Real-time Monitoring System Using Dynamic Response of Vehicles and Its Application for Road Investigation in Kyrgyzstan

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ABSTRACT: The Government of the Kyrgyz Republic has implemented project for building the capacity of road maintenance in Kyrgyz in cooperation with Japan International Cooperation Agency. In Kyrgyz, most of transports depend on road traffics. Nevertheless, even arterial roads have many potholes and damaged shoulders; they have not been maintained sufficiently except those repaired by international donors. In the cooperative project, the Kyrgyz government institution and JICA has worked on the renewal of road inventory. As a part of the project, JICA has considered measuring International Roughness Index. On the other hand, the real-time monitoring system using dynamic response of vehicles has been proposed for inspection of road surface conditions. The monitoring system is able to grasp physical conditions of road surface quantitatively, objectively, promptly and inexpensively. The system estimates International Roughness Index (: IRI) by capturing the vehicle's dynamic response from vertical acceleration. In this study, a real-time monitoring system using dynamic responses of a vehicle is introduced for road inspections in the cooperative project. Firstly, Kyrgyz Roughness Index is defined as an index for evaluating road surface roughness in Kyrgyz. Then, surface conditions of major arterial roads in Kyrgyz were measured by a local car with the system. From measurement results, analytical approaches are given to make road maintenance scheme more appropriate and efficient.

KEY WORDS: Maintenance, monitoring, road surface roughness, IRI.

1 INTRODUCTION

In the Kyrgyz Republic, most of transports depend on road traffics. The overland transports carry out important traffic connections in Central Asia and thus South-West Asia, and also basic services in local communities. Nevertheless, apart from roads improved by international donors, development and maintenance of a road system is not thorough enough in the country; the proportion of paved roads is 40 percents. Even arterial roads have many potholes and damaged shoulders. It is estimated that about 200km road system has gone out of function every year as a result of inadequate maintenance. Road inventory that is a basic tool of the road maintenance management planning has not been updated since the disintegration of the Soviet Union. Designing methods of pavement have not been standardized with a confused mixture of a design standard in the time of the Soviet Union and the standard of American Association of State Highway and Transportation Officials. Furthermore there is no firm budget system for road maintenance and improvement projects. In these situations, existing condition of roads needs to be grasped, and the road maintenance system should be reconstructed to deal with problems.

The Kyrgyz Government has implemented the project for the capacity building of road maintenance in Kyrgyz (hereinafter referred to as "the project") in cooperation with Japan International Cooperation Agency (hereafter referred to as "JICA") since April 2008. The Ministry of Transport and Communications that is the road maintenance organization in Kyrgyz (hereinafter referred to as "MOTC") and JICA carry out on the renewal of road inventory to arrange information of road conditions, which should be shared and standardized among organizations concerned. As one part of the project, JICA has considered measuring International Roughness Index: IRI as baseline data for utilizing to select cooperation priority sections.

The present monitoring works for measuring IRI are conducted by several kinds of method and system, for instance a road-profiling vehicle, a portable road profiler and numerical calculation, and simplified monitoring systems, which have been developed by research institutions or developers. A road-profiling vehicle is able to capture precise data of physical road conditions quantitatively, but it is too expensive and time-consuming to utilize in the project. A portable road profiler is not suite to practical road monitoring because the distance that can be measured once by the profiler is extremely short, and a long time is required for the measurement. The project requires that road conditions are grasped in short term, and also the system installed into Kyrgyz in the project will be continually operated after implementation period. Simplified monitoring that can measure the road properties simply and promptly with low-cost is the most suitable.

On the other hand, a monitoring system referred to as "*Vehicle Intelligent Monitoring System: VIMS*" has been proposed for inspecting road surface conditions objectively, promptly and inexpensively (Fujino et al. 2005). The system consists of an accelerometer, GPS and portable PC installed on an ordinary car, and it estimates road roughness by capturing the vehicle's dynamic response from vertical acceleration. The system achieves quantitatively measurement over a wide area in a short time (Furukawa et al. 2007). So the VIMS has introduced into the project to measure roughness of roads in Kyrgyz.

This paper presents a monitoring system for road inspection and its application for road investigation in Kyrgyz. Firstly, *Kyrgyz Roughness Index* is defined as an index for evaluating road surface roughness. A local car with system components of the VIMS measured surface conditions of major arterial roads. From measurement results, analytical approaches are given to make road maintenance scheme more appropriate and efficient.

2 TARGET AND OBJECTIVE OF STUDY

A basic policy of the project is to support MOTC to recover and improve road maintenance capacity of Kyrgyz by developing institutions, techniques, and human resources in field of construction and equipment/material managements. The project focuses on renewal of road inventory to enable MOTC adequately to plan and to execute road maintenance and repair operations.

In this study, based on the target of the project, physical condition of road and situation of road maintenance in the object route are investigated by executing measurement with the VIMS. This study also considers possibility of the VIMS introduction in Kirgiz; moreover the effectiveness of the VIMS in other developing countries.

3 VEHICLE INTELLIGENT MONITORING SYSTEM

3.1 Outline of the System

General idea of the VIMS is simple, inexpensive, quantitative, frequent monitoring and real-time analysis. The VIMS consists of an accelerometer, GPS and portable PC, and they are installed on an ordinary car. Then, the system captures the vertical acceleration while the vehicle travels at a constant speed of 60km/h on the road. From the vehicle response, the system calculates IRI. System components and the place for fixing accelerometer are illustrated in Figure1 and Figure2, respectively.

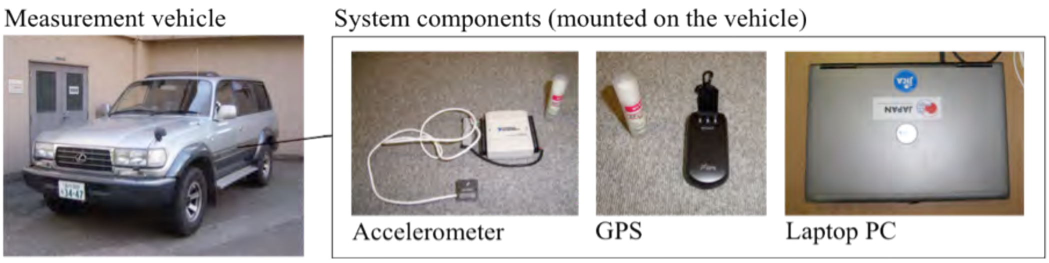

Figure1: System components of the *VIMS*; a measurement vehicle, an accelerometer, a GPS unit, and a laptop PC

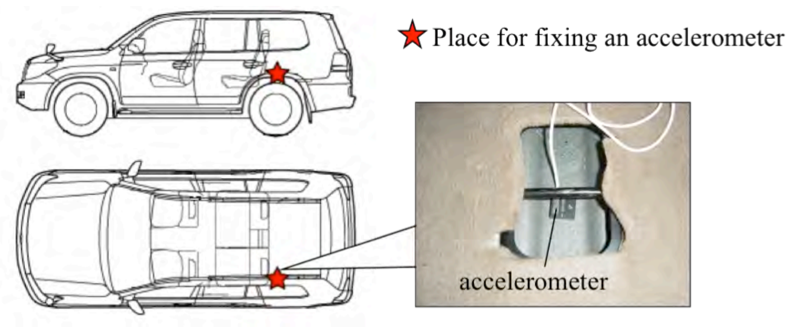

Figure2: Place for fixing an accelerometer; it is point for measuring acceleration responses of the measurement vehicle

3.2 IRI Estimation by VIMS

IRI is a widely-used roughness index proposed by the World Bank (Sayers et al. 1985), and is used for evaluating road conditions in many road projects. The index is defined as the accumulated relative velocity between the sprung weight and the un-sprung weight of a

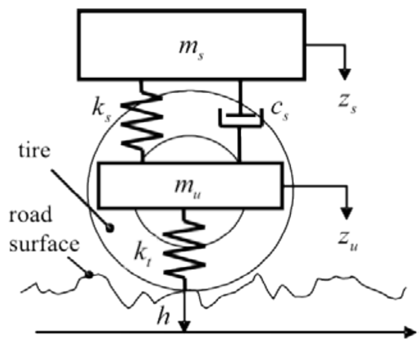

Figure3: *Quarter car* model; c_s is the damping ratio of suspension, k_s is the suspension's coefficient of elasticity, k_t is the tire's coefficient of elasticity, m_s is sprung weight, weight supported by one wheel, and m_u is un-sprung weight.

quarter car divided by travel distance. *Quarter car* is an ideal one-axis car with specified mechanical properties, shown in Figure3. Response velocity of *quarter car* is given by simulation in which *quarter car* travels on a profile of real road to be IRI-estimated at a steady speed 80km/h. The definition of IRI is described in equation (1).

$$IRI = \{\int_0^{L/V} |\dot{z}_s - \dot{z}_u| dt\}/L \tag{1}$$

where z_s and z_u are vertical ground speed [mm/s] of the sprung weight and un-sprung weight, respectively, L is travel distance [m], V is running speed [22.2 m/s = 80 km/h] and dt means integration in time domain.

The IRI estimation described above is a conventional procedure in which a profile of real road surface is absolutely necessary; therefore it is very time-consuming and requires expensive equipments for collecting a profile of road. The VIMS estimates IRI in a short time through the following procedure:

(i) Firstly, vertical acceleration response of *quarter car*'s sprung weight is estimated by one of the measurement vehicle using Parseval's theorem as described in equation (2).

$$RMS^2 = \int_0^T \ddot{z}_s^2(t)dt = \int_{-\infty}^{\infty} |\ddot{z}_s(\omega)| d\omega = \int_{-\infty}^{\infty} |\ddot{z}_m(\omega)|^2 |T(\omega)|^2 d\omega \tag{2}$$

where RMS denotes the root mean square of vertical acceleration response of *quarter car*'s sprung weight $\ddot{z}_s(t)$, $|\ddot{z}_s(\omega)|$ and $|\ddot{z}_m(\omega)|$ are given by the Fourier transform of $\ddot{z}_s(t)$ and measured vertical acceleration of the measurement vehicle $\ddot{z}_m(t)$, respectively. $|T(\omega)|$ denotes a kind of transfer function that is defined as the ratio of *quarter car*'s acceleration amplitude to the measurement vehicle's one, and ω means quantity in spatial frequency domain.

(ii) The transfer function from the measurement vehicle's response to *quarter car*'s one $|T(\omega)|$ is defined as equation (3).

$$|T(\omega)| = \sqrt{\frac{P_{QC}(\omega)}{P_{mv}(\omega)}} \tag{3}$$

where $P_{QC}(\omega)$ and $P_{mv}(\omega)$ are power spectrum density of acceleration response of quarter car and the measurement vehicle, respectively. In this study, the transfer function is estimated by measurement data recorded at test roads that contain widely distributed profiles. Figure4 shows the transfer functions.

(iii) In general, response of vehicle is correlated with IRI. In this study, a significant correlation between IRI and the root mean square of *quarter car*'s acceleration response is ascertained at the test course. The relationship is described as equation (4) and shown in Figure4. A coefficient α is given as 0.0476 by regression of measurement results. Finally, the root mean square of the quarter car's acceleration is converted into IRI. Procedure of IRI estimation is illustrated in Figure5.

$$IRI\,[mm/m] = \alpha \times RMS\,[gal] \tag{4}$$

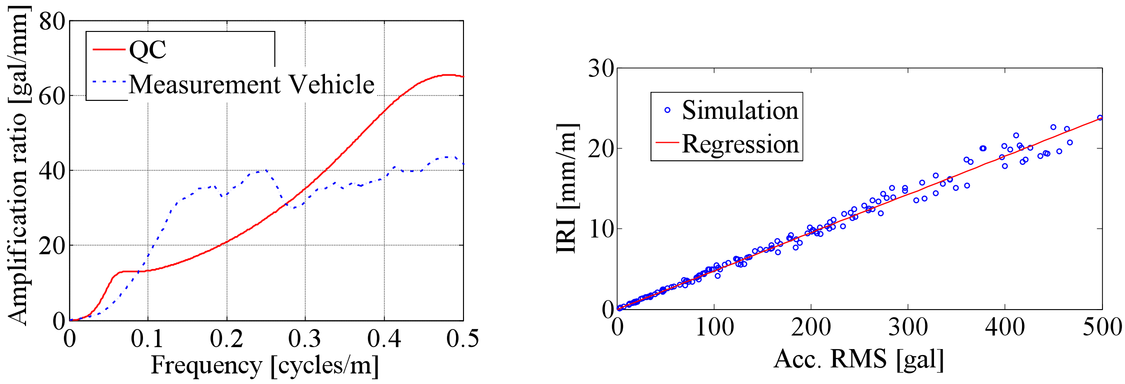

Figure4: The transfer function from the measurement vehicle's response to *quarter car*'s one (on the left), correlation between IRI and the root mean square of *quarter car*'s acceleration response (on the right)

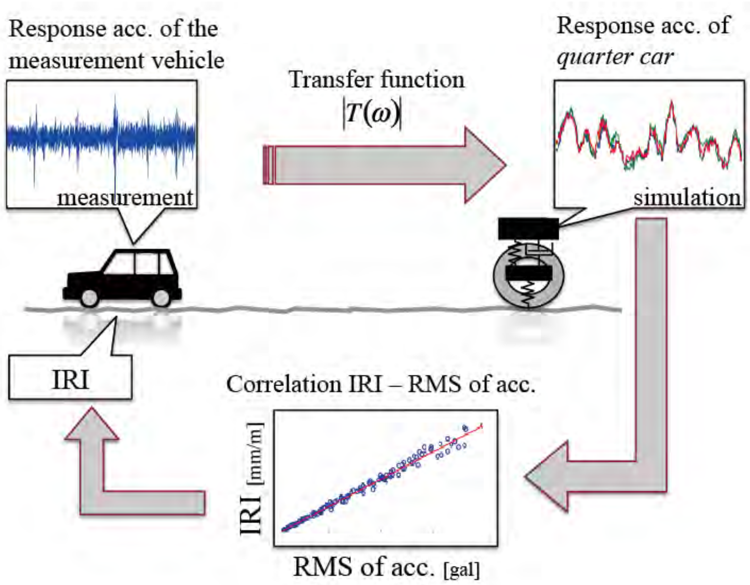

Figure5: Procedure of IRI estimation by the VIMS

3.3 Repeatability of IRI Estimation

Several experimental measurements evaluate repeatability of the system for estimating IRI.

Conditions are standardized each measurement. Figure6 shows results of each measurement that repeatability of acquisition of acceleration response and the root mean square of acceleration response are enough to estimate IRI.

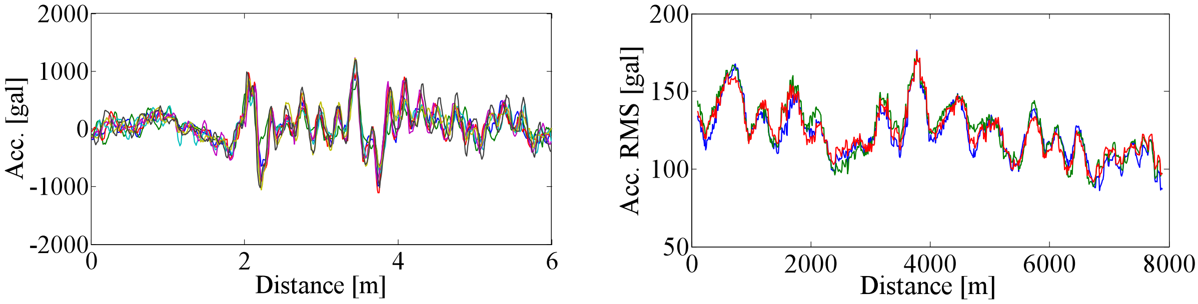

Figure6: Repeatability of acquisition of acceleration response (on the left) and the root mean square of acceleration response (on the right)

4 MONITORING ROAD ROUGHNESS IN KRYGYZ

4.1 Measurement System in Kyrgyz

The VIMS has been applied to road monitoring in Kyrgyz. In the operation, acceleration responses of a Russian-made vehicle, which is shown in Figure7, at travel speed of 60km/h are measured and calculated to estimate road roughness. System components expect for the measurement vehicle and installation procedures follow the original system as shown in Figure1. An accelerometer is installed at the place as shown in Figure7.

The VIMS is originally designed on assuming the vehicle that is shown in Figure1 as the measurement vehicle. Because of a difference in vehicle used, road roughness calculated by the system in Kyrgyz is initially different from IRI. The roughness index is tentatively assigned as "*Kyrgyz Roughness Index*" (hereinafter referred to as "KRI"), which is calculated by the same procedure as the original system. The unit of KRI is also mm/m.

Figure7: Measurement system in Kyrgyz; measurement vehicle of Russian make, installation of an accelerometer

4.2 Results of Measurement

Measurement results of all sections being measured in the operation are shown on a map in Figure8. In Figure8, sections in which road roughness is remarkably large are plotted with balloons in different colors according to the extent of its roughness. Then, two analyses based on the survey reveal several findings. Figure9 shows distribution of KRI in all sections being measured in the operation. The sections have paved roads and also rough gravel roads, and the result shows a wide-ranging distribution of KRI from 2.0[mm/m] to 17.7[mm/m]. The average of KRI in the sections is 5.2 [mm/m].

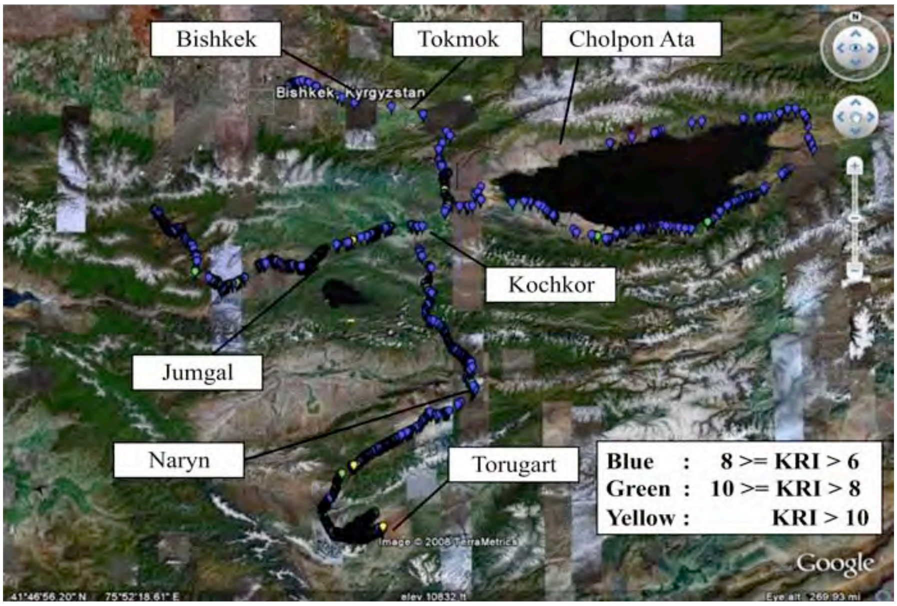

Figure8: Measurement results of all sections being measured in the operation; "KRI" is roughness index defined with reference to IRI

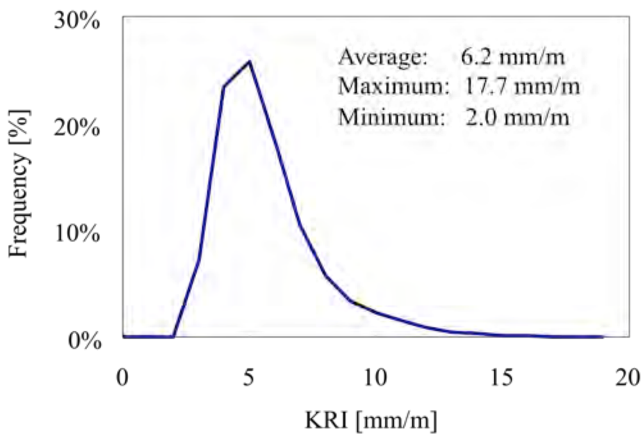

Figure9: Distribution of KRI in all sections

4.3 Data analysis and application

Road maintenance management should be considered based on assessment of road condition with quantity data being regularly updated. Some kinds of analysis can be made with measurement results by the VIMS.

In case of need for assessment by management section, comparison of measurement results by section. Figure10 shows the distribution of KRI by section that are divided as sections in Table1. In the analysis of the distribution of KRI, years in service, traffic volume, and so of each route, differences of tendency toward deterioration of each road become apparent. Comparison of measurement results by section is helpful to decide a road management plan and budgetary allocations.

Analysis by classifying KRI criteria is useful for fixing a priority order on maintenances. Figure11 shows measurement results classified by KRI criteria in the same section. As shown in Figure11, sections in which road roughness shows large value are quite obvious. Priority of maintenance should be given in the sections viewed from road roughness.

Regularly and frequently monitoring by the VIMS and analyzing acquired data in the time series can quantitatively identify the progression of aging deterioration of roads. Accumulating monitoring data and investigating the change in KRI and other conditions of road make an effective database for deciding a long-term plan of road maintenance, and forecasting model of the deterioration progress of the road. Through this application, the VIMS is shown to be a useful monitoring tool, providing the quantitative road roughness estimation. The quantitative estimation allows a further analysis on road infrastructure conditions in response to the demand of an organization for management.

Table1: Measurement results by section being measured

Section No.	Measurement section	Distance of section [km]	Average of KRI [mm/m]
1	Cholpon Ata - Karakol - Kochkor	413.2	4.57
2	Naryn - At Bashy – Torugart	170.6	7.55
3	Kochkor – Naryn	106.2	5.52
4	Kochkor - Jumgal – Bishkek	263.8	4.87
5	Kochkor - Tokmok – Bishkek	162.2	4.73

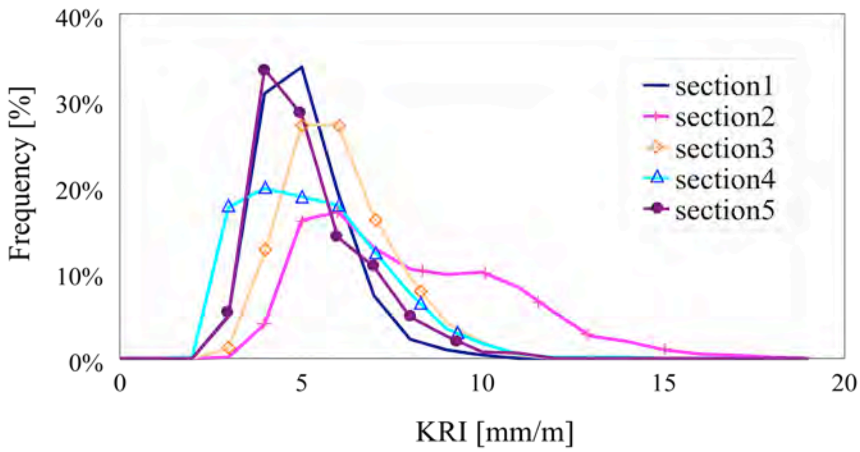

Figure10: Distribution of KRI by section being measured

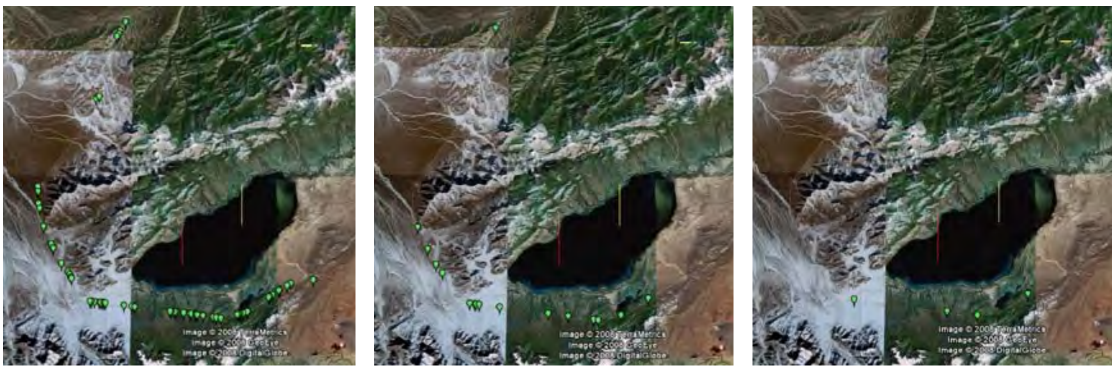

Figure11: Results classified by KRI criteria; criterion equal to 12 (left), 14 (center), and 16

(right) of KRI

5 CALIBRATION OF ROUGHNESS INDEX

Because different measurement vehicles result in different vehicle responses, and final index estimation becomes also different value, the VIMS requires a calibration method for the difference of vehicles.

In this study, calibration is achieved by introducing transfer functions between the acceleration response of the original vehicle and those of other vehicles. Measurements were conducted with the original vehicle, a minivan (1-box car) and a sedan on a section of the Tokyo Metropolitan Expressway. Conditions of the measurements were standardized each time. Then, the transfer function between the original vehicle and the other is derived by a ratio of the power spectral density of the vehicle's acceleration response to the original vehicle's one. Then, instead of the original transfer function, the transfer function for the other vehicle is adopted in the estimating process. For verifying the accuracy of calibration, several measurements were conducted on other section of the Tokyo Metropolitan Expressway. The average IRI of the measurements with three different vehicles are calculated for every 200m with overlapping 150m. The left side figure in Figure12 shows the results without calibration and the right side figure in Figure12 shows the results with calibration. The average estimations of the measurements for each vehicle were calculated. From these results, the vehicle calibration is shown to be possible by the method mentioned above.

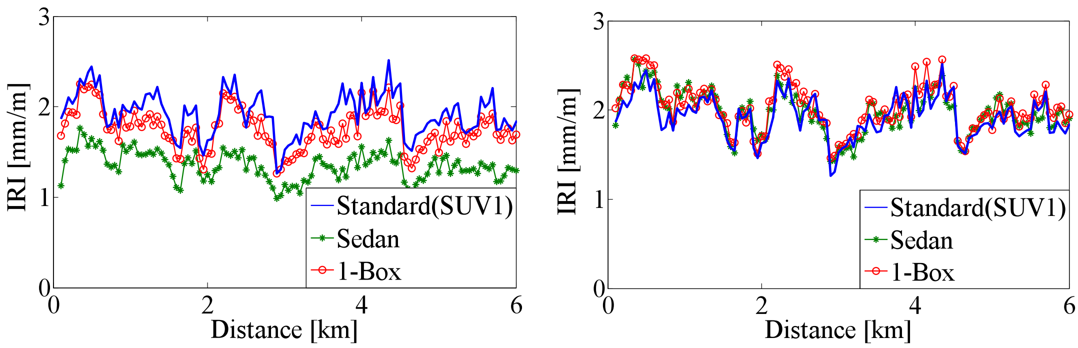

Figure12: Result of calibration; IRI estimation without calibration (on the left), and IRI estimation with calibration (on the right)

6 CONCLUSIONS

In this study, based on the project of the Kyrgyz government and JICA, physical condition of road and situation of road maintenance are investigated by executing measurement with the VIMS.

The VIMS has been applied to monitor the arterial road and other major section in the Kyrgyz Republic, and some kinds of analysis were made with measurement results by the VIMS. In Kyrgyz, The roughness index was tentatively assigned as *"Kyrgyz Roughness Index: KRI"* because of a difference in the measurement vehicle.

In the analysis of the distribution of KRI, years in service, traffic volume, and so of each route, differences of tendency toward deterioration of each road become apparent. Comparison of measurement results by section is helpful to decide a road management plan and budgetary allocations. Analysis by classifying KRI criteria is also useful for fixing a priority order on maintenances.

Regularly and frequently monitoring by the VIMS and analyzing acquired data in the time series can quantitatively identify the progression of aging deterioration of roads. Accumulating monitoring data and investigating the change in KRI and other conditions of road make an effective database for deciding a long-term plan of road maintenance, and forecasting model of the deterioration progress of the road.

The calibration method for difference of vehicles was developed. The transfer functions between vehicles were derived with the measurement data on the same course. Using these transfer functions, the IRI estimations of other vehicles can be calibrated. The measurement results of the other types of car were calibrated, and the variability between the result of the original and those calibrated is less than 7%. The calibration method is shown to be successful.

As a final remark, VIMS is a useful road-surface assessment tool and can be used for routine monitoring or other analyses. However, further improvement can be made to put it into practical use. Establishing the speed calibration method or more versatile vehicle calibration method might be such examples. So, further studies will be continued.

REFERENCES

Fujino, Y., Kitagawa, K., Furukawa, T., Ishii, H., 2005. *Development of Vehicle Intelligent Monitoring System (VIMS)*, SPIE's Smart Structures/NDE Joint Conference on Sensors and Smart Structures Technologies for Civil, Mechanical and Aerospace Systems, San Diego, USA.

Furukawa, T., Fujino, Y., Kubota, K. and Ishii, H., 2007. Real-Time Diagnostic System for Pavements Using Dynamic Response of Road Patrol Vehicles (VIMS), The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-3), Vol. 3, Vancouver, Canada.

Sayers, M. W., Gillespie, T. D. and Paterson, W. D. O., 1985. *The International Road Roughness Experiment*, World Bank Technical Paper, Number 45.