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REAL-TIME DIAGNOSTIC SYSTEM FOR PAVEMENTS USING DYNAMIC RESPONSE OF ROAD PATROL VEHICLES (VIMS)

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Abstract

Visual checking by road patrol vehicles, which is one of the inspection methods used for pavements, is highly dependent on the skill of the inspector, and therefore quite subjective. The road profiler system which can capture the surface condition of the road accurately, on the other hand, has a very high operating cost and it takes a long time to get the results. Therefore a new assessment technique that allows a real-time, objective and low-cost inspection is needed for the maintenance of pavements and expansion joints. “Vehicle Intelligent Monitoring System (VIMS)” developed for this purpose is described in this paper. VIMS uses a road patrol vehicle, equipped with an accelerometer and a GPS, running on the road, calculates an index based on acceleration response of the vehicle, and the abnormal location would be displayed on the map based on the index. In this paper, the repeatability of dynamic response of a vehicle is confirmed and the relation between acceleration and International Roughness Index (IRI). This system was tested along the Tokyo Metropolitan Expressway, and the effectiveness to the road maintenance management is confirmed.

INTRODUCTION

In many countries, roads have aged and require maintenance. Pavements are damaged because they receive load directly from the vehicle, and the damage has a large influence on neighborhoods and drivers, for example, the traveling performance, the accident generation, safety, etc. of the vehicle. Therefore, to detect conditions of pavements is a very important issue for road maintenance. There are mainly two detection methods to inspect pavements: visual checking from a road patrol vehicle and detection by a road profiler[1]. Although visual checking from a road patrol vehicle is easy without using specific instrumentation, the problem is that it is highly dependent on the skill of the inspector. On the other hand, a road profiler can capture accurately the road surface condition. However, the measurement frequency cannot be higher because the operating cost is very high and the system cannot show the real-time condition because the processing of surface conditions from the measurement needs a few months to be completed. A new system, which can monitor in real-time the condition of the pavement objectively, at a low-cost, and high accuracy, is required for the maintenance of pavements and the prevention of accidents. In this work, a new detection method, VIMS (Vehicle Intelligent Monitoring System[2-7]), using dynamic response of a road patrol vehicle is suggested (Figure 1). In this system, a road patrol vehicle equipped with an accelerometer and a GPS, running on the road, calculates an index based on acceleration response of the vehicle, and accumulates the data into a server. When a road administrator accesses the server, the abnormal location would be displayed on the map based on the index.

The three methods of inspection are compared in Fig. w with respect to their cost and accuracy. VIMS can objectively detect damage as low as the existing detection method can by using a road patrol car and adding to visual checking. High frequency checking is possible by using simple instruments although it is not so accurate as a road profiler.

In developing this system, assignments are to derive a check index from acceleration of a vehicle and to develop a diagnostic system aimed at supporting road maintenance. Check index being studied in this research is IRI; International Roughness Index.

DEVELOPMENT OF MEASUREMENT SYSTEM AND DATA ACQUISITION SYSTEM

Measurement system: constituting hardware and data acquisition system, getting acceleration data and GPS data, are needed to get the dynamic response of a road patrol car on the road. In developing measurement system and data acquisition system, objectives are: able to get accurate data, not needing complex rebuilding, low cost, and able to operate easy. These are detailed below.

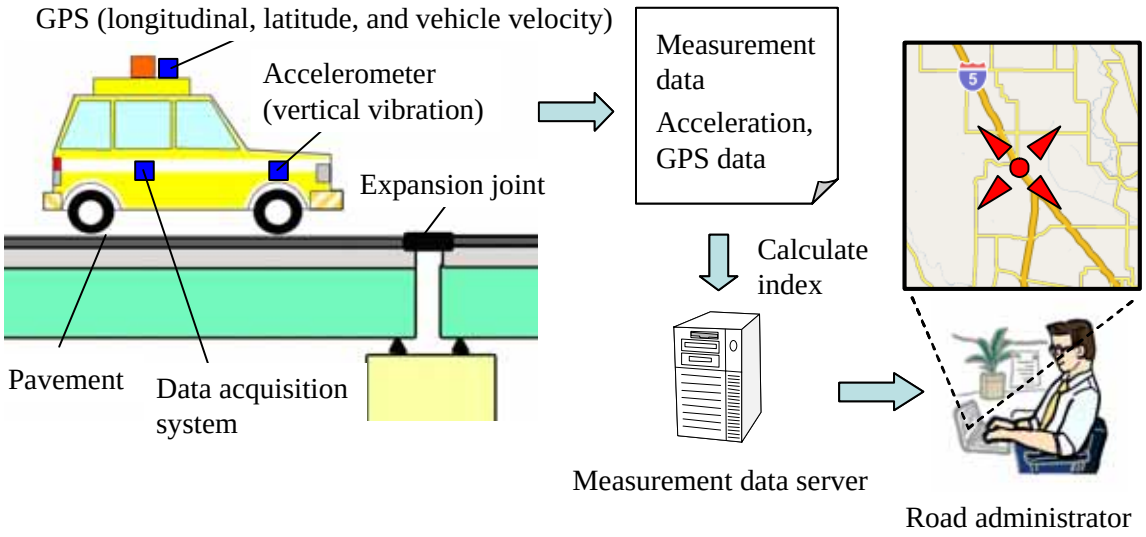


Figure 1. Outline of VIMS

Measurement System

In measurement system (Figure 3), the type of the measurement vehicle is the same as a common road patrol vehicle to get the same level of dynamic response as a road patrol vehicle for visual check. An accelerometer which measures the vertical vibration is located on the left rear upper spring of the vehicle because pavements receive damages on the left rutting from transverse slope and handle operating have an influence on the vibration; the measurement vehicle is front wheel drive. A GPS using vehicle speed pulse is selected because it can receive signals where signal reception is bad and can get the moving speed as accurate as possible.

Data Acquisition System

In data acquisition system, acceleration data and GPS data are synchronized by LabVIEW7.1 (National Instruments) to match acceleration response to location information. Specifically, this system triggers the footer output when this system gets GPS data and acceleration data is started to get with next GPS data.

IDENTIFICATION OF VEHICLE'S LOCATION AND REPEATABILITY OF ACCELERATION DATA

An acceleration data and a GPS data are taken twice on the same day and the same route by this system. Driving speed of the vehicle is maintained almost constant at 60km/h. In the processing of data,

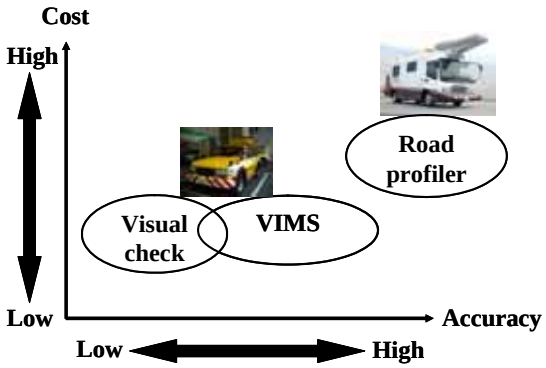


Figure 2. Comparison of inspection methods

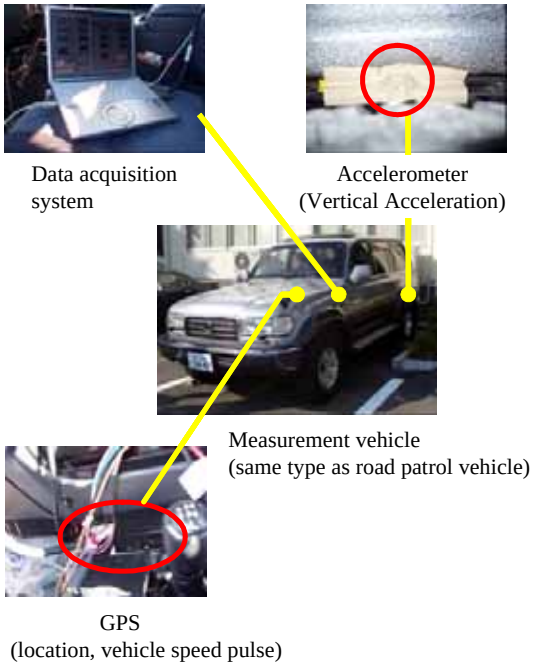
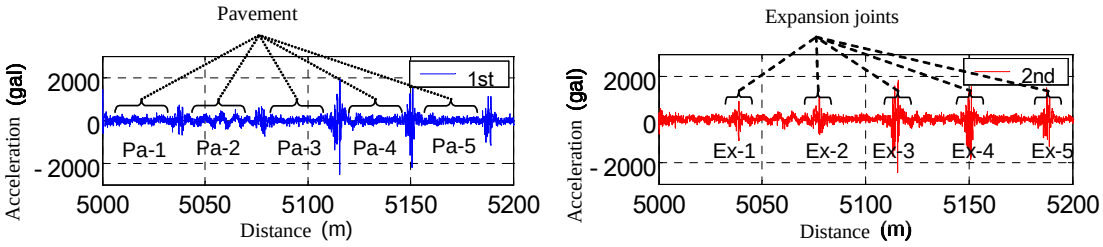


Figure 3. Measurement system



(a) First data (60km/h) (b) Second data (60km/h)

Figure 4. Comparative examples of acceleration response on the same date and same road

an acceleration data on time scale is needed to change to an acceleration data on distance scale because measured acceleration data has to correspond to pavement on that location. Therefore, changing time scale to distance scale for acceleration is considered by vehicle speed data of GPS data. This speed data is taken from vehicle speed pulse, taken directly from the vehicle, and it is more accurate than the vehicle speed from a GPS satellite. This speed is

substituted into a trapezoid formula and changed to distance. Two acceleration data are shown in Figure 4. On expansion joints, the vehicle experiences shocking response as Ex-1 to Ex-5 because the road surface is uneven near expansion joints. Others, are response on pavements (Pa-1 to Pa-5). Comparing the two data, the wave is almost the same and even if expansion joints are expanded, repeatability is high (Figure 5). Table 1 shows when the part of expansion joint and the part of pavement are separated and calculated, there is a difference of two RMS acceleration.

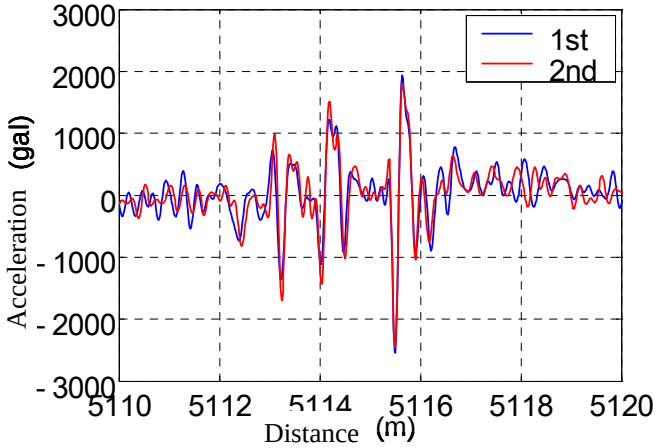


Figure 5. Comparative example of acceleration response near an expansion joint

Table 1. Comparison of RMS acceleration on the same date and same road

		1st (gal)	2nd(gal)	1st /2nd
Pavements	**Pa - 1**	**95.7**	**95.0**	**1.01**
	Pa - 2	**124.1**	**124.6**	**1.00**
	Pa - 3	**99.2**	**100.0**	**0.99**
	Pa - 4	**87.9**	**83.0**	**1.06**
	Pa - 5	**95.4**	**102.2**	**0.93**
	Average	**114.6**	**114.7**	**1.00**
Expansion joints	**Ex - 1**	**219.7**	**212.6**	**1.03**
	Ex - 2	**216.4**	**237.4**	**0.91**
	Ex - 3	**480.4**	**487.2**	**0.99**
	Ex - 4	**463.3**	**430.6**	**1.08**
	Ex - 5	**306.6**	**335.2**	**0.91**
	Average	**261.9**	**264.6**	**0.99**

(Unit ; gal)

The maximum difference is within 10 % and the error is within 5 %. In comparison of the entire route, the difference of the two data is within 10% as average on the part of expansion joints and pavements, and it can be confirmed that the repeatability is high*. Therefore, measured data from this measurement and data acquisition system reflects the condition of road.

Table 2. Calculation method of IRI[8]

1	**Precision profiles:** measure the longitudinal profile of a wheeltrack, as a series of accurate elevation points with no more than 25cm interval.
2	**Other profilometric methods:** the profile is measured as the basis for direct computation of the IRI, but with less accuracy than for a class 1 method.
3	**IRI estimates from correlation equations:** roughness measuring instruments capable of generating a roughness numeric reasonably correlated to the IRI. Must be calibrated by correlation to the IRI.
4	**subjective ratings and uncalibrated measures:** since there is no verifiable link to the IRI scale, the measurements are matched based on descriptions of benchmark roughness levels.

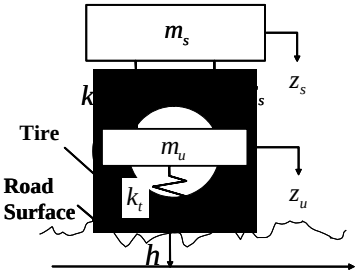


Figure 6. Quarter car model

DERIVATION OF MONITORING INDEX FROM VEHICLE'S ACCELERATION

About IRI

IRI (International Roughness Index) indicates the index of evenness of the road which influences the comfortable driving of a vehicle, based on research which measures the response of suspension and is suggested by World Bank[8]. The most practical calculation method of IRI is class 2. Class 2 measures a longitudinal profile of any measurement device, inputs the result to a quarter car model as Figure 6, and simulates the response with an 80km/h drive. IRI is derived by substituting the response result into formula (1). Formula (1) means that the response of the suspension is divided by moving distance.

$$IRI = \left\{ \int_0^{L/V} \left| \dot{z}_s - \dot{z}_u \right| dt \right\} \Big/ L \qquad (1)$$

Zs: vertical absolute displacement of the mass of the upper spring (mm), Zu: vertical absolute displacement of the mass of the down spring (mm), L: driving distance (m), V: driving speed (22.2 m/s = 80 km/h), t: time (s)

Although IRI is the index which can evaluate the comfortable driving and uses the difference of vertical relative velocity, it is said that human comfort ability depends on vertical acceleration and the reason for using the difference of vertical relative velocity is it is not explicit. The practical issue of this method is that it must measure the real road surface to calculate IRI.

Calculation method of IRI

The practical calculation method of IRI is considered when road surface is measured by road profiler and IRI is calculated by quarter car simulation. However, frequent monitoring is difficult because of operating cost. Therefore, in this research, we recommend the use of the quarter car acceleration directly calculated from the acceleration of road patrol vehicle and IRI is measured from approximation formula. From reference, the acceleration response of the mass of the upper spring and the relative velocity of the mass of both springs is close in theory, and IRI can be calculated by the acceleration of the mass of the upper spring. When vehicle speed is 80km/h, the approximation formula which calculate IRI from quarter car acceleration is as follows.

$$IRI = 0.0429 \times a_{qc_rms} + 0.0618 \qquad (2)$$

Here, IRI: IRI(mm/m), a_{qc_rms}: acceleration RMS of quarter car model (gal)

Following this method, IRI can be measured easily by locating one acceleration on a road patrol vehicle. However, a vehicle characteristics and vehicle speed is different in the measurement vehicle and the quarter car, so it needs to be corrected by a transfer function. This transfer function is calculated by dividing the quarter car model's transfer function, acceleration of the quarter car model to the road surface shape, by the measurement vehicle's transfer function, and acceleration of the measurement vehicle to the road surface shape, as formula (3). Although the quarter car model's transfer function can be calculated by the parameter of the quarter car model, the measurement vehicle's transfer function needs the acceleration of the measurement vehicle on the road which measures the road surface shape because the dynamic characteristics of measurement vehicle is not declared by automobile makers. From the relation of input (road surface shape) and output (measurement vehicle acceleration), the transfer function from the measurement vehicle acceleration to the quarter car acceleration is as follows.

$$F_{tr} = \frac{f_{qc}}{f_{mc}} = \frac{f_{qc} / f_p}{f_{mc} / f_p} = \frac{F_{qc}}{F_{mc}} \qquad (3)$$

Here, f_{qc}: Fourier transform of the quarter car model's acceleration, f_{mc}: Fourier transform of the measurement car acceleration, F_{qc}: transfer function of the quarter car model's acceleration to the road surface shape, F_{mc}: transfer function of the measurement vehicle's acceleration to the road surface shape.

Experiment for derivation of the transfer function $F_{tr}(f)$ from measurement vehicle's acceleration to quarter car's acceleration

The road surface shape and the acceleration response of the measurement vehicle are measured on a general road in Kawagoe. This location is selected because this road has various conditions of pavements, from new pavements to bad pavements, like having steps. Dual purpose automatic measuring kit (DAM[9] as Figure 7) was used for measurement of the pavement surface shape and the shape was measured every 1cm. Acceleration response of the measurement vehicle measured by the system which is described before and driving speed was 20km/h, 30km/h, 40km/h, 50km/h, 60km/h (every 10km/h) to derive the transfer function $F_{tr}(f)$ which corresponded to change of the driving speed.

Figure 7. Measurement of road surface shape by DAM[9]

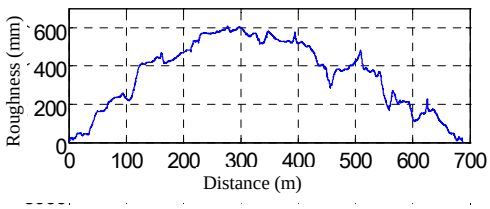


Figure 8. Road surface shape measured by DAM

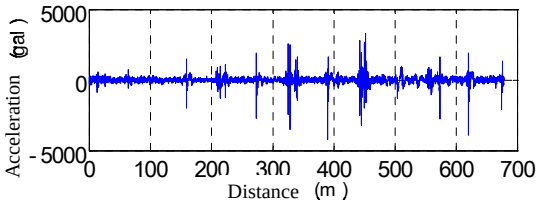


Figure 9. Acceleration response of measurement vehicle on the same road (60km/h)

Compared to the pavement surface shape (Figure 8) measured by DAM with the vehicle response (Figure 9), it is understood that uneven shape of road surfaces sharply influence the acceleration of the measurement vehicle, for example, near 160m, 390m, 630m. Transfer function $F_{tr}(f)$ (Figure 10) is derived from formula (3) by using

these two waves.

Reproduction of quarter car acceleration

Although the quarter car's acceleration can be calculated from the measurement vehicle's response by the transfer function which was derived, the driving line and speed is different every time, so the repeatability of measurement vehicle's acceleration is low, especially for high frequency areas. Therefore, measurement acceleration is low-pass-filtered (pass frequency is 0.3 cycles/m). Comparison of the quarter car's accelerations calculated by the quarter car simulation and by the transfer function, reproduction of impulse response is difficult because of low-pass-filter, however, others are almost the same and repeatability is high (Figure 11). The max error of acceleration RMS without impulse response is about 12 %, so IRI can be calculated directly from the acceleration of the measurement vehicle. However, this result is only one example and more comparisons are needed.

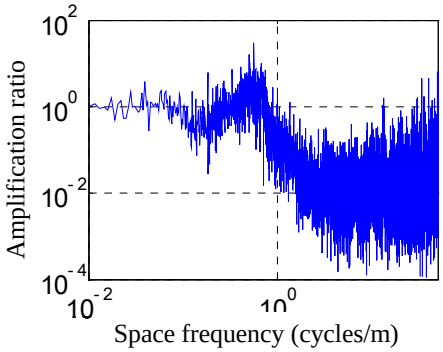


Figure 10. Transfer function from quarter car's acceleration to measurement vehicle's acceleration

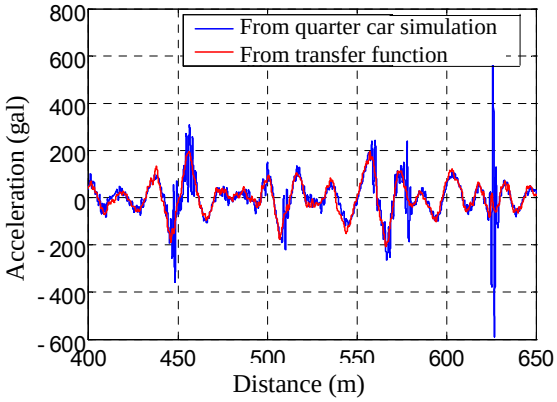


Figure 11. Reproduction of quarter car acceleration

Figure 12. Result of VIMS on Tokyo Metropolitan Expressway (bad condition)

APPLYING VIMS TO TOKYO METROPOLITAN EXPRESSWAY

As one application, VIMS for Tokyo Metropolitan Expressway is given in Figure 12. Icons are IRI more than 2mm/m which shows bad conditions. Almost 4 % of the entire route shows bad conditions.

CONCLUSIONS

In this research, VIMS (Vehicle Intelligent Monitoring System) is developed as a moving monitoring system which can objectively understand the condition of pavements, low-cost, has high accuracy, and real-time by using dynamic response of a road patrol vehicle. The following are the results of this research.

1) Measurement and data acquisition system is developed and repeatability of the acceleration response of a measurement vehicle.
2) An approximation formula, can derive IRI from acceleration of a road patrol vehicle, is suggested and it is indicated that IRI can be measured directly from acceleration of a road patrol vehicle.
3) The effectiveness of this system is confirmed by applying VIMS to the Tokyo Metropolitan Expressway

To maintain roads more effectively by VIMS, comparing actual IRI with IRI from this system and improving the accuracy of the analyzing system are needed.

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