Maintenance and Rehabilitation

Optimising road pavement maintenance using vibration monitoring

Berthold Best[1], Amir Shtayat[2], Sara Moridpour[2], Avina Shroff[3], Divyajeet Raol[3]
[1]Faculty of Civil Engineering, Nuremberg Institute of Technology, Nuremberg, Germany, [2]Civil and Infrastructure Engineering Discipline, School of Engineering, RMIT University, Australia, [3]Civil Engineering Discipline, School of Engineering and Technology, Central Queensland University

Abstract

Road maintenance planning determines the type of maintenance and the timeframe for completion. Currently, road maintenance plans are mostly based on condition monitoring in fixed intervals. Mistakes in detection of pavement faults and wrong estimation of the maintenance time result in high maintenance costs. Therefore, there is a need to introduce a framework to predict the deterioration of road pavement using continuous pavement attributes and minimise the cost and time of road maintenance activities. Optimising pavement maintenance has sustainable benefits to the society and road organisations. Road pavement condition has direct influence on ride quality and passenger comfort. Thus, ride quality measures can be used to predict the pavement damage. To measure the ride quality, the use of a vibration monitoring system is comfortable, cheap and available in various models. Using ride quality measures is relatively cheap, accurate and less time consuming compared to manual inspections. This innovative method can bring direct benefits to the society and road authorities by minimising cost and saving time. Road surface monitoring and data collection with the proposed innovative method using a wireless vibration monitoring device and video cameras will be cheaper, more accurate and less time consuming compared to manual inspections which are currently practiced. For the first time, road pavement deterioration prediction models will be developed combining traditional variables (e.g. road geometry, traffic parameters) with ride quality measurements. This will provide the opportunity to predict the status of road pavement and potential maintenance activities through a more accurate and cost/time efficient procedure.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

Nowadays, the advancement in the transportation industry provides enough space for transportation agencies and organisations to focus on the monitoring of road pavement more systematically. In recent decades, the advances in intelligent transportation systems and the new technologies lead the world toward the sustainable transport infrastructure by applying the advanced monitoring systems in road pavement maintenance prediction and planning.

These new technologies make the monitoring of the pavement easier compared to the past. The advanced pavement monitoring systems are essential part of transport infrastructure maintenance and focus on evaluating the road pavement condition. In addition, advanced pavement monitoring systems have a significant contribution to the development of the transportation system. Some past research tried getting the best evaluation system using new technologies that can detect, analyse, and solve all the pavement distresses and degradation within a short time and high accuracy. Others focus on how they can get a better monitoring system without any damages on the pavement. Also, some researchers used new technologies such as smartphone or tablet applications and cameras to identify the degree of road pavement distresses and the severities. Vibration monitoring is a new method that is used to measure and evaluate the road surface condition. According to Sattar et al. (2018) smartphone applications have become widely and commonly used in road pavement monitoring with high accuracy in some cases.

The position of smartphones on test vehicles is very important to get accurate vibration data. Thus, the best place for fixing a smartphone is at the centre of the handlebar of a bicycle (Zang et al. 2018 and Taylor et al. 2018). The analysis of the vibration data will be done according to the signals for road pavement vibrations in different variable speeds. The upcoming section focus on the literature review and past research around the road pavement vibrations and its relationship with the test vehicle speed. Then, the data, methodology, and the location of this study will be explained. It is followed by explaining the results of data analysis. Finally, the section describes the discussion and the conclusion.

2. LITERATURE REVIEW

Different types of pavement need different systems of pavement monitoring and maintenance. Choosing the best method of maintenance depends on the accuracy of monitoring results and the severity of the road problems. Therefore, the maintenance system requires a careful monitoring system that focusses on the road surface distresses and degradation. Some researchers still use a field survey as a traditional method of road surface monitoring. Others use modern technologies and techniques to measure the severity of road surfaces distresses such as sensors and cameras for all types of road. Also, several studies aimed at focusing on the relationship between the vibration data and pavement problems using the accelerometer (Wang and Easa 2016). Souza (2018) performed an evaluation system of road pavement condition using a smartphone accelerometer application. This System also used a video recording during the vehicle movement. Recording video and image techniques by using regular single cameras have been used in many research to detect the road pavement distresses and severity (Mathavan et al. 2015; Yoo and Kim 2016).

Smartphone sensor technology has become one of the common techniques used to measure and detect the vibration data by measuring the vertical vibration on the road surface. On the same side of research, many research has been conducted on the interaction between the test vehicle speed and the magnitude of vibration. Riverson et al. (1987) used a subjective assessment using a scale ranging from 0 to 5 which represents form very good to very poor road condition. The monitoring system in that method focused on the percentage of areas that is covered by degradation and distress. In that study, the test vehicle speed was around 65 km/h. They revealed that this speed is good enough to get an accurate measurement of road distresses. The test vehicle speed has influence and impact on the vibration values during a vehicle movement. Gordan and Bareket (2007) reported that speed is one of the main factors that should be considered in measuring the vibration data. They also recommended that the test vehicle speed should be around 90 km/h along the road segment. Also, Kirbas and Karasahin (2017) measured the road pavement vibration at different speed levels and using vibration sensors fixed inside the test vehicle. They found that the best speed during the test was constant at 40 km/h.

Meanwhile, some research focus on using different types of test vehicles rather than same with different speed values. Holzel et al. (2012) measured the vibration data using test bicycle on two different types of roads including paved roads and unpaved roads to measure the vibration data using an accelerometer fixed under the seat of the bike. The test was applied using different speed values including 10, 15 and 20 km/h. Moreover, for sports purposes, Giubilato and

Petrone (2012) studied the impact of road surface condition on the speed of the racing bicycle and how the vibrations can affect the ride comfort during the bicycle movement. In their analysis, they used three different test speeds including 15, 25 and 35 km/h. Many research revealed that there was an interaction between the test vehicle speed and vibrations on the road pavement. Kirbas and Karasahin (2017) explained that there is a clear relationship between the speed of the vehicle and the magnitude of vibration. They recommended that the best speed value during the test is about 40 ± 5 km/h. Also, Holzel et al. (2012) found that there is a linear dependency between the speed of the test bicycle and vibrations from the road surface distresses. They also revealed that the typical speed during the monitoring should be up to 30 km/h. The vibration acceleration will increase when the travel speed and the severity of pavement distress increase during the monitoring test (Zhang et al. 2011). The previous studies show that there is an explicit interaction between the travel speed of a test vehicle with the accuracy and sensitivity of vibration data.

A few researchers have focused on the impact of test vehicle speed on vibration monitoring accuracy. In this paper, a subjective study about the interaction between vehicle speed and vibration data is conducted to evaluate the influence of speed factor on the magnitude of vibration on road pavement. In this study, the monitoring system is applied using a smartphone application called "Sensor Log" and a scooter as a test vehicle.

3. DATA COLLECTION

All information about the site location, the instruments used for data collection and the methodology of data collection in the site location is covered in this section. Figure 1 shows the site location of this study at Spring Street between Johnston Street and Kerr Street, Melbourne, Australia. The study site is located in the Fitzroy suburb which is located in North-East of Melbourne's Central Business District. Spring Street is a two-way street with two lanes and has on-street parking. The speed limit for the vehicles at the site location is 40 km/h. The traffic volume in the study area is considered to be light compared with the surrounding roads. Also, there are many types of pavement distresses such as alligator cracks, transverse cracks, longitudinal cracks, and potholes.

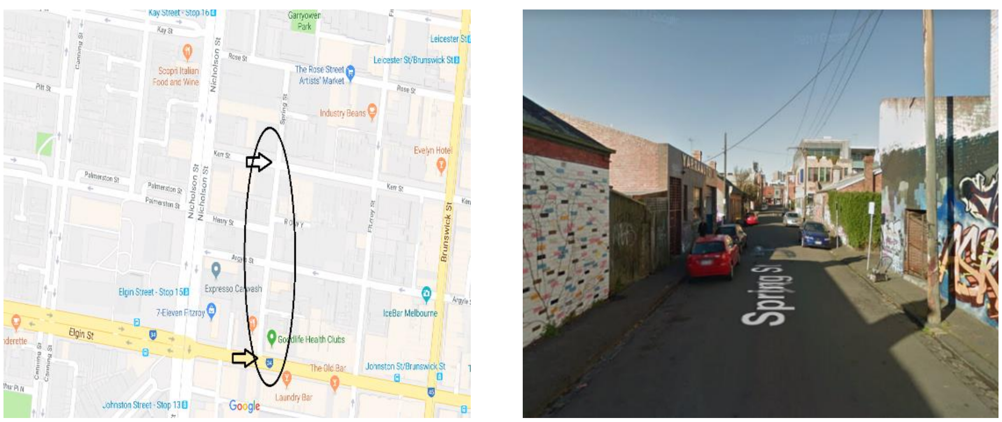

Figure 1: The site location.

Figure 2 shows the process of using smartphones in the data collection of this study. The smartphones used to record the vibration data along the road surface using a mobile application named Sensor Log. This phone was set-up at the top side of the scooter. In this study, a scooter was used as a test vehicle because the speed can be easily controlled better than a bicycle. Four different speeds include (5, 10, 15 and 20 km/h) with several trials for each speed were used in this monitoring system to collect the vibration data along the road. This equipment has an influence only on the surface layer by measuring the pavement vibration data of road surface damages. According to the previous research, speed has an important role in the accuracy of vibration data. Thus, a model has been developed to present the relationship between the vehicle speed and the magnitude of vibration.

The following section will present the developed model which describes the relationship between the speed and vibration. The developed model identifies the impact of speed on the magnitude of vibration. It also identifies whether the vehicle speed is the only factor influencing vibration.

Figure 2: Instrument set-up

4. RESULTS AND ANALYSIS

Figure 3 shows the relationship between the vibrations data measured along the road surface pavement according to different speeds including 5, 10, 15 and 20 km/h. There were five trials per speed, and then the average of the five trials was conducted and used in data analysis. Figure 3 shows that fluctuation of vibration data along the road segment depends on the values of average speeds. The vibration data were analysed, and a model was developed using the EViews 10 software to present the relationship between vehicle speed and road surface vibrations.

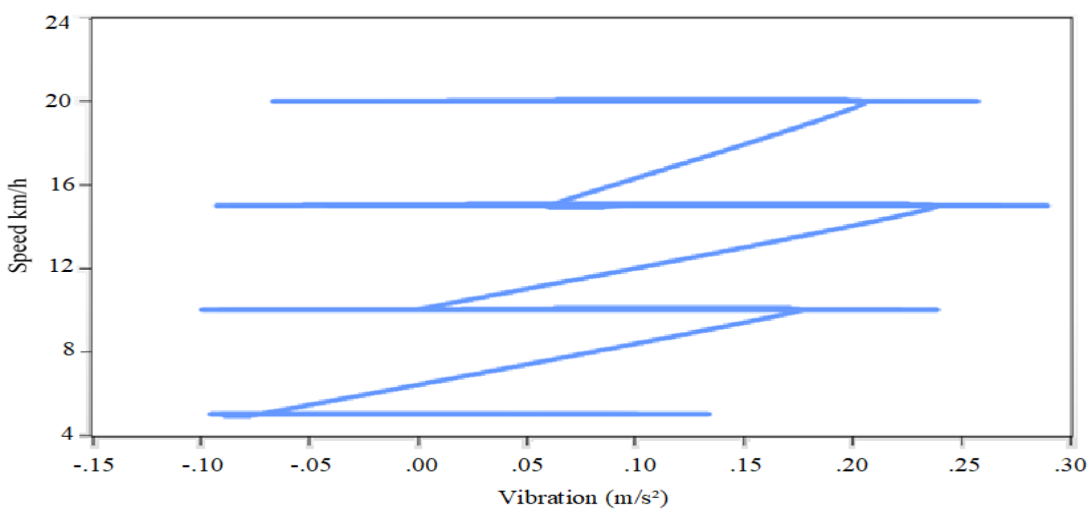

Figure 3: The relation between the vibration and speed

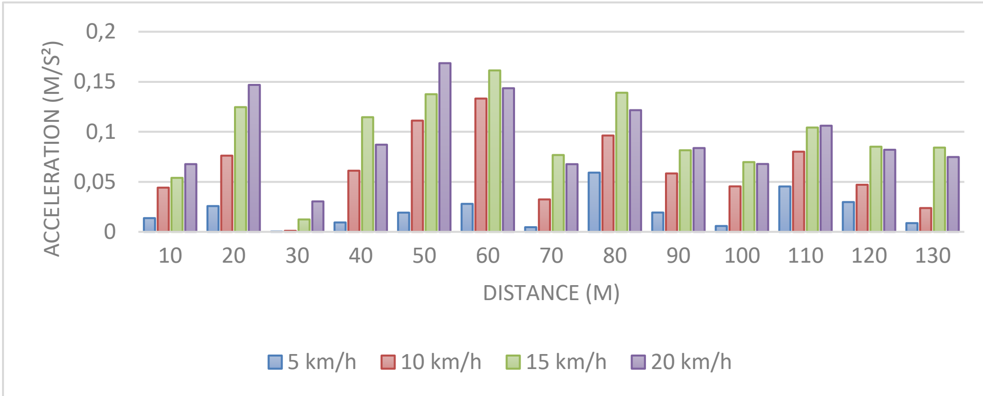

Figure 4: The relationship between the vibration and the speed along the road segment

In this study, the study site has two-way traffic directions, and there was ongoing traffic during the data collection. This street has light traffic movement because it is a local street. The results of Figure 3 and Figure 4 show that there was an unsteady state in the magnitude of road surface vibrations during the test. This fluctuation in vibration values comes from the road surface conditions which represents the severity of the degradation and distresses. Both the speed and the degree of road damage are related to the fluctuation of vibration values. From the previous figures, at speed (5 km/h) the results show that the magnitude of vibration was shallow and not clear enough. The range of the vibration data was between (-0.0955 m/s²) and (0.1335 m/s²). In some cases, the vibrations data cannot be correctly detected especially in medium and low severity of cracks. At speed (10 km/h) the vibration data became clear and probably close to clarifying the real state of the road pavement condition. This speed still has poor detection accuracy especially in medium and low severities of some types of cracks. The range of vibrations at this speed was between (-0.0998 m/s²) and (0.2375 m/s²) higher than the range at the speed (5 km/h). But the range of vibration data was between (-0.0902 m/s²) and (0.2895 m/s²) at the speed (15 km/h). The vibration of the scooter engine appeared with low comfort during the movement on road pavement. This speed was clear enough to detect the road surface distress according to the vibration data. The magnitude of vibration was higher than the previous speeds (5 and 10 km/h) which mean that high speed leads to getting high vibration values. Also, at speed (20 km/h) the comfort riding was very low while the noise was high. The magnitude of vibrations ranged from (-0.0667 m/s²) to (0.2573 m/s²) according to Figure 3. The previous results showed that the speed has a role and impact on the magnitude of vibrations. So, the speed increases the road pavement vibration increases. Equation 1 presents the impact of speed on the magnitude of vibration.

$$VIB = \alpha_0 + \alpha_1 SPD \tag{1}$$

Where; VIB: represents the vibrations value (m/s^2), SPD: represents the speed by (km/h).
After the analysis, the coefficients values for the previous equations is explained in Equation 2.

$$VIB = 0.0083 + 0.0059\ \text{SPD} \tag{2}$$

Table 1: The outputs of data analysis

$\mathbf{VIB = \alpha_0 + \alpha_1 SPD + \varepsilon}$	
R-squared	0.280
Standard Deviation	0.081
Mean	0.326
Median	2.645

Table 1 presents the main outputs of the data analysis. The R-squared value represents that there is a relationship(s) between the independent (speed) and the dependent (vibration) variables. R-squared is a handy, seemingly intuitive measure of how well the model fits a set of observations. Also, R-squared in this model provides an estimate of the strength of the relationship between the vehicle vibration and the independent variables. The 28% value of R-squared indicates that there is a relationship between the speed of test vehicle and vibrations of road pavement distresses. It also means that the vehicle speed influences the magnitude of vibration. The above equation describes the relationship between the vehicle speed and the pavement vibration when the test vehicle speed increase by one unit, the road pavement vibration will increase around 0.0059 unit.

Table 2: Estimated ARDL approach (4, 3)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
VIB(-1)	0.105375	0.062788	1.678272	0.0946***
VIB(-2)	-0.101389	0.061983	-1.635768	0.1032
VIB(-3)	0.015825	0.061019	0.259347	0.7956
VIB(-4)	-0.131095	0.05995	-2.186742	0.0297**
SPD	0.032636	0.008197	3.981195	0.0001*
SPD(-1)	-0.055676	0.011761	-4.733749	0.0000*
SPD(-2)	0.003615	0.012167	0.297069	0.7667
SPD(-3)	0.026009	0.00855	3.041978	0.0026*
C	-0.00922	0.010932	-0.843451	0.3998

Note: * $p < 0.01$, ** $p < 0.05$, *** $P < 0.1$

An analytical model was used to get the best and accurate model. This model named an Auto Regressive Distributed lag (ARDL) model. It is the best model to find the short-run and long-run impact of test vehicle speed on pavement vibration. In this study, the ARDL model automatically applied four lags of road pavement vibrations (VIB), and three lags of the test vehicle speed (SPD). As shown in table 2, the speed and the first lag of speed SPD (-1) are significant at probability 1%, while the fourth lag of vibration VIB (-4) is significant at probability5%. The first lag of the vibration VIB (-1) is significant at probability 10%. The previous results show that there are positive long-run and short-run impact and significant relationship between the vehicle speed and the pavement vibration.

This study found that the value of R-square is a bit low. That means other variables have an impact on the vibrations. To some extent, there is a relationship between the test vehicle speed and road pavement vibration data. There were many factors affected. On the other hand, some factors have significant impacts on the vibration data and the accuracy of measurement. K. Bogsjo (2008) revealed that a wheel path and width of the track of test vehicle are significant factors that directly related to highly accurate measurements. In this study, the wheels of the scooter are thin compared with typical test vehicles. These wheels are unable to measure the vibrations resulting from some types of road pavement distresses. Also, Yuchuan Du et al. (2016) found that there was an impact of engine vibration on vibration data during the pavement monitoring test. They suggested that the sensors should fix inside the vehicle room to minimize the impact of engine noise. These findings are consistent with this study that the engine noise increases when the scooter speed increase. Also, the ongoing traffic during the monitoring task has a significant contribution to the accuracy of vibration data. That is also consistent with some past research. Type of mobile phone has also a significant impact on the accuracy of pavement vibration data, the modern smartphone has higher sensitivity to detect vibration data compared with the old version of devices. In addition, using a high-quality device leads to getting high-resolution images of pavement damages, and then a more accurate evaluation of road surface degradation.

5. CONCLUSIONS

Due to the increase in using the smartphones these days, continuous monitoring of road pavement condition become wide and available anytime and anywhere. Many software programs are also available to complete the monitoring system with highly accurate evaluation. However, many factors affect the accuracy of data during the collection data task. In this study, speed is one of the factors that are directly connected with the magnitude of vibrations. The results of this study showed that the impact of speed on vibration is positive and there is an interaction between the speed of the vehicle and the magnitude of vibrations that come from the severities of road pavement distresses. Using typical speed value and appropriate test vehicle for road pavement monitoring purposes can lead to getting accurate measurements of vibration. These measurements are useful to identify the best, cheapest and shortest maintenance process. Finding all factors that directly affect the vibration data can also lead to satisfying high accuracy of monitoring pavement condition and applying the right treatment process.

REFERENCES

[1] Bogsjö K., Coherence of road roughness in left and right wheel-path, Vehicle System Dynamics, 46(S1), 2008, pp.599-609.

[2] Christin Hölzel, Franz Höchtl, Veit Senner, Cycling comfort on different road surfaces, Procedia Engineering, 34, 2012, pp.479-484.

[3] Du Y., Liu C., Wu D., and Li S., Application of vehicle mounted accelerometers to measure pavement roughness. International Journal of Distributed Sensor Networks, 12(6), 2016, p.8413146.

[4] Federico Giubilato, Nicola Petrone, A method for evaluating the vibrational response of racing bicycles wheels under road roughness excitation, Procedia Engineering, 34, 2012, pp.409-414.

[5] Feng Wang, Said Easa, Analytical evaluation of ride comfort on asphalt concrete pavements, Journal of Testing and Evaluation, 44(4), 2015, pp.1671-1682.

[6] Hyun-Seok Yoo, Young-suk Kim, Development of a crack recognition algorithm from non-routed pavement images using artificial neural network and binary logistic regression, KSCE Journal of Civil Engineering, 20(4), 2016, pp.1151-1162.

[7] Jinxi Zhang, Yanhua Du, Ruiwei Su, September. Investigating the relationship between pavement roughness and heart rate variability by road driving test, In Proceedings of the 3rd International Conference on Road Safety and Simulation, Washington, DC, USA, 2011, pp. 14-16.

[8] John D. N Riverson, Charles F. Scholer, David Middendorf, "A Road Maintenance Management Information System for Counties and Cities," *Indiana Local Technical Assistance Program (LTAP) Publications, 1987,* PP.80.

[9] Kaiyue Zang, Jie Shen, Haosheng Huang, Mi Wan, Jiafeng Shi, Assessing and mapping of road surface roughness based on GPS and accelerometer sensors on bicycle-mounted smartphones, Sensors, 18(3), 2018, pp. 914.

[10] Mark D. Taylor, Alan Edgar, Matthew Raine, Cycling Pavement Assessment Using Hand-Arm Vibration Exposure, Infrastructure Asset Management, 2018, pp.1-53.

[11] Senthan Mathavan, Khurran Kamal, Mujib Rahman, A review of three-dimensional imaging technologies for pavement distress detection and measurements, IEEE Transactions on Intelligent Transportation Systems, 16(5), 2015, pp. 2353-2362.

[12] Sattar, Songniam Li, Michael Chapman, "Road surface monitoring using smartphone sensors: a review," Sensors, 18(11), 2018, pp.3845.

[13] Timothy J. Gordon, Vibration transmission from road surface features: Vehicle measurement and detection, 2007.

[14] Ufuk Kırbaş, Mustafa Karaşahin, "Estimating PCI using Vibration Data for Asphalt Concrete Pavements," In Proceedings of the 2nd World Congress on Civil, Structural, and Environmental Engineering (CSEE'17), Barcelona, Spain, April 2017, pp. 2-4.

[15] Vinicius M.A. Souza," Asphalt pavement classification using Smartphone accelerometer and Complexity Invariant Distance," Engineering Applications of Artificial Intelligence, Vol. 74, 2018, pp. 198-211.