smooth surface condition of expressway but also shows the results of the excellent management and maintenance works. The thresholds of IRI obtained by the road administrations of the two countries have proved again with the strong results.

6.1.2 Future study plan

According to the establishing of a pavement management system, road roughness is not the only parameter that is taken into consideration to implement a PMS. In fact, structural capacity parameters (FWD), maintenance history and others are also considered to contribute in the development of a Decision Process and comprehensive maintenance program at this stage. In this study, the only a components taken into consideration were roughness.

Future study plan include:

- Completion of the database with all the types of surveys, such as surface distresses, C&M history and so on.
- Completion of the creating tabular attribute data to assist C&M works.
- Compilation of establishing simple PMS for the deteriorated surface section/

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