

# A MOBILE PROFILOMETER FOR ROAD SURFACE MONITORING BY USE OF ACCELEROMETERS

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## ABSTRACT

Surface roughness of a pavement has been recognized to be an important parameter for determining maintenance and rehabilitation needs for road networks. To predict roughness condition reliably, an objective and repeatable profilometer must be used. However, most road agencies, especially for local governments, frequently monitor and determine the pavement condition through visual inspections. This study introduces a new mobile profilometer for more effective data collection and real-time monitoring of the pavement roughness. It consists of two small accelerometers attached to a vehicle suspension system enabling directly measurement of surface profiles using the back calculation of measured acceleration of a vehicle. The measured profile data in the proposed profilometer can be immediately converted to a summary roughness index such as the IRI. The roughness information is simultaneously displayed on an onboard computer in real time. This study also presents profile measurement experiments to verify the accuracy of the new profilometer for roughness data collection and demonstrates its benefits to pavement monitoring of local roads through an application case study.

## 1. INTRODUCTION

Surface roughness of a pavement has been recognized to be an important parameter for determining maintenance and rehabilitation needs for road networks. A reliable roughness condition survey requires an objective and repeatable profile measurement, which is often called “profiling”. However, a quantitative survey using conventional profiling devices such as a high-speed profiler is restricted to once in three years by expressway authorities due to the initial and running cost of the profiler. When it comes to local governments, the frequency is still lower. Most road agencies, especially for local governments, frequently monitor and determine the pavement condition through visual inspections.

Some roughness indices such as the International Roughness Index (IRI), Root-Mean-Square Vertical Acceleration (RMSVA), Mean Absolute Vertical Acceleration (MAVA), and Slope Variance (SV) are currently in use by each road authority for predicting the condition of their pavements [1]. These indices are generally calculated based either on the two measurements: the response of a vehicle, which is known as a response type road roughness measuring system (RTRRMS) or a road surface profile. The response-based

indices are neither repeatable nor stable with time even when the same system is used. The indices can be made more useful by a valid calibration of the measuring system. The profile-based indices, on the other hand, are both repeatable and stable with time because they are based on mathematical modeling of the measured profile. They, however, have not so far been efficient and economical way due to the cost and lack of portability of profiling devices. Therefore, many road authorities require a profilometer that is inexpensive, simple to install, and simple to operate. The profilometer should be used to directly measure surface profiles and/or its summary roughness indices such as the IRI.

Against the above background, we have developed a new mobile profilometer enabling more effective data collection and real-time monitoring of the pavement roughness. The new profilometer is intended to make the cost-effective, time-stable, and easily workable profiling. It consists of two small accelerometers, which can be simply attached to a suspension system for any passenger and commercial vehicles, instead of laser sensors for conventional high-speed profilers. Nevertheless, this profilometer has been designed to directly measure the surface profiles unlike RTRMSs. In the new system, the measured profile data is immediately converted to summary roughness indices such as the IRI. This roughness information is simultaneously displayed on an onboard computer.

In this paper, we introduce the basic concepts and system configuration of the new profilometer. This paper also describes a profile measurement experiment to verify the accuracy of the profilometer for roughness data collection and demonstrates its benefits to pavement monitoring of local roads through an application case study in Hokkaido, Japan.

## 2. BASIC CONCEPTS OF THE NEW MOBILE PROFILOMETER

To address specifics of roughness measurement, or issues of accuracy, it is first necessary to define the roughness scale [2]. The IRI is a standard roughness scale related to measurements obtained by response-type profiling systems. It has been selected in the interest of encouraging use of a common roughness measure in all significant projects throughout the world. A primary conception in designing the new profilometer is that the measuring mechanism is based on the quarter-car model simulating the mathematical IRI model. The subsequent sections describe the details of the concepts.

### 2.1. Quarter-Car Model for the IRI Simulation

The IRI is a mathematical model applied to a measured longitudinal road profile. The model simulates a quarter-car model shown in Figure 1. The quarter-car model predicts the spatial derivative of suspension stroke in response to a profile using standard settings for speed and the vehicle properties depicted in Figure 1 [3].

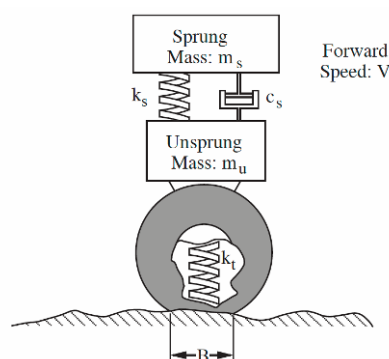


Figure 1 - Quarter-Car Model [3].

In Figure 1,  $V$ ,  $m_u$ ,  $m_s$ ,  $k_t$ ,  $k_s$ , and  $c_s$  denote vehicle forward speed, unsprung mass, sprung mass, tire spring rate, suspension spring rate, and suspension damping rate, respectively. The values called the Golden Car parameters are:  $V=80$  (km/h),  $m_u/m_s=0.15$ ,  $k_t/m_s=653$  (1/s<sup>2</sup>),  $k_s/m_s=63.3$  (1/s<sup>2</sup>), and  $c_s/m_s=6$  (1/s<sup>2</sup>). The moving average baselength (B) is set to 250 mm as a standard aspect of the IRI calculation.

## 2.2. Conception of the System Development

Nowadays, many approaches for measuring surface roughness have been developed. According to Sayers [4], the approaches can be grouped into the following four classifications on the basis of how directly their measures pertain to the IRI.

- Class 4 – a roughness measure is not reproducible or stable with time, and can only be compared to IRI by subjective estimation,
- Class 3 – a measure obtained from an RTRRMS is calibrated to the IRI scale by correlation with reference measures from a Class 1 or 2 system,
- Class 2 – a profile-based method is used that is reproducible and stable with time, and that is calibrated independently of other roughness measuring instruments, and
- Class 1 – a profile-based method similar to Class 2 is used. A profile-based measurement qualifies as a Class 1 measure if it is so accurate that further improvements in accuracy would not be apparent.

These classifications accompany a conflict between accuracy and convenience on the roughness measurement. The more accurate the measurement, the convenience is sacrificed. The more convenient the measurement, on the contrary, the accuracy is impaired. The developed profilometer is intended to combine the accuracy of Class 2 and the convenience of Class 3. In other words, it can directly measure surface profiles using vehicle dynamic responses. Figure 2 shows the profiler classification and the target of the profilometer development.

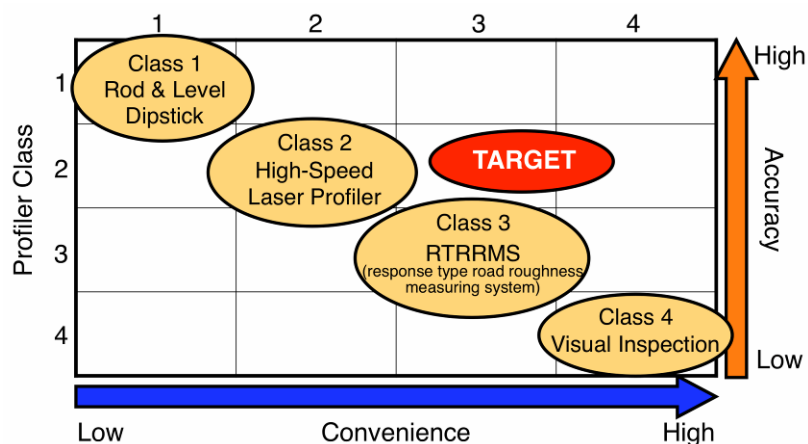


Figure 2 - Classification of the Profiler and the Target of the New Mobile Profilometer

## 3. SYSTEM CONFIGURATION AND MEASUREMENT ALGORITHM

The conventional profile-based profilers require too much cost and time for their instrumentation and operation. Although the profiling equipment has grown more robust and has become easier to operate, the RTRRMSs are still difficult to keep the accuracy and save the effort needed to obtain a valid calibration. This chapter describes system

configuration and measurement algorithm of the new profilometer which is based on the quarter-car simulation using two accelerometers.

### 3.1. System Configuration

The new profilometer can be mounted in any passenger and commercial vehicles. The system of the profilometer consists of two small accelerometers, a GPS (Global Positioning System) sensor, a transducer, and an onboard laptop computer, as shown in Figure 3. A small GPS sensor is put on near the front window of the vehicle for measuring the vehicle traveling speed and location. A transducer converts the strain of accelerometers into the electrical signal. An onboard computer records and displays the measurement results in real time.



Figure 3 - System Configuration: (a) an Accelerometer, (b) a GPS Sensor, (c) a Transducer, and (d) an Onboard Computer Displaying Monitoring Software

### 3.2. Measurement Algorithm

The main feature in designing the mobile profilometer is measuring surface profiles using accelerometers. Using accelerometers contribute to save the installation costs over the use of laser sensors. Two small accelerometers are attached to the sprung and unsprung mass at a suspension system of a four-wheel vehicle as shown in Figure 4. This instrumentation mechanically implements the quarter-car model used for the IRI simulation on a real car. The roughness measurement using the accelerometers is performed by the following procedures in real time.

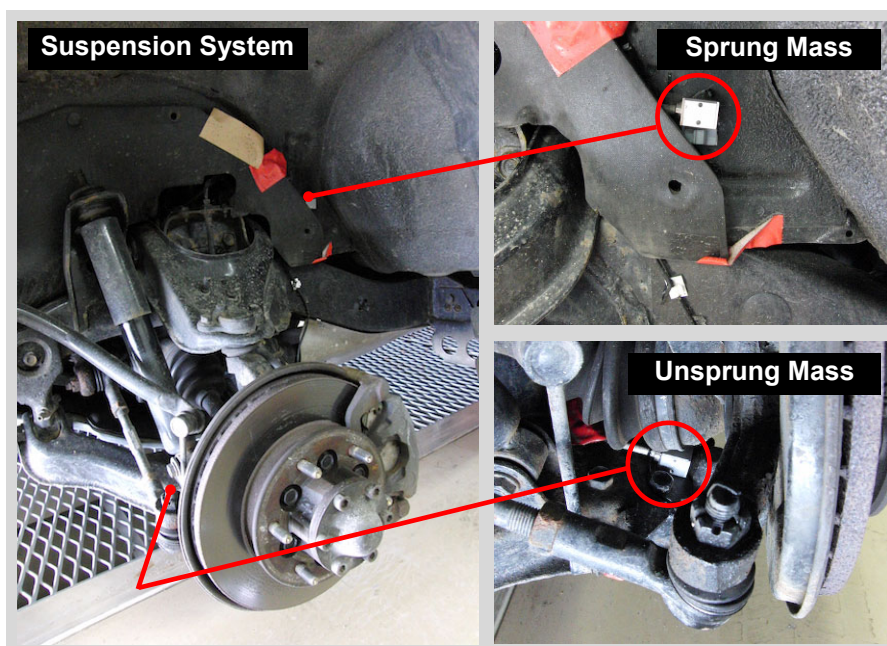


Figure 4 - Two Accelerometers Attached to a Suspension System

### 3.2.1 Acceleration Measurement

First, vertical accelerations of the sprung and unsprung masse (denoted by  $\ddot{X}_s$  and  $\ddot{X}_u$ ) are measured by using two accelerometers. The measurements are mathematically converted to the velocities and displacements of each mass by subsequent steps. Note that the two dots over a variable indicate a double derivative of the variable with respect to time.

### 3.2.2 Pre-processing

Second, as a pre-processing, the noise, trend, direct current excitation, and velocity dependence factors of vehicle vibrations are removed from  $\ddot{X}_s$  and  $\ddot{X}_u$  by use of digital filters. As the first step of this process, a Kalman filter is applied to detrend the measured acceleration. Then, as the second step, a narrow-bandpass filter of which frequency and phase characteristics are shown in Figure 5 removes the velocity dependence factors. As the final step, high frequency components over 30 Hz are removed by using a low-pass filter.

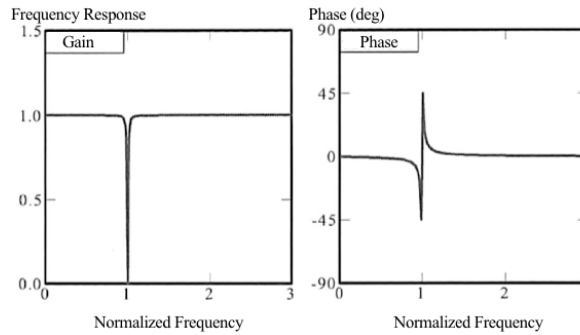


Figure 5 - Response of Narrow-Bandpass Filter

### 3.2.3 Integration of Acceleration Data

Third,  $\ddot{X}_s$  and  $\ddot{X}_u$  are integrated over time to calculate the velocities (denoted by  $\dot{X}_s$  and  $\dot{X}_u$  respectively) and the displacements (denoted by  $X_s$  and  $X_u$  respectively). Here, the dot over a variable indicates a time derivative of the variable.

### 3.2.4 Back Calculation of a Surface Profile

Fourth, a longitudinal elevation profile denoted by  $X_p$  is calculated based on the back calculation of the equations related to motions of the mechanical suspension system which reproduces the quarter-car model. The equations of motions for the suspension system are described as follows:

$$m'_s \ddot{X}_s + c'_s (\dot{X}_s - \dot{X}_u) + k'_s (X_s - X_u) = 0 \quad (1)$$

$$m'_u \ddot{X}_u + c'_s (\dot{X}_u - \dot{X}_s) + k'_s (X_u - X_s) + k'_t X_u = k'_t X_p \quad (2)$$

Here, in the equations, a single prime for each coefficient indicates the value obtained from the survey vehicle.

### 3.2.5 Golden Car Simulation

Fifth, the response of the Golden Car model to the measured profile  $X_p$  is simulated by use of the following equations.



$$m_s \ddot{x}_s + c_s (\dot{x}_s - \dot{x}_u) + k_s (x_s - x_u) = 0 \quad (3)$$

$$m_u \ddot{x}_u + c_s (\dot{x}_u - \dot{x}_s) + k_s (x_u - x_s) + k_t x_u = k_t X_p \quad (4)$$

Here, for the variables, a small letter “ $x$ ” is used instead of the capital letter “ $X$ ”.

### 3.2.6 IRI Caluculation

Finally, IRI values for an arbitrary interval are computed by using the result of the Golden Car simulation regarding the slope profile. The IRI is an accumulation of the suspension stroke of the Golden Car in response to a slope profile, normalized by the traveled distance. Thus, the IRI represents average rectified slope, with units such as mm/m or m/km. The IRI over a number of profile samples ( $n$ ) is as follows:

$$IRI = \frac{1}{n} \sum_{i=1}^n |s_{s,i} - s_{u,i}| \quad (5)$$

Here, the motion variables  $x_s$  and  $x_u$  are redefined in terms of slope valuables  $s_s$  and  $s_u$ . Note that the feature of the developed profilometer is its ability to directly obtain surface profiles. Consequently this profilometer can calculate any other profile-based indices instead of the IRI.

## 4. VERIFICATION EXPERIMENT OF THE PLOFILOMETER

To verify the accuracy of the new profilometer for roughness data collection, a profile measurement experiment was conducted in the test course of WAcorn Hokkaido Co., Ltd. The test section consisted of 200-m long asphalt pavement assuming national highway in use. During the experiment, a SUV (Sport Utility Vehicle) -type survey vehicle equipped with the new profilometer was used for measuring surface profile data of the test section. Many road authorities often use this type of vehicle for monitoring activities of their pavements. Figure 6 shows the survey vehicle used for the experiment.



Figure 6 – A SUV Type of Survey Vehicle

For the analysis, one profile of the two test runs for the driving speeds of 40, 60 and 80 km/h was selected in consideration of measurement adequacy such as consistency of driving speed and non-deficiency of data required. A reference profile, often called “true profile”, was manually surveyed by using the rod-and-level and low-speed profilometer referred as Class 1 measures on the same trace of the developed profilometer. According to the results of the experiment, in this chapter, the profile measurements of the developed profilometer are compared with the reference profile measurement.

#### 4.1. Comparison of Profile Measurements

Both the developed profilometer and the reference profilers have ability to measure road profiles at the sample interval of less than 0.05-m. In this study, the measured profiles were re-sampled at an interval of 0.1-m to reduce the computational processing effort. The profiles were then filtered to limit the wavelengths to the range between 0.5 and 50-m which define the wavy characteristics in terms of pavement roughness [5]. Figure 7 shows the measured profiles by each device. As shown in the figure, three measured profiles by the developed profilometer closely agree with the reference profile measure regardless of the driving speeds. The measure of the developed profilometer, as well as the Class 1 measures, captured a severe dip at 120-m.

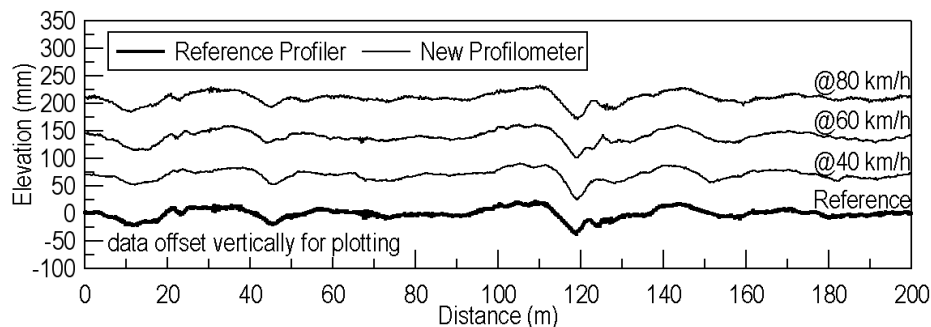


Figure 7 - Comparison of the Measured Profile Data

Figure 8 shows power spectral density (PSD) functions for the measured profiles. A PSD plot shows a characteristic of road roughness that is very important in understanding some measurement problems. The PSD amplitudes cover many orders of magnitude of a profile. As for road profile elevation, for low wave numbers, the amplitudes are commonly much higher than for high wave numbers. With this commonality, the figure reveals the same spatial characteristic of the profiles. Therefore, the results of the profile comparison show that the back-calculated profile data of the new profilometer is reliable in the road roughness characteristics.

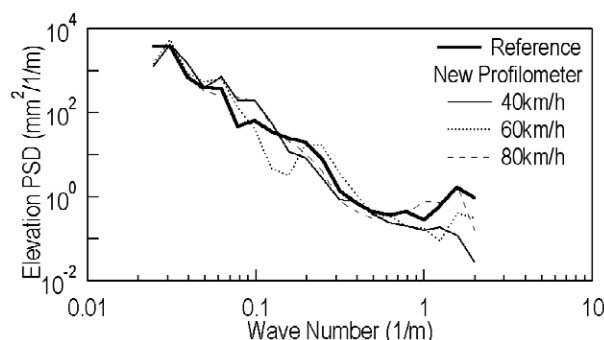


Figure 8 - Comparison of the Elevation PSD Functions

#### 4.2. Comparison of IRI Calculation Results

The new profilometer can compute the IRI from measured profile data for arbitrary intervals in real time. The IRI values are simultaneously displayed in the onboard computer. They are also stored in an electronic file formatted as comma separated value (CSV) for off-line analyses. This feature contributes to the efficient monitoring and data collection of surface roughness condition. Table 1 shows the IRI calculation results of the measured profiles for the interval of 200-m. As shown in the table, the new profilometer achieves the accuracy within 10 percent as compared with the reference measures.

Table 1 - Comparison of the IRI Values for the Interval of 200-m

The New Profilometer (Driving Speed)	Reference Profiler
2.80 (40km/h)	2.78
3.03 (60km/h)	
2.72 (80km/h)	

(Unit: mm/m)

As an advanced idea, a continuous IRI report helps to illustrate localized roughness condition. Figure 9 shows the continuous IRI on a base length of 10-m for the measured profiles. As shown in the figure, the new system accurately provides the localized roughness information. Notice the severe disease at 120-m due to the severe dip in the profile. This representation allows finding easily the most severe parts of profile in terms of surface roughness.

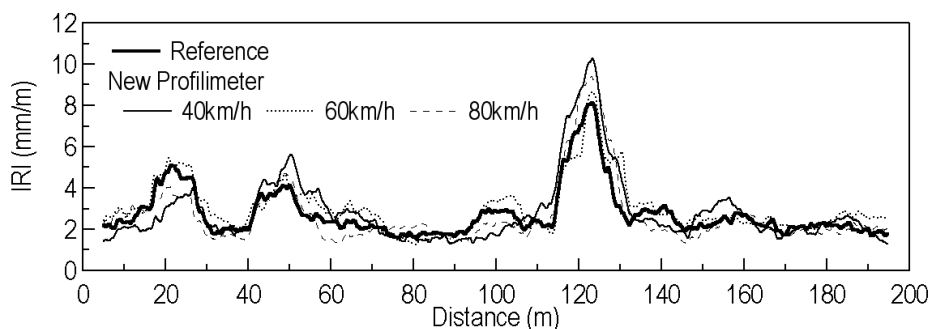


Figure 9 - Comparison of the Continuous IRI Reports on the Base Length of 10-m

## 5. AN APPLICATION CASE STUDY

For an application case study, we performed a pavement roughness data collection survey in the urban area of Kitami city, Hokkaido, Japan in November 2011. The survey widely measured the IRI values of 100-m Interval on a national highway, prefectural roads, and city roads in the area by use of the new profilometer. The profilometer was mounted on a SUV which has similar vehicle specifications to road patrol car generally used by local governments and was operated by the driving speed of normal use for each road.

### 5.1. IRI Mapping

The collected IRI information can be visually inspected through a map presentation as shown in Figure 10. In the figure, the map shows roughness condition categories for the road network. The selected levels of IRI categories were chosen for demonstration purpose, and can be modified to reflect the user's criteria for pavement quality. As shown in the figure, deteriorated pavement sections can be clearly identified. This IRI mapping allows road authorities to plan pavement maintenance and rehabilitation projects by evaluating the roughness severity at the network level.

### 5.2. Frequency Distribution of IRI in the Urban Area

A frequency distribution of the IRI values obtained by the survey was performed to demonstrate the IRI distribution for the national highway, prefectural roads, and city roads. Results obtained from this analysis can be used by road authorities in evaluating the current status of roughness levels against an IRI distribution of the whole of a road network.



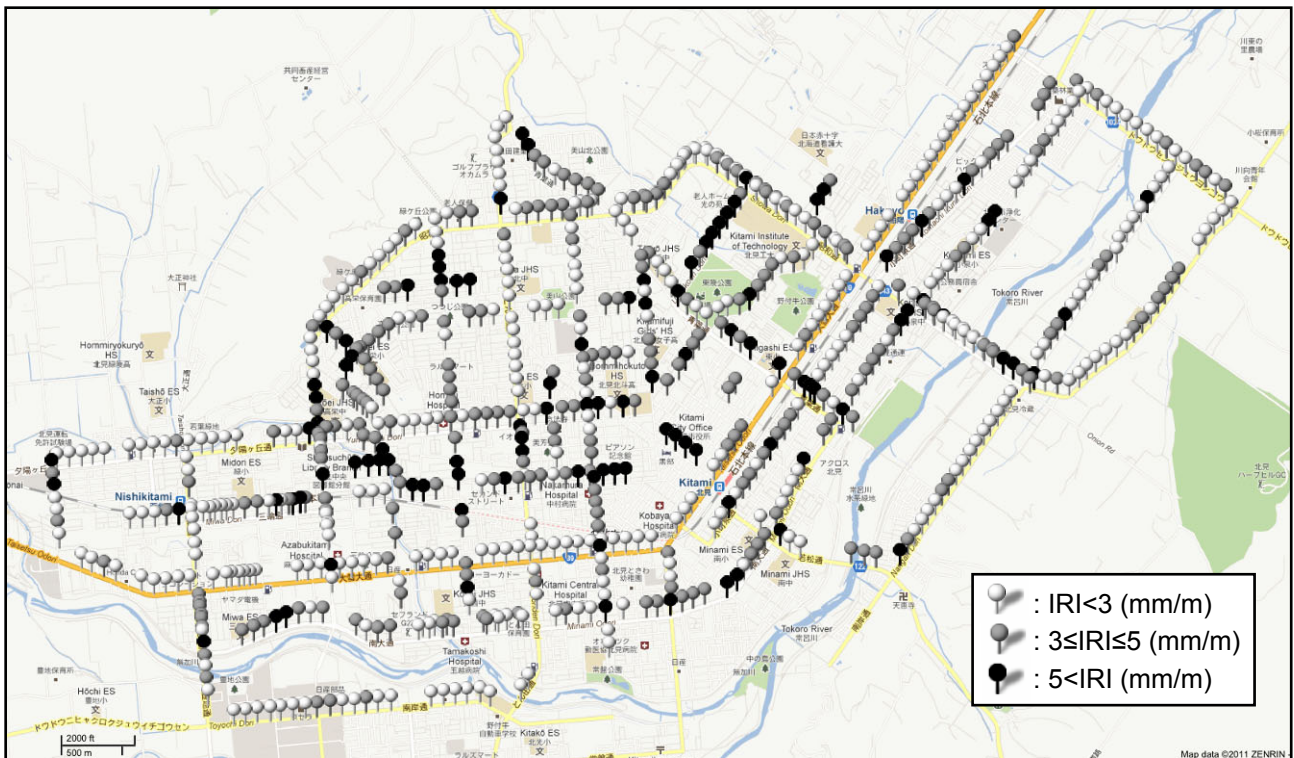


Figure 10 - Map Presentation of Levels of IRI Categories (IRI Mapping) in Kitami

Figure 11 shows a frequency distribution and its cumulative distribution function of the IRI for each class of roads. In the data collection survey, we obtained 81, 338, and 435 of 100-m pavement sections from the national highway, prefectural roads, and city roads. Although the results of the frequency distribution will be improved after more data collection surveys have been performed, this IRI distribution contributes to prioritize budget allocation for pavement maintenance and rehabilitation projects according to the current level of roughness in the road network.

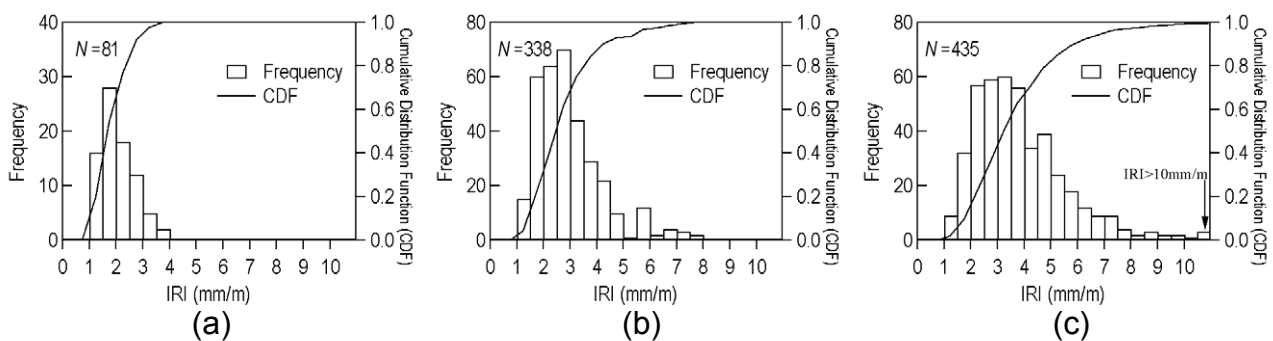


Figure 11 - Frequency Distribution and Cumulative Distribution Function of IRI for (a) a National Highway, (b) Prefectural Roads, and (c) City Roads

## 6. CONCLUSIONS

Today, many local governments require a proper method of monitoring their pavement roughness. This paper proposed a new mobile profilometer for more effective data collection and real-time monitoring of road surface roughness condition. The system of the profilometer uses two accelerometers mounted on any passenger and commercial vehicles to measure surface profiles based on the mechanical reproduction of the quarter-car model. The profilometer achieves both of the accuracy of Class 2 measures and the convenience of Class 3 measures. In other words, it enables directly calculation of profile-

based indices based on the vehicle response unlike the conventional RTRRMSs that compute roughness indices by empirical correlations between roughness profiles and vehicle motion.

According to the validation experiment results, the profiles measured by the new profilometer closely agreed with the reference profile measured by the Class 1 measures. The PSD analysis also verified the accuracy of the new profilometer in terms of the spatial characteristic of the profile elevation. Unlike the conventional response-type profilers, the new profilometer can directly compute the IRI for arbitrary intervals based on the measured profile data. As for the IRI measurement, the new profilometer achieved the accuracy within 10 percent as compared with the reference measures. For more advanced pavement monitoring approach, the new profilometer provided the adequate localized roughness information based on the continuous IRI for the measured profiles. These results show that the back-calculated profile data of the new profilometer is reliable for measuring the road roughness characteristics.

This paper also presented an application case study of pavement roughness data collection on a national highway, prefectural roads, and city roads in the urban area of Kitami city. The result showed that the map presentation visually identified deteriorated pavement sections in terms of the IRI in the road network. This mobile profiling by the new profilometer contributes to plan pavement maintenance and rehabilitation projects by evaluating the roughness severity at the network level. The frequency distribution of the measured IRI was performed to evaluate the current status of roughness levels against the IRI distribution of the whole of a road network. The IRI distribution enables road authorities to prioritize budget allocation for pavement maintenance and rehabilitation projects according to the current level of roughness in the road network.

## **ACKNOWLEDGMENT**

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