The Development of a Simple Method for Network-wide Road Surface Roughness Condition Estimation and Monitoring Using Smartphone Sensors

By
Viengnam Douangphachanh

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Department of Civil and Environmental Engineering
Graduate School of Urban Environmental Sciences
Tokyo Metropolitan University

Tokyo, Japan
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ADVISORY COMMITTEE

Supervisor:

Prof. Hiroyuki ONEYAMA
Graduate School of Urban Environmental Sciences
Department of Civil and Environmental Engineering
Tokyo Metropolitan University, Tokyo, Japan

Co-supervisors:

Associate Prof. Tomoki ISHIKURA
Graduate School of Urban Environmental Sciences
Department of Civil and Environmental Engineering
Tokyo Metropolitan University, Tokyo, Japan

Associate Prof. Hitoshi NAKAMURA
Graduate School of Urban Environmental Sciences
Department of Civil and Environmental Engineering
Tokyo Metropolitan University, Tokyo, Japan

DEDICATION

To my father and mother, Bounheuang and Oumaly DOUANGPHACHANH, your tireless supports, love and inspiration have helped making this journey possible and rewarding

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ABSTRACT

Road infrastructure maintenance planning and monitoring is a very important task. Its main objective is to help properly maintaining the state of the roads so that they remain in good condition, safe, and accessible to users without obstruction. In many countries, the task is often viewed as one of the biggest burdens, mainly due to its extensive need for information, planning, and implementation, which required significant time, man power, technology and importantly budget.

Information especially road condition data is very essential and crucial in the process of road maintenance planning and monitoring. Road surface roughness is regarded as one of the most important road conditions, because it affects vehicle maintenance costs, fuel consumption, comfort, and safety. International Roughness Index (IRI) is an indicator that is widely adopted as a measurement for road surface roughness condition. IRI measurement is normally done either by one or a combination of two main approaches, which include subjective rating or visual inspection, an approach that is labor intensive and very time consuming; and the use of sophisticated profilers, which are highly accurate but costly to obtain, operate and maintain, requires skillful operators as well as cumbersome calibration before deployment. Since the condition of the road infrastructure changes over time, therefore frequent inspections are necessary to identify up to date condition status. With the current practice it is very challenging for almost all of road authorities and governments, particularly in developing countries where insufficient budget is often an issue.

Whereas, a recent innovation of information technology is very remarkable and its symbolic instruments are smartphones. Smartphones usually come with so many kinds of sensors, some of them are very useful for road surface condition estimation similarly to those used in many high-tech equipment. The number of smartphone users is rapidly increasing even in developing countries, meaning that chance of having plenty of up to date data with inexpensive investment is huge. Thus,

smartphones may provide a great contribution in solving the issues regarding the road surface monitoring mentioned above. The objective of this study is to develop a method to estimate road roughness condition using smartphones with the following main original focuses: 1) the method that is simple and easy to implement with certain accuracy that is acceptable for road maintenance planning and monitoring; and 2) the method that is taking advantages of huge data being made available by anonymous road and smartphone users. The study could be a significant contribution in the mentioned field, because it could lead to a practicable measuring tool that could be used to collect data more frequently and regularly, which is very difficult to achieve in the current practice.

This dissertation is structured into 6 chapters as briefly summarized below:

Chapter 1 contains the introduction and background of road maintenance planning and monitoring, the importance of road surface roughness condition information, and the potential of smartphones. The objective, motivation, and the methodology are also introduced in this chapter.

Chapter 2 presents some literature review on road surface roughness condition, the state of the art for measuring IRI, the most relevant previous work on the use of mobile/smartphone sensors to detect/estimate road and traffic conditions.

Chapter 3 describes a study and analysis on the relationship between smartphone sensor data and the actual IRI. Two experiments, using many smartphones and vehicles, have been conducted in Vientiane, Laos, to collect data from the smartphone accelerometers, gyroscopes and GPS. The collected data is analyzed in the frequency domain using Fast Fourier Transform method to calculate the magnitude of the vibration. It has been found that IRI can be roughly modeled as a linear function of the vibration magnitudes and average speed. At high frequency (frequency range of 40-50Hz), the effect of irrelevant vibration as well as noise, from the driver or vehicle maneuver and engine for instances, which are not related to the vibration caused by road surface roughness, appears to be minimal, thus it is believed that at this high frequency range the effect of the vibration caused by road surface roughness can be observed effectively. The parameters of the relationship function depend on vehicles as well as smartphone locations and settings. Furthermore, it is also found that consideration of gyroscope as additional explanatory variables brings higher estimation accuracy, in the case that existence of error is observed in the simple model of magnitudes from the accelerometer and the average speed.

Chapter 4 lays out a study on the formulation of a simple model to estimate road roughness condition from numbers of unidentified smartphones, presumably from anonymous drivers. To formulate the model, an objective function is constructed based on the relationship and findings of Chapter 3, and under Least Square Method assumption; subsequently, all unknown parameters of the relationship function for all anonymous drivers and IRIs on all road sections are estimated simultaneously provided that some observed road sections with actual IRI are available. Numerical examples have been carried out, where a road network, consisting of road sections with different road conditions; a number of anonymous road users, passing though the road network on different routes, number of trips as well as magnitudes and average speeds; and simulation scenarios consisting of different observed actual IRI are assumed. In general, the method produces good estimates, which are better in scenarios where diverse classifications of observed actual IRI are available, in contrast to the scenarios where only single classification of actual IRI is assumed. Simulations using real data from the experiments in Vientiane are also conducted, using the same approach in the numerical example. The results confirm the findings obtained from the numerical examples.

Chapter 5 describes the development of a smartphone app based on the findings from Chapter 3 and the model described in Chapter 4. The app, called "IRI Sensing", can be installed on Android smartphones and is capable of recording relevant sensor data, performing analysis to calculate the vibration magnitudes and estimate IRI of road sections. The app also has map viewing, route tracking, data uploading and some other basic functionality, which will be further enhanced for better user experience. It is confirmed that the app works satisfactory on some testing road sections. The usability and accuracy are expected to be improved after some extensive tests and piloting.

Chapter 6 is the conclusion. It summarizes the proposed methodology, findings of the study and the remaining issues for future studies.

PUBLICATIONS

Some parts and selected results of this dissertation have been published, presented, and submitted for publications and/or presentations in peer reviewed international and domestic journals as well as conferences. Details of the publication can be viewed in the following list.

Peer Reviewed Journals:

1*. V. Douangphachanh, H. Oneyama. 2012. A Study on the Use of Smartphones for Road Roughness Condition Estimation. Journal of the Eastern Asia Society for Transportation Studies, Vol.10, pp.1551-1564

2*. V. Douangphachanh, H. Oneyama. 2014. A Study on the Use of Smartphones under Realistic Settings to Estimate Road Roughness Condition. EURASIP Journal on Wireless Communications and Networking, 2014:114

3*. V. Douangphachanh, H. Oneyama. 2014. A Model for the Estimation of Road Roughness Condition from Sensor Data Collected by Android Smartphones. Journal of JSCE, Division D: Infrastructure Planning and Management, Accepted for publication in Vol.70, No.5.

Book:

1*. S. Thammanosouth, V. Douangphachanh, L. Khounphakdy. 2012. Gender analysis of changes in livelihoods at the border: A case study of Houayxai, Lao PDR. Gender, Roads, and Mobility in Asia, Part II. Chapter 9.

Full Paper Peer Reviewed Proceedings

1*. V. Douangphachanh, H. Oneyama. 2013. Estimation of Road Roughness Condition from Smartphones under Realistic Settings Proc. of International Conference on ITS Telecommunication, pp. 433-439

2*. V. Douangphachanh, H. Oneyama. 2014. Formulation of a Simple Model to Estimate Road Surface Roughness Condition from Android Smartphone

Sensors. Proc. of IEEE Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing, pp. 1-6

3*. V. Douangphachanh, H. Oneyama. Exploring the Use of Smartphone Accelerometer and Gyroscope to Study on the Estimation of Road Surface Roughness Condition. 11th International Conference on Informatics in Control, Automation and Robotics, accepted for publication.

International Conferences:

1*. V. Douangphachanh, H. Oneyama. A Study on the Use of Smartphones for Road Roughness Condition Estimation. Proceeding of the Eastern Asia Society for Transportation Studies Conference, Taipei, Taiwan September 9-12, 2013, Vol.9, P297.

2*. V. Douangphachanh, H. Oneyama. Using Smartphones to Estimate Road Pavement Condition. Proceeding of the International Symposium on Next Generation Infrastructure, Wollongong, NSW, Australia, September 30 - October 4, 2013.

3*. V. Douangphachanh, H. Oneyama. Estimation of Road Roughness Condition from Smartphones under Realistic Settings. Proceeding of the International Conference on ITS Telecommunication, Tampere, Finland, November 5-7, 2013.

4*. V. Douangphachanh, H. Oneyama. Formulation of a Simple Model to Estimate Road Surface Roughness Condition from Android Smartphone Sensors. Proceeding of the IEEE Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing, Singapore April 21-24, 2014.

5*. V. Douangphachanh, H. Oneyama. Exploring the Use of Smartphone Accelerometer and Gyroscope to Study on the Estimation of Road Surface Roughness Condition. 11th International Conference on Informatics in Control, Automation and Robotics, Vienna, Austria, September 1-3, 2014.

Other Conferences or Oral Presentations:

1*. V. Douangphachanh, H. Oneyama. A Numerical Model to Estimate Road Roughness Condition from Sensor Data Collected by Android. Biannual Conference of the Committee of Infrastructure Planning and Management, Osaka, Japan, November 2-4, 2013

2*. V. Douangphachanh. Road Surface Condition Detection Using Smartphone Devices. International Seminar on Traffic Management and Data Utilization, Tokyo, Japan, July 27, 2012.

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API	Application Programming Interface
APK	Android Application Package File (File format)
ARRB	Australia Road Research Board
ASTM	American Society for Testing Materials
BI	Bump Integrator
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
GDP	Gross Domestic Product
GPS	Geographical Positioning System
GSM	Global System for Mobile Communications
HDM	Highway Development and Management
IRI	International Roughness Index
IRRE	International Road Roughness Experiment
LAK	Lao Kips (Lao Currency)
NAASRA	National Association of Australian State Roading Authority
PTI	Public Works and Transport Institute
RMS	Road Management System
ROMDAS	Road Measurement Data Acquisition System
RTRRMS	Response Type Road Roughness Measuring System
USD	U.S. Dollars (U.S. currency)
VIMS	Vehicular Intelligent Monitoring System
VOC	Vehicle Operating Cost
2WD	2 Wheel Drive
4WD	4 Wheel Drive

Chapter 1: INTRODUCTION

1.1. Background and motivation

Road infrastructure maintenance planning and monitoring is one of the most important tasks for all road authorities and governments around the world. The task is a critical element in the actual implementation of road infrastructure maintenance, which has the principal objective of preserving the status of the roads so that they remain in good condition, safe, and accessible to road users without obstructions. Being properly maintained, the roads can continuously serve its main objective in supporting the mobility of people, goods and the economy of a country. “Proper road maintenance contributes to reliable transport at reduced cost, as there is a direct link between road condition and vehicle operating costs (VOC). An improperly maintained road can also represent an increased safety hazard to the user, leading to more accidents, with their associated human and property costs” (World Bank, 2014).

Road maintenance planning, monitoring and management is usually viewed as one of the biggest challenges for many governments, mainly due to its extensive need for information, planning, and implementation. All of these require significant time, man power and importantly substantial budget. Information or data is very important, and road roughness condition is a vital data in the process of road maintenance, monitoring planning and management. Regular road infrastructure inspections are necessary to identify up to date condition status, since the condition data changes over time. Therefore, it is very challenging for all most all of the road authorities and governments, particularly in developing countries where insufficient budget is often an issue.

In Laos, for instance, which is a small developing country in Southeast Asia, with a total land area of 236,800 km^2, a population of 6,770 million and a GDP of USD11.14 billion (2013; according to World Bank); there is a total road length of 30,585 km; of which 4,885 km are paved, 13,336 km are gravel, and 12,364 km are earth roads, respectively (PTI, 2011a). According to the 2011 annual report of Lao Road Management System (RMS), in order to properly maintain this huge road network, the government has to spend approximately USD162.5 million (13 trillion LAK) per year. In practical, because of budget constraint, only approximately less than 30% of the total road length can be maintained. RMS is a system that helps the government in the planning and prioritizing for the maintaining and managing of the road infrastructure accordingly to the available budget. It comprises of a set of software, procedures and data base. RMS requires extensive data, particularly road condition data (including roughness), which is among the most important data needed for RMS analysis. The collection of road condition and roughness data in Laos, in 2011, costs USD16 per Km for paved roads and USD5 per Km for unpaved roads (PTI, 2009). See Appendix A.

Road pavement condition can be classified by the irregularity and/or defects, which may be in the form of surface unevenness, potholes, cracks, deterioration or damages and so forth, in the pavement surface that adversely affects the ride quality of vehicles (See Figure 1-1 for examples of different road pavement conditions). Road roughness is an internationally accepted indicator to which it is usually used to measure the condition of road pavement. Roughness is an important pavement characteristic because it affects not only ride quality but also vehicle delay costs, fuel consumption and maintenance costs. International Roughness Index (IRI) is a measurement indicator that has been used internationally for road pavement condition (M.W. Sayers et al., 1986). IRI is the condition index obtained from the measurement of longitudinal road profiles with the measuring unit of slope (m/km, mm/m for instance).

Bad pavement condition can cause damages to vehicles, may increase fuel consumption, increase road user costs for vehicle maintenance, unpleasant driving experience, and sometimes it may pose traffic safety threats to road users. Therefore, pavement condition information is usually of the interests of the general public, road users and particularly the government or road authorities. For the authorities, the information is crucial in their decision making process especially for strategic planning such as management planning, maintenance planning and programming of the road infrastructure. The lack of sufficient availability of funding, technology and skillful manpower often leads to infrequent collection of road roughness condition data, thus the data is usually left outdated. Consequently, sound management and maintenance of the road infrastructure have often been compromised, which is usually viewed as a great challenge for many road authorities in maintaining good quality of road infrastructure under budget constraint, particularly in developing countries.

Figure 1-1: Examples of road defects
Source: the internet

To obtaining road roughness condition data, there are 2 main approaches. The first approach is subjective rating surveys and the second approach involves the use of sophisticated profilers. The former approach is labor intensive and very time consuming, because it relies mainly on visual inspection and judgment of trained inspectors. The later approach relies on the use of one or many types of sophisticated road profilers, which are costly to obtain, operate and maintain. Skillful operators are also recommended. Additionally, in order to properly use such profilers, majority of them would require cumbersome physical calibration before deployment.

For developing countries, mainly due to budget constraint, time consuming and intensive human intervention approach is usually an unavoidable option for road surface condition data collection. However, with the need to update the information regularly, this may put further pressure on already heavy-loaded road authorities in terms of budget for actual maintenance, particularly. Therefore, exploring the use of smartphones to estimate road surface condition may be a great help, since smartphones nowadays are increasingly popular; and they usually come with many useful sensors in which many researchers and developers have been exploring their use for many applications in many fields.

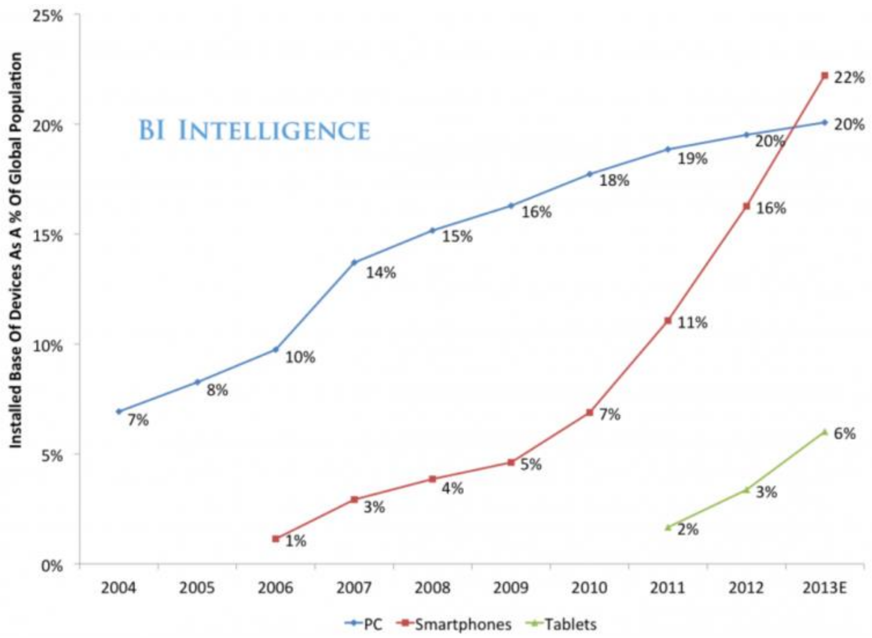


Figure 1-2: Global smartphone penetration per capita
Source: BII estimates, Garner, IDC, Strategy Analytics, company fillings, World Bank 2013 cited in (Heggestuen, 2013)

According to an online statistics (Heggestuen, 2013) from a well-known business and technology news website (the Business Insider), global smartphones penetration per capita increases sharply and continuously in since 2010 (See Figure 1-2).

It is believed that smartphones may be also potentially useful for the purpose of road infrastructure maintenance planning because, on the one hand, smartphones already have sensors that are capable of recording useful signal for road surface condition estimation similarly to those used in many high-tech equipment. On the other hand, the number of smartphone users is rapidly increasing, meaning that chance of having plenty of up to date data with inexpensive investment is huge. Furthermore, it may also be useful for continuous monitoring the soundness of road infrastructure as a whole. For this purpose, it may be beneficial not only for developing but also for developed countries.

1.2. Objective

The main objective of this dissertation is to study on the development of a method to estimate road roughness condition using smartphone devices. It is one of many interesting topics in recent researches and studies in road maintenance planning and monitoring as well as mobile/sensor data sensing and processing areas. The approach considered in this study is unique in comparison to previous studies and researches. The main advantage of the approach proposed in this dissertation is surrounded on the classification of roughness condition of road sections, using simple techniques, which involve frequency domain analysis and a simple linear estimation model. The method is innovative, in the above mentioned field, in the sense that it is low-cost, simple, and taking advantages from huge data being made available by anonymous users. The method is simple because there will be no fixed location and setting of the smartphones, no time consuming and troublesome physical calibrations, and only real roughness condition data of a small number of road sections would be needed to be used in the estimation process to predict the condition of the remaining road sections in the network.

The approach could be a significant contribution because it could lead to a practicable measuring tool that could be used to collect data more frequently and regularly, which is considerably difficult to achieve in the current practice. Therefore with up to date data being made available for Road Management System, road maintenance planning and monitoring, in particular, are believed to be more efficient and carried out in a timely manner.

1.3. Methodology

The basic concept of the proposed approach involves anonymous road users (car owners), who presumably agree to download and install an application onto their smartphones, and enable it to collect data from the relevant sensors, analyze, calculate and estimate, and send back the information for further analysis, which then will be used for the purpose of road maintenance planning and monitoring. See Figure 1-3.

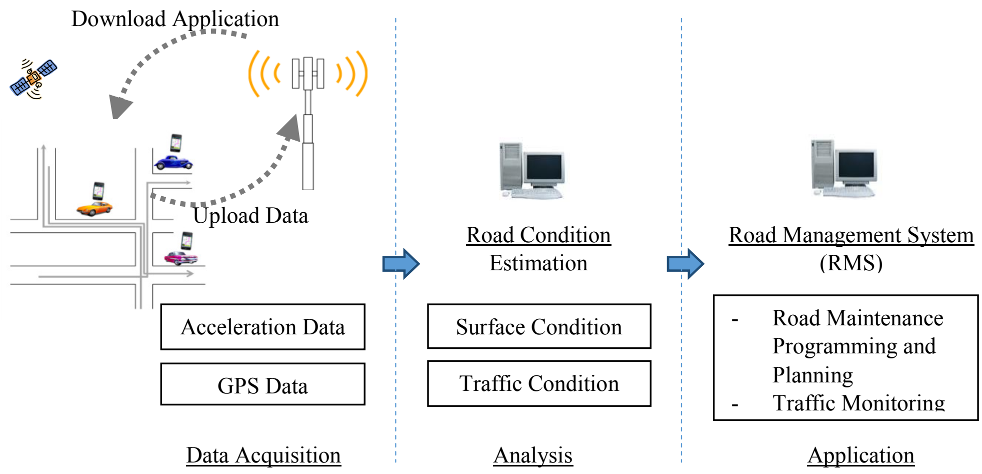


Figure 1-3: Conceptual framework of the proposed system

To realize this goal, the smartphone application must be proposed and put in place (details in Chapter 5), and it must have a considerably good estimation model, so that the accuracy of the estimation is acceptable for the use in road maintenance planning and monitoring.

To achieve this, first of all, there is a need to study on the relationship between smartphone sensor data and the actual road surface roughness condition (details in Chapter 3). The study would enable the understanding on features, parameters and relationship functions, which are very critical for the formulation of the estimation model.

After obtaining prospective functions for the estimation model, the model will be formulated, investigated and tested to ensure that it works for the purpose. The most important point in the model formulation is that the model must be able to estimate road surface roughness condition from anonymous drivers (detail in Chapter 4). The process of the studies carried out in this dissertation can be summarized in Figure 1-4 below.

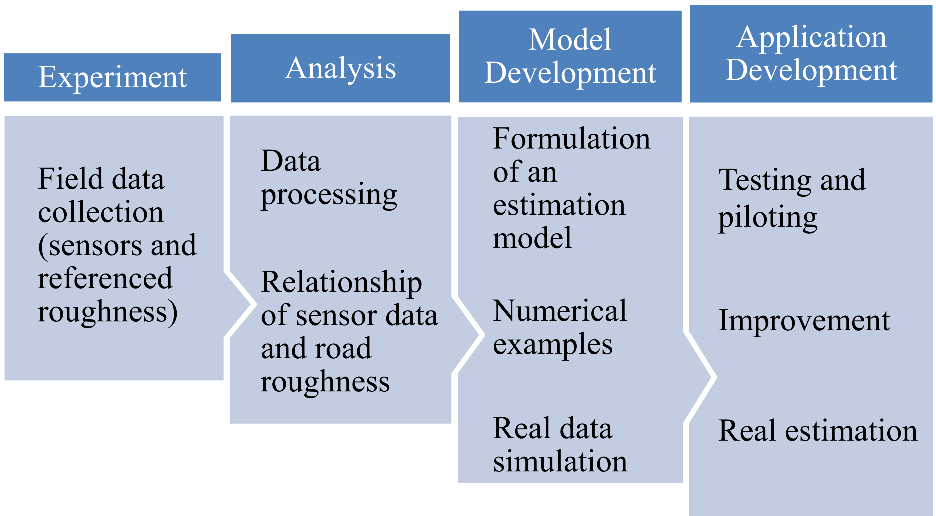


Figure 1-4: Main process of the studies included in this dissetation

1.4. Outline of this dissertation

This dissertation is structured into 6 chapters. Chapter 1 introduces background of road maintenance planning and monitoring, the importance of road surface roughness condition information, and the potential of smartphones. The objective, motivation, and the methodology are also introduced in the chapter. Chapter 2 reviews some relevant aspect, previous literature and most relevant work to this dissertation. Chapter 3 presents the study on the relationship and feature between smartphone sensor data and the actual road surface roughness condition. This chapter also describes the data collection experiments and a referenced data measurement tool. Chapter 4 presents the model formulation, numerical example and simulation using real life data. Chapter 5 proposes a smartphone application to be used for the estimation of road surface roughness condition. Finally, Chapter 6 is the conclusion.

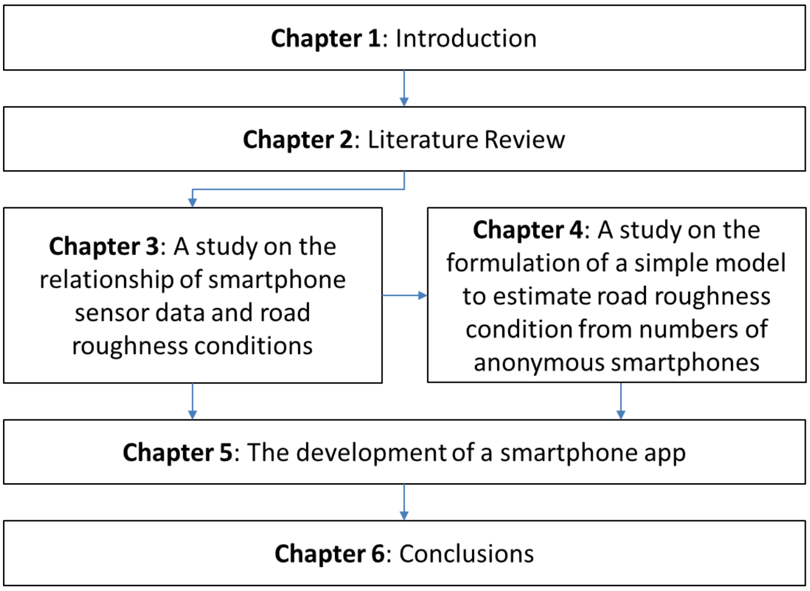


Figure 1-5: Structure of the dissertation

Chapter 2: LITERATURE REVIEWS

2.1. Road Roughness condition and road maintenance planning

Road roughness is defined as "the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for example, longitudinal profile, transverse profile, and cross slope." ASTM E867-87 cited in (Bennett et al., 2007).

Figure 2-1 below shows different levels of roughness condition.

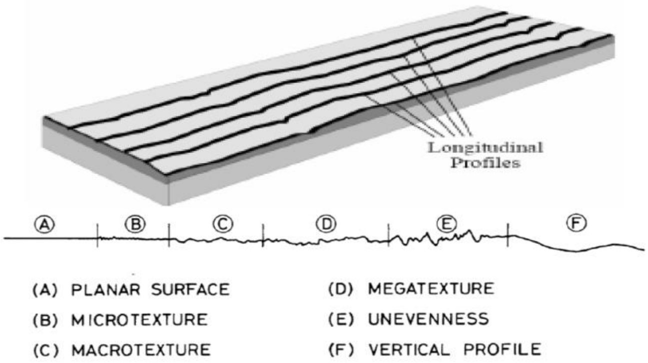


Figure 2-1: Road roughness condition
Source: (Sayers & Karamihas, 1998)

It is widely recognized that road condition has a direct impact on the economic benefits to the road users (Morrow, 2006) and (World Bank, 2005). It is one of the factors that affect and cause increased vehicle operating costs, mainly due to vehicles wear and tear and increased fuel consumption. Roughness also causes unpleasant driving experience, affects travel time and sometimes accidents. Therefore, roughness is a globally accepted indicator to monitor the performance of road pavement. It is a key performance indicator that is used in the management and planning of road asset maintenance and monitoring.

Roughness can be measured using different methods and in many different units ranging from counting the number roughness per distance traveled (count/km etc.), the slope of longitudinal road profile (mm/m, m/km etc.), and ride number (Morrow, 2006). Before the adoption of IRI, results of roughness condition measured by different instruments are also different and thus difficult to compare.

Lao RMS uses Highway Development and Management (HDM) based models in its analysis. HDM (latest version is HDM-4) is developed by the World Bank to be used for technical and economic appraisal of road projects, to prepare road investment programs, and to make road network strategy analysis (Kerali et al., 2006). Similar to HDM-4, RMS analytical framework is also based on the concept of pavement life cycle analysis. RMS analyzes different options of maintenance by comparing the total costs to determine economic benefits before prioritizing the maintenance accordingly. The total costs considered include: 1) costs to the road authorities: capital and maintenance costs, which depend on the standard of maintenance selected for the road network (Figure 2-1); and 2) road user costs: vehicle operating costs (fuel, tires, oil, spare parts, etc.), costs of travel time, economic costs from accidents, and social-environmental costs (emission, traffic noise, etc.)

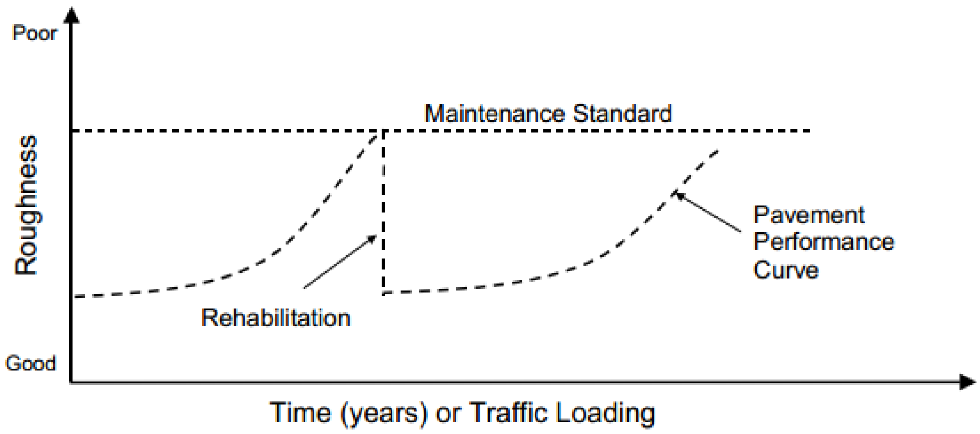


Figure 2-2: Concept of life cycle analysis
Source: (Kerali et al., 2006)

As already mentioned, road user costs are affected directly by road roughness condition. The effects of the road roughness condition on the vehicle operating costs are shown in the Figure 2-3 below.

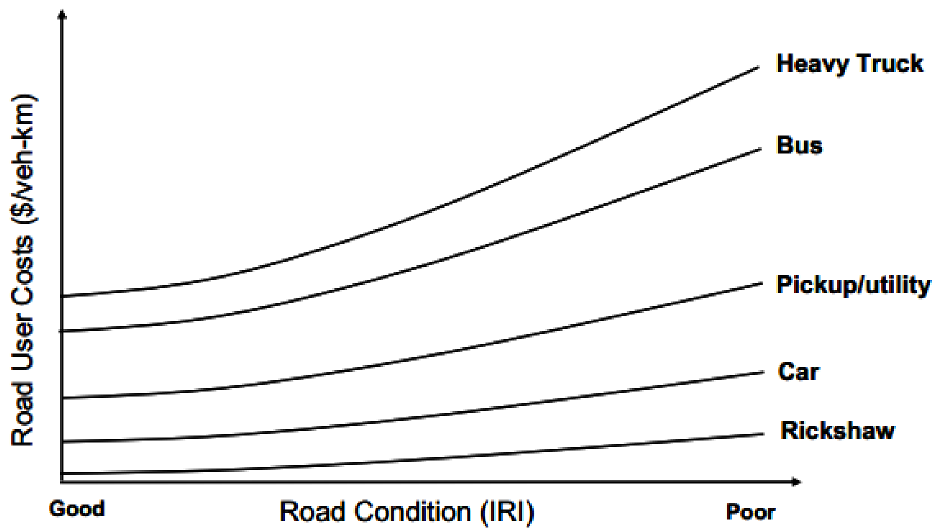


Figure 2-3: Effect of road condition on road user costs
Source: (Kerali et al., 2006)

2.2. International Roughness Index (IRI)

To standardize the measurement of road pavement roughness across different available methods and profilers, in 1982, the World Bank has funded a large scale International Road Roughness Experiment (IRRE) in Brazil (M.W. Sayers et al., 1986). IRRE uses a quarter-car mathematical model to calculate IRI, which is the quotient of the linear accumulated motion of the suspension divided by the length of the longitudinal road profile (Figure 2-4). Thus, IRI has a measurement unit of slope, such as mm/m, m/km or in/mi, for instances.

The IRRE concludes that factors that are affecting IRI are:

- Measurement vehicle, which can be minimized by calibration;
- Speed, which can also be minimized by calibration; and
- Pavement type

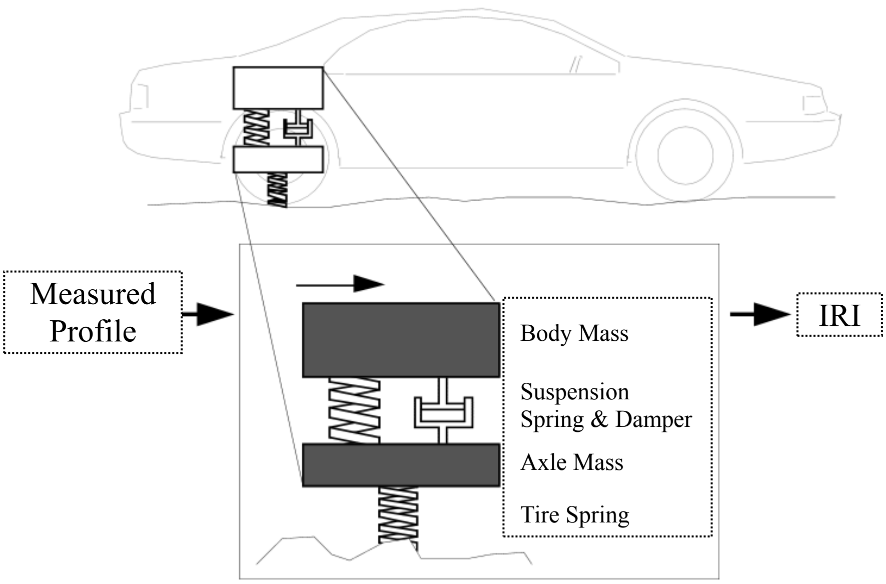


Figure 2-4: Quarter-car model
Source: (Sayers & Karamihas, 1998)

As a result of this experiment, a standardized measurement indicator (IRI) is adopted. IRI enables the measurement of pavement roughness from different types of tools in different countries to be comparable, reproducible and consistent over time (Sayers & Karamihas, 1998).

2.3. Conventional ways to measure IRI

2.3.1. Types of IRI measuring equipment

The World Bank has classified the measurement techniques of road roughness (IRI) into 4 classes according to their ability to measure precision accuracy (Sayers & Karamihas, 1998). Class I to III involve the use different types of profilers and class IV is the subjective rating. See Table 2-1.

Table 2-1: IRI measurement methods

Class	Description	Example of the equipment
Class I: Precision Profilers	This class of IRI measurement is the most precise and accurate. The measurement (sample) interval is 250mm or less with a precision of no greater than 0.5mm on very smooth road surface. The tools can be laser profilers, which normally are non-contact lightweight and portable devices, as well as manually operated devices.	Face Technology dipstick, ROMDAS Z-250, ARRB walking profilometer
Class II: Other Profilometer Methods	Other devices that do not meet Class I requirement, but still considered as precise and accurate. The maximum sampling intervals of this class are 500mm, with a precision of less than 1mm on smooth roads.	APL Profilometer, California and Rainhart profilographs, optical profilers, and inertial profilers
Class III: Simple profilers or response type tools	This class of instruments machanically or digitally measure the response of the instruments relatively to the road profile. Some other simple profilers are also classified under this class.	Roadmaster, ROMDAS, Roughometer, TRL Bump Integrator, Rolling straight edge, VIMS
Class IV: Subjective rating	Measurement that is judged by inspectors from visual surveys or the use of uncalibrated roughness meters	Key code rating system, visual inspection, ride over section

Source: (Morrow, 2006; Sayers et al., 1986)

Figure 2-5 below shows some popular IRI measuring tools.


ROMDAS Z-250 (Class I manual) | SSI 9300 (Class I laser) | ARRB Walking Profilometer (Class I manual)



California Profilograph (Class II) | ROMDAS Bump Integrator (Class III) | Roughometer (Class III)

Figure 2-5: Examples of IRI measuring tools
Source: (ARRB, 2010; ROMDAS, 2011; SSI, 2012)

2.3.2. A brief review on the existing IRI measuring equipment

(Bennett et al., 2007) and (Morrow, 2006) have extensively studied on the technologies for road management data collection, and a comparison of road roughness measuring instruments. Each instrument in the 4 classes of the measuring methods has its own advantages and constraints, which can be summarized below:

Subjective rating (Class IV): evaluation of road roughness condition, using this approach, is usually adopted in cases when there is no need to obtain high accuracy; or when the high accuracy methods are not affordable. For the implementation of a subjective rating, inspectors will have to drive a car over the road sections to assess the ride smoothness, or conduct a visual evaluation of the road section using rating manuals or by experience. This approach does not require a measuring tool, but trained inspectors. Therefore, the main costs for implementing this approach only involve with labor cost. Results from subjective rating are the least accurate and depend largely on the judgment of the inspectors, which may differ from one to another.

Table 2-2: Cost/performance trade-off matrix

		Operational Performance				
Equipment Global Cost	**Scale**	**1 (Low performance)**	**2**	**3**	**4**	**5 (High performance)**
	1 (High cost)			• Skid Resistance Dynamic - Vehicle	• Imaging for Surface Distress	
	2			• Ground Penetrating Radar – Dynamic • FWD - Trailer	• Macrotexture – Dynamic High Speed • Precision INU for Geometry • Roughness – Class I (Laser)	
	3			• Deflection Beams • FWD - Portable • Ground Penetrating Radar – Static • Skid Resistance – Dynamic Trailer	• GPS with INU • Macrotexture – Dynamic Low Speed • Rut Depth Profilers • Roughness – Class II	
	4		• Roughness-Class IV	• Roughness – Class I (Manual) • Skid Resistance – Static	• Video Logging • Roughness – Class III	• GPS
	5 (Low cost)			• Macrotexture – Static		• Digital DMI

Source: (Bennett, 2008)

According to the study conducted by (Bennett, 2008) performance and suitability of this approach is very low. See Table 2-2 and Table 2-3 for the cost/performance trade-off matrix, and suitability ranking developed by (Bennett, 2008) to assess different types of the instruments for road management.

Therefore, in brief, main advantages of this approach are:

- Relatively low cost;
- Can be implemented often, if the road network is not big; and
- Does not require complicated tools or equipment.

Main disadvantage:

- Labor intensive and very time consuming, thus low performance and low suitability; and
- Inaccurate results.

Table 2-3: Suitability ranking

EQUIPMENT CLASS	SUITABILITY RANKING
Referencing- Digital DMI	4.62
Referencing- GPS	4.29
Geometry GPS With INU	4.01
Macrotexture- Dynamic Low-Speed	3.88
Referencing- Video	3.82
Geometry Precision INU	3.76
Roughness- Class III	3.60
Macrotexture- Static	3.57
Macrotexture- Dynamic High Speed	3.51
Roughness- Class I Manual	3.50
Roughness- Class II	3.41
Rut Depth Profilers	3.41
Surface Distress Imaging	3.31
Roughness- Class IV	3.30
Skid Resistance- Dynamic (Trailer)	3.24
Skid Resistance- Static	3.12
Deflections- Beams	3.07
Roughness- Class I Laser	2.91
Deflections- Portable FWD	2.71
Ground Penetrating Radar- Dynamic	2.69
Ground Penetrating Radar- Static	2.61
Deflections- Trailer FWD	2.55
Skid Resistance- Dynamic (Vehicle)	2.23

Source: (Bennett, 2008)

Equipment based measurement (Class I to III): there are 2 main techniques for the equipment based measurement. The first technique is based on response type devices (Class III), and the second technique is based on profiled systems (Class I and II).

- Class III or Response Type Road Roughness Measuring Systems (RTRRMS): as its name suggests, an instrument using this method measures the response of a vehicle relatively to the road pavement surface. It deploys tools or devices, such as mechanic devices or accelerometers, to attach to the vehicle and measures the displacement of the vehicle chassis relative to the rear axle per distance travelled (Bennett et al., 2007). This type of instruments usually use standard quarter car model to estimate IRI from the data collected by the devices. Measuring units used by these instruments are normally m/km (IRI) or count/km (NAASRA).

To properly use an instrument of this class, it is necessary to carry out a calibration for each vehicle before measurement. This is because each vehicle has a different setup of the suspension, which tends to change over time.

Figure 2-6 shows an example on how to setup a RTRRMS device called ROMDAS Bump Integrator (BI).

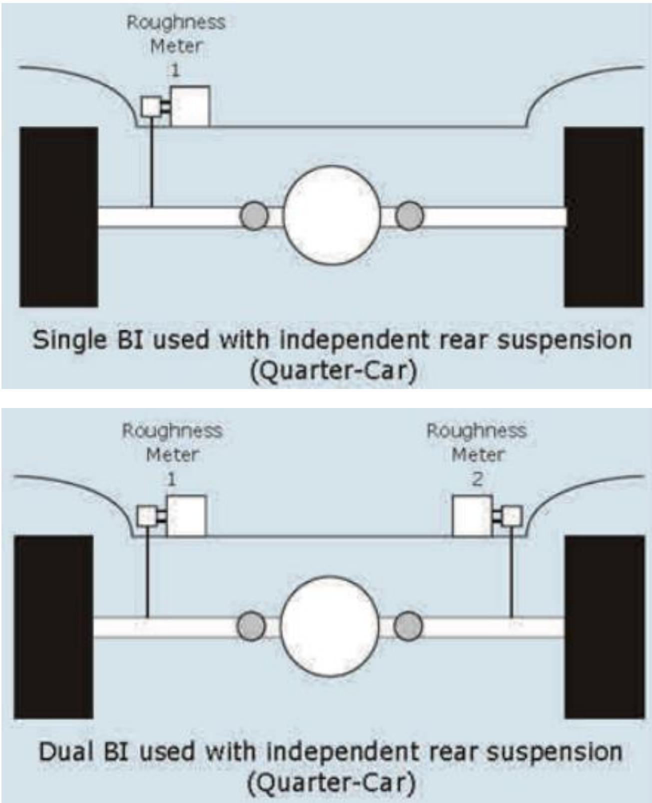


Figure 2-6: ROMDAS Bump Integrator (BI) setup
Source: (ROMDAS, 2011)

Main advantages of this approach are:

- Relatively low cost;
- Fast and moderate accuracy;
- Quite high performance; and
- Very high suitability among roughness measurement instruments.

Main disadvantage are:

- Involve some costs to obtain; and
- Involve tedious initial setup and calibration.

- Profiled based technique (Class I and II): this technique does not involve the measurement of the response of the vehicle to measuring road profiles. It uses lasers or sound waves to record the motion of the vehicle through space and the high of the vehicle relative to the road surface, instead. After profile data is collected, some software will be used to interpret the profiles into roughness condition, normally IRI (m/km). For Class I, there are manual and automatic profilers. Manual profilers are usually small, portable, low speed and slightly more expensive in comparison to other instruments in other classes; while automatic ones are usually very high-tech, high speed and the most expensive. Class II tools are similar to Class I automatic instruments, but with a lower accuracy.

In general, the main advantages of these profilers are:

- Sophisticated and advance;
- Manual profilers are not very expensive;
- Fast, for automatic profilers (high performance); and
- Highly accurate and reliable.

Disadvantages:

- Automatic profilers are expensive to obtain, operate and maintain;
- Cannot implement frequently because of the costs (automatic) and speed (manual);
- Can also be time consuming if precision is high (data analysis);

- Skillful operators are also recommended;
- Generally, suitability is low; and
- Majority of the instruments in these classes requires cumbersome installation and physical calibration before deployment.

Figure 2-7 below shows an example of detail of a Class I automatic profiler called SSI 9300.

Figure 2-7: Example of a Class I automatic profiler, SSI 9300
Source: (SSI, 2012)

2.3.3. Vehicle Intelligent Monitoring System (VIMS)

VIMS is developed with an objective to offer an alternative low cost solution or option for road authorities to monitor their road networks. It is a response type IRI measurement instrument (RTRRMS) Class III. It uses an accelerometer to attach to the body of the vehicle to measure the displacement of the vehicle, and translate the measurement result into IRI through a set of estimation algorithms, which is based on the standard quarter care model (Fujino et al., 2005). See Figure 2-8. Beside the accelerometer, VIMS consists of a number of other hardware including a data acquisition module, a GPS and a laptop PC. All of the hardware is connected to each other via cables.

After installation, 2 types of calibrations are needed. The first one is a speed calibration, which involves several constant speed runs on a preselected road section. The second calibration involves several drives at a constant speed of 20km/k over special plastic humps placed on the wheel path of the vehicle (Figure 2-9). All of the calibrations are to ensure that estimation model is adjusted to the vehicle, before it can be used for actual measurement (Nagayama et al., 2013).

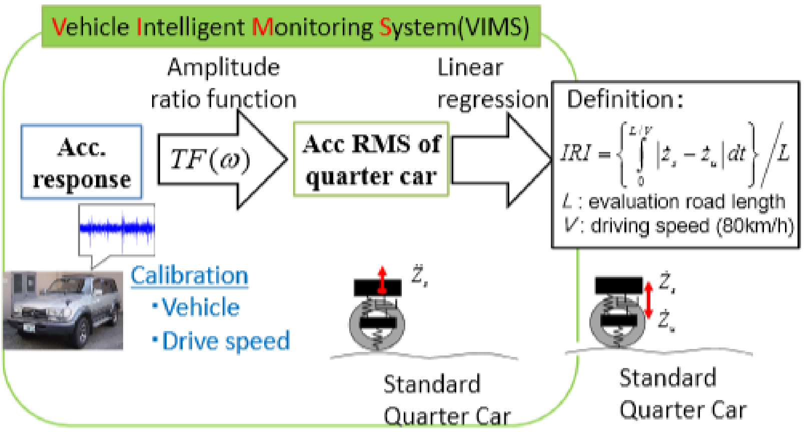


Figure 2-8: VIMS estimation framework
Source: (Nagayama et al., 2013)

Figure 2-9: VIMS hump calibration
Source: (Nagayama et al., 2013)

According to (Nagayama et al., 2013), the main merit of VIMS is that despite being simple in terms of installation without a need to modify the vehicle, it enable inexpensive and frequent quantitative evaluation of IRI. A further development has also seen an inclusion of a smartphone to make VIMS even useful. In contrast, VIMS still have some limitations. The main issue that may hinder the use of VIMS is its time consuming calibrations. Another issue is that because VIMS consists of many components, which are connected to each other via cables, it is not easily handled by not well trained users as mention in (Nagayama et al., 2013).

VIMS will be used to measure real IRI of the selected roads for this study, therefore more details of VIMS can also be found in Chapter 3.

2.4. Relevant smartphone sensors

Most smartphones today have many useful built-in sensors. The sensors are categorized into 3 main groups based on the types of measurement such as motion, position, and the environmental conditions (Android Developers, 2014).

Motion sensors, which include accelerometer, gyroscope, gravity sensors and rotational vector sensors, are capable of precisely and accurately measure 3 dimensional acceleration and rotation forces along and/or around X, Y, and Z axes.

Position sensors are used to measure the physical position of a device. This category of sensors includes GPS, orientation sensors and magnetometers.

Environmental sensors that may also come built-in with a smartphone may include barometer, photometer and thermometer. These sensors are used to read different environmental conditions such as air temperature, air pressure, humidity, and illumination.

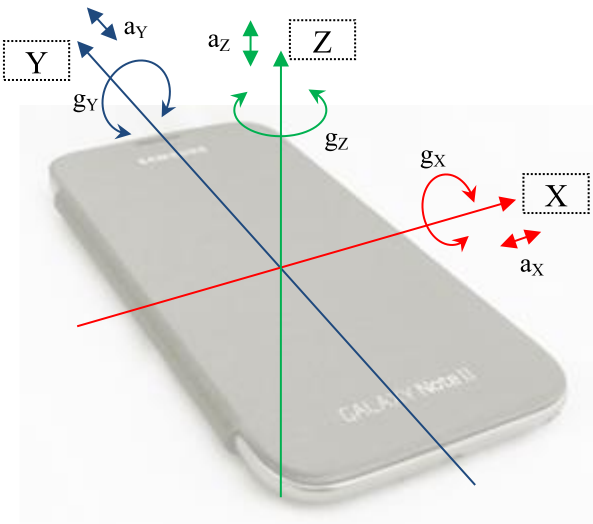
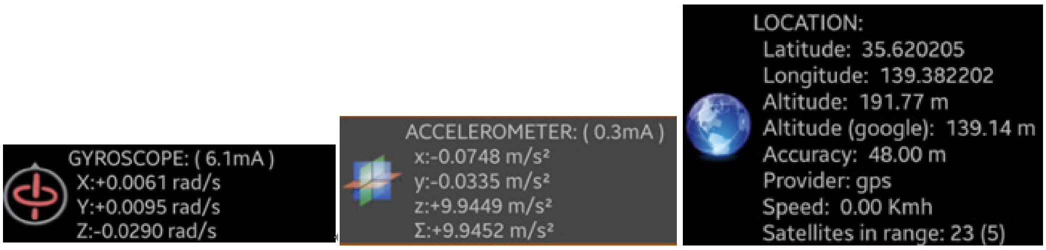


Figure 2-10: Smartphone referencing frame and the sensors' sensing axes

For the purpose of this study, only accelerometer, gyroscope and GPS are used. The 3 axis or 3D accelerometer sensors can monitor the motion or acceleration vibration of a device along each X, Y and Z axes of the smartphone reference frame (Figure 2-10). It can be used as an inertial measurement of velocity and position, tilt or orientation as referenced from the acceleration of the gravity, and shock vibration. The measuring unit of this sensor is m/s^2. The 3D gyroscope sensors measure angular acceleration force in rad/s (degree per second) around each axis.

Figure 2-11 presents samples of accelerometer, gyroscope and GPS data.



Gyroscope Accelerometer GPS

Figure 2-11: Samples of sensor data

2.5. Related work on using mobile sensors and smartphones to estimate road condition

There are very few studies that have directly explored the use of smartphone to estimate IRI of road pavement. In previous studies, while there is a lot of interest in detecting road bumps and anomalies using mobile sensors, majority of them focus on identifying and locating road bump and anomalies instead of estimating road pavement condition, particularly in terms of IRI measurement and/or estimation.

The most relevant work to the studies, undertaken in this dissertation, can be summarized as the following: (González et al., 2008) use a standalone accelerometer to fit in a simulation car and use it to assess road roughness condition. Their simulations conclude that roughness of the road can be estimated from acceleration data obtained from the sensor. (Eriksson et al., 2008) develop a system, called Pothole Patrol, which utilizes standalone accelerometers to successfully detect road anomalies. Pothole Patrol mainly analyses patterns and features of acceleration data in time domain to identify potholes. See Figure 2-12.

(Mohan et al., 2008) use many sensing component from mobile phone such as accelerometer, microphone, GSM radio, and GPS to monitor road and traffic condition. By analyzing data from the sensors, potholes, bumps, braking and honking can be detected. The information is then used to assess road and traffic conditions. (Mednis et al., 2011), and (Strazdins et al., 2011) use an Android smartphone device with accelerometer to detect location of potholes. Their approach includes many simple algorithms to detect events in the acceleration vibration data. (Tai et al., 2010), and (Perttunen et al., 2011); analyze data obtained by smartphone accelerometers in frequency domain to extract features that are corresponding to road bumps.

Figure 2-13 explains experiment equipment used in the experiment of Tai et al., 2010.

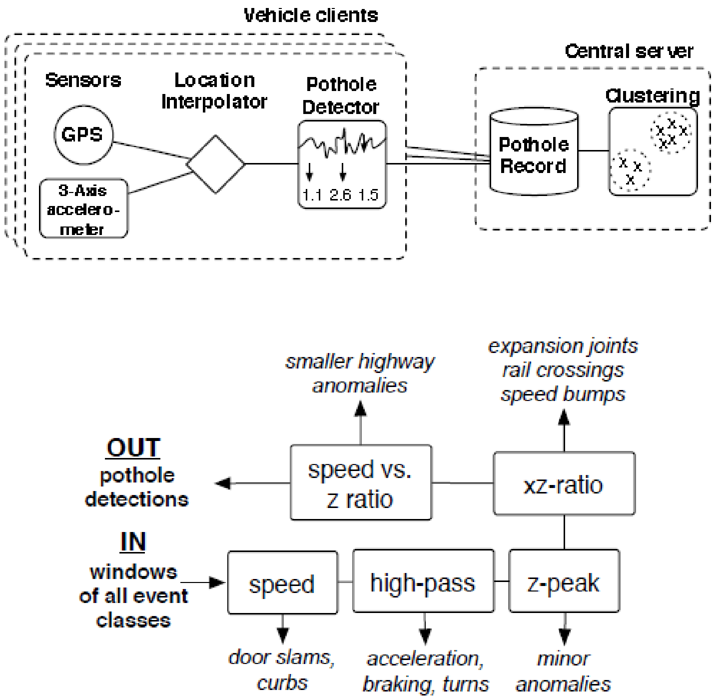


Figure 2-12: System architecture and approach of Pothole Patrol
Source: (Eriksson et al., 2008)

Figure 2-13: Tai et al (2010) experiment

2.6. Smartphone apps to estimate road condition

BumpRecorder:

This Android app is developed by a group of researchers in Japan (BumpRecorder, 2014). The app is originally developed to access the road network that has been affected by the March 11, 2013 earthquake in Tohoku region. It can be downloaded and installed on Android smartphones to be used for detecting the location and severity of road bumps on the road network. In implementation, the smartphones must be fixed on the dashboard of the vehicle while driving. The app analyzes data from accelerometer to detect road bumps and the bumps height or depth in centimeter. It also uses GPS data to mark the location of the bump on the map. Figure 2-14.

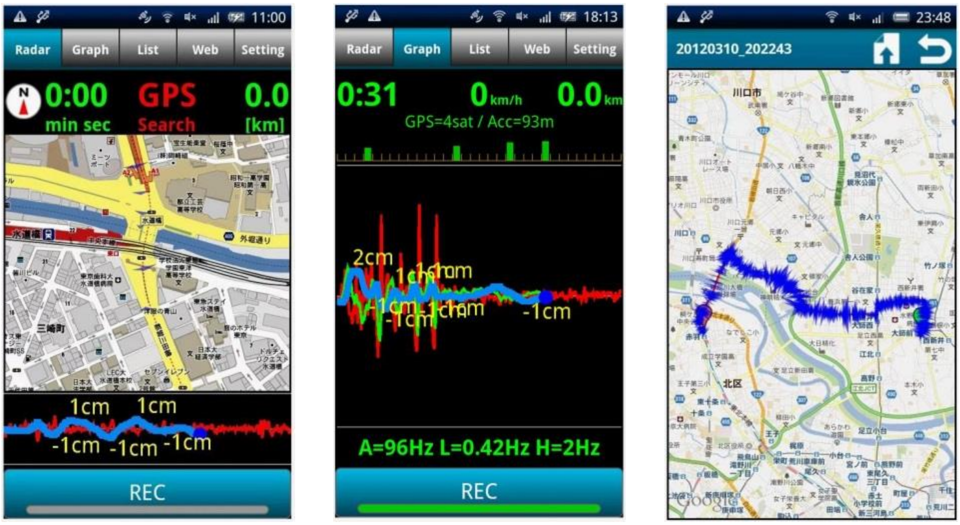


Figure 2-14: Screenshots of BumpRecorder
Source: (BumpRecorder, 2014)

Roadroid:

Roadroid (Roadroid, 2013) is also an Android app, developed by a Swedish engineer. This app estimates IRI based road roughness condition from data obtained from accelerometer in time domain, based on a peak and root mean square vibration analysis (Lars, 2013). To use the app, a smartphone has to be mounted on the vehicle's windshield using a special handle. After calibrating, the vehicle can run on the road to estimation pavement roughness. Results of the estimation can be presented on a map. Figure 2-15.

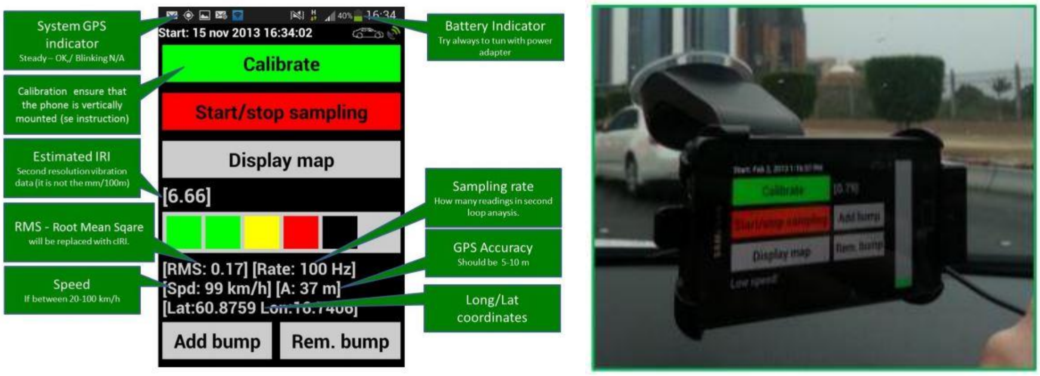


Figure 2-15: Roadroid
Source: (Roadriod, 2013)

Although both apps are innovative and promising, particularly Roadroid, they still have some limitations. The main limitations include:

- BumpRecorder only identify bumps, their severity and location. It cannot be used to assess IRI based road roughness condition;
- For both app, smartphones have to be carefully placed at a specific location, such as dashboard or with a special holder on the vehicle windshields, in order for the estimation to work (fixed orientation); and
- Physical calibrations before use are required.

2.7. Conclusions

In summary, road roughness condition, which is normally measured in the form of IRI, is a very important indicator in the field of road maintenance planning and management. Because, IRI affects the choice of road maintenance work and vehicle operating costs; thus the bigger the IRI of road networks, the greater the costs that will incur to the road authorities and road users, economically and socially.

IRI can be measured using many instruments based on many techniques. The instruments or approach are categorized into different classes in accordance to their measurement accuracy. Many of the instruments, especially in cases where high measurement accuracy is needed, are expensive to obtain and operate; while the others are less expensive to obtain and operate, but are usually come with less accuracy and time consuming process. Another issue is that almost all of the existing instruments are required to go through physical (hardware) calibrations before use.

There are many attempts by many researchers and developers to develop methods and instruments that are cheaper and easier to implement frequently. Introducing mobile sensors and smartphones is one of the promising directions. Despite the merits of the increasing smartphone users everywhere, there are only few studies that are seriously taking the advantage of the smartphones to estimate IRI based road roughness condition. The recent development of smartphone app and low cost tools, such as Roadroid and VIMS for instances, though seem to be simple and working promisingly, they still have some inconvenient limitations and the need to carry out hardware calibrations before employment still exists.

This dissertation focuses on the development of a simple method to estimate road roughness condition from smartphone sensors. Throughout the course of the studies, the final goal is to develop a system or a smartphone app to estimate IRI based road roughness condition that minimizes the above mentioned limitations. The smartphone app is expected to be much simpler and convenient for users. Physical calibration and the restriction on location and orientation of the smartphones should be no longer needed. Importantly, the app shall have an estimation model that takes advantages of data being collected and analyzed by anonymous drivers. In other words, the method will be positioned as an estimation instrument that is carried out by anonymous drivers on the actual traffic. Despite the fact that a single estimation from an individual or anonymous driver may not be accurate, in comparison to the use of profilers or VIMS, for instance; with increased or accumulated estimations being made available by many drivers would enable the approach to improve the accuracy of the estimation to an acceptable level needed for the purpose of road infrastructure maintenance planning and management.

Chapter 3: A STUDY ON THE RELATIONSHIP OF SMARTPHONE SENSOR DATA AND ROAD ROUGHNESS CONDITION

3.1. Introduction

The main objective of this chapter is to explore for features and relationships between smartphone sensor data and the actual road roughness condition. To achieve this objective, experiments are carried out on selected roads to collect the needed actual sensor as well as other data needed for the analysis. The analysis covers wide-range of investigations particularly on:

- The analysis of the relationship of data from only accelerometers, and the analysis of the relationship of data from both accelerometers and gyroscopes on IRI;
- The analysis of the relationships in cases where the sum of magnitudes is (1) the sum of magnitudes from all acceleration vibration axes as a single variable, and (2) the sum of each axis as an individual variable (the sum of magnitudes for X, Y and Z axes separately); and
- Detailed analyses into the relationships at different ranges of frequency, the effect of a variable such as speed, and the classification of roughness condition from the sum of magnitudes are also presented.

Some results and findings from this chapter has been published, presented and submitted in international journals and conferences: (DOUANGPHACHANH & ONEYAMA, 2013b), (DOUANGPHACHANH & ONEYAMA, 2013c), (DOUANGPHACHANH & ONEYAMA, 2013d), (DOUANGPHACHANH & ONEYAMA, 2014b), and (DOUANGPHACHANH & ONEYAMA, 2013e).

3.2. Experiments for data collection

3.2.1. Approach

Assuming that different road surface conditions cause vehicles to vibrate differently, therefore by placing smartphones that come built-in with accelerometer and gyroscope sensors, the variation of the vibration is believed to be captured. With this assumption, the main experiment has been carried out in Vientiane Capital City, Laos from 16th to 21st November 2012. Vientiane is chosen for these experiments because within the city area there are different types of road conditions, ranging from bad to excellent, which are very important for the purpose of this study.

In this main experiment, four smartphones and four vehicles are used. The specific objective of this experiment is to collect sensor data that can be analyzed to find basic relationships to the actual road surface condition. The smartphones are placed at 3 different locations inside the vehicles, which are running in normal traffic and driving situation along many roads that have different surface condition (IRI).

The 3 locations of the smartphones are:

- The vehicle dashboard in which the orientation of the smartphones is assumed to be fixed;
- The driver's shirt front pocket, where the orientation of the smartphones is free; and
- The box near the vehicle gearshift, where the orientation of the smartphones is also free.

A small number of driving under speed controlled conditions, in which the driving has been controlled at some approximately fixed speeds, is also performed on four selected short sections. The lengths of all four short sections are approximately in between 0.6 to 1 km; and the surface condition of each section also differs from each other, in which there is one section with surface condition of good, fair, poor, and bad, respectively.

A preinstalled app (detailed in section 3.2.2) on each smartphone is set to record data from accelerometer, gyroscope and GPS. A video camera and a GPS logger are also used. The video footage and route tracks from GPS will be used for data verification in case there is a need.

Totally, a road length of more than 300 km has been covered by the four vehicles. Vehicle 1 and Vehicle 3 cover approximately 110 km each; while Vehicle 2 and Vehicle 4 cover approximately 49 km each. See Table 3-1 and Figure 3-1.

Furthermore, an additional experiment has also been conducted in Vientiane Capital City, from 3^{rd} to 10^{th} March 2014. In this additional experiment, 11 smartphones (including 4 smartphones from the main experiment and additional 7 new smartphones) and two experiment vehicles are used. The specific objective of this experiment is mainly to collect additional data for further analysis on the effect of smartphones types and their locations on the relationship between the sensor data and road surface condition, for the studies of parameter coefficients of the model, and the data from this experiment is also used for analysis to verify some results of the first experiment.

Similar to the main experiment, the smartphones are placed at various locations inside the vehicles running on selected roads. The locations include fixed orientation (dashboard), and free orientation settings (driver's shirt pocket, driver's trousers pocket, on the front/rear passenger seats, in the box near the gear handle, in the box on the dash panel, on a handle attached to the windshield, for instance). Each smartphone in this experiment has also been rotatably placed at different location on the same vehicle and the same road section. See Table 3-2 and Figure 3-2.

In both experiments, the Vehicle Intelligent Monitoring System (VIMS) is also used to estimate the actual condition (IRI) of road sections selected for the experiments. Results from VIMS are used as a referenced road roughness condition data.

Table 3-1: The scope of the main experiment

Date	Experiment description	
	Vehicle type	Total road length covered
16-18 Nov 2012	Toyota VIGO 4WD Truck	110 Km
19-21 Nov 2012	Toyota Camry Sedan	49 Km
16-18 Nov 2012	Toyota VIGO 2WD Truck	110 Km
19-21 Nov 2012	Toyota Yaris Sedan	49 Km

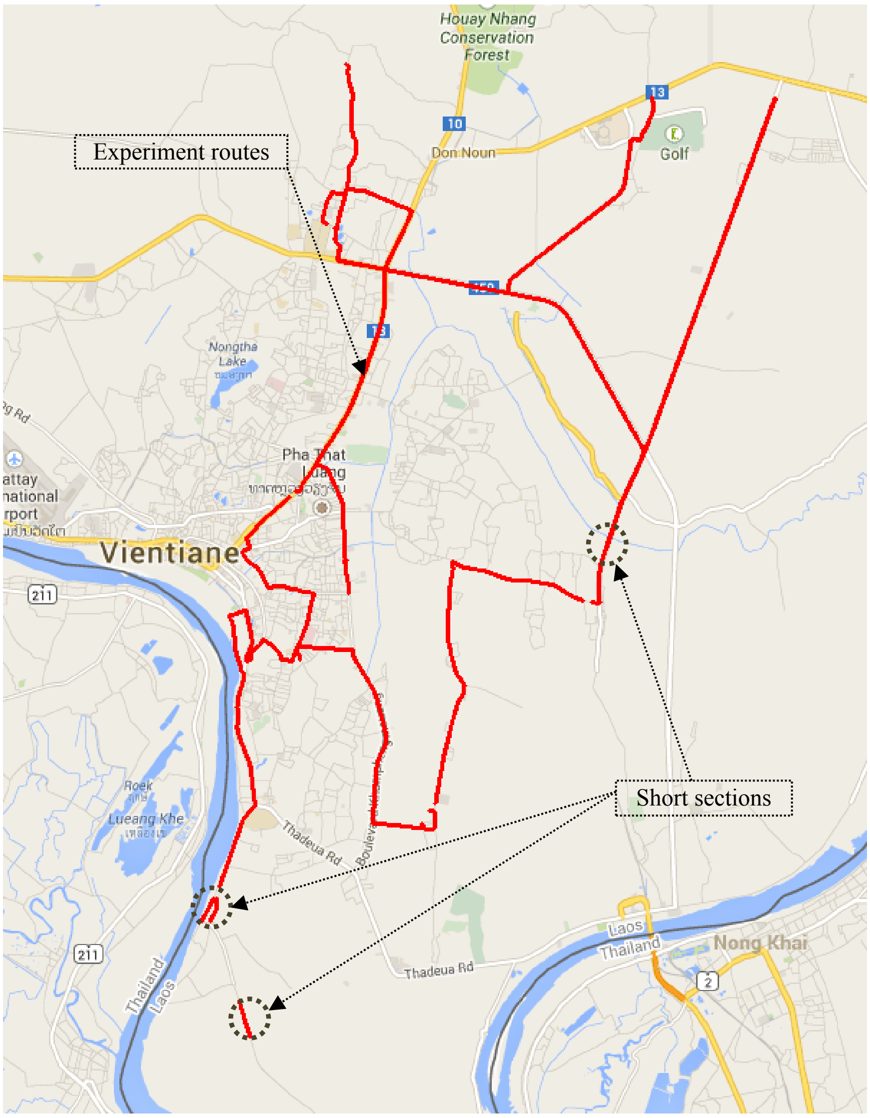


Figure 3-1: Routes of the main experiment

Table 3-2: The scope of the additional experiment

Date	Experiment description	
	Vehicle type	Total road length covered
3-8 Mar 2014	Toyota VIGO 4WD Truck	80 Km
10 Mar 2012	Toyota Land Cruiser	40 Km

Figure 3-2: Routes of the additional experiment

For both experiments, after obtaining and processing the data, analysis has been carried out. The whole process includes data filtering, matching, sectioning of sensor data into small files, and then each file is converted to analyze in frequency domain, has been carried out. See Figure 3-3.

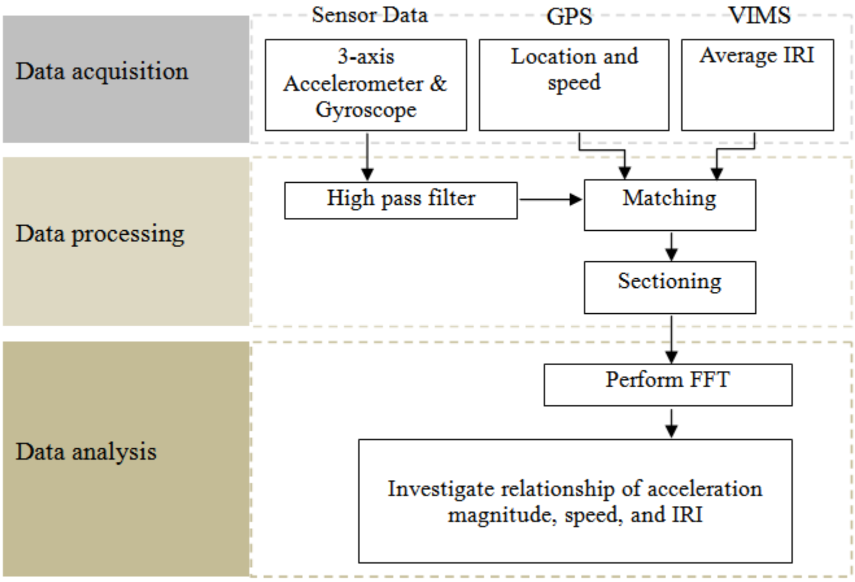


Figure 3-3: Process for the study of the relationship

3.2.2. Equipment and Software

The main equipment of the experiment in this study includes Android smartphones, vehicles, a GPS logger, a video recorder and VIMS.

Figure 3-4: Experiments equipment

Four vehicles in the main experiment include a Toyota VIGO 4WD pickup truck, a Toyota VIGO 2WD pickup truck, a Toyota Camry, and a Toyota Yaris; while the two vehicles in the additional experiment are the Toyota VIGO 4WD (the same vehicle used in the main experiment) and a Toyota Land Cruiser.

Table 3-3: List of smartphones

No	Smartphone	Model	Main experiment	Additional experiment
1	Samsung Galaxy NOTE II	GT-N7100	Yes	Yes
2	Samsung Galaxy NOTE II	GT-N7100	Yes	Yes
3	LG 4XHD	LG-P880	Yes	Yes
4	Samsung Galaxy S3	GT-I9300	Yes	Yes
5	Google Nexus 5	LG-D821	-	Yes
6	Google Nexus 5	LG-D821	-	Yes
7	Google Nexus 5	LG-D821	-	Yes
8	Sony Xperia Z1	C6903	-	Yes
9	LG G2	LG-D802	-	Yes
10	Samsung Galaxy NOTE III	N9005	-	Yes
11	OPPO Find5	OPPO X909	-	Yes

All smartphones are pre-installed with an application called "AndroSensor", AndroSensor (2012). AndroSensor is a data sensing app that can collect data from almost all of the sensors available on the smartphone handsets. The app is available for free download in Google Play Store.

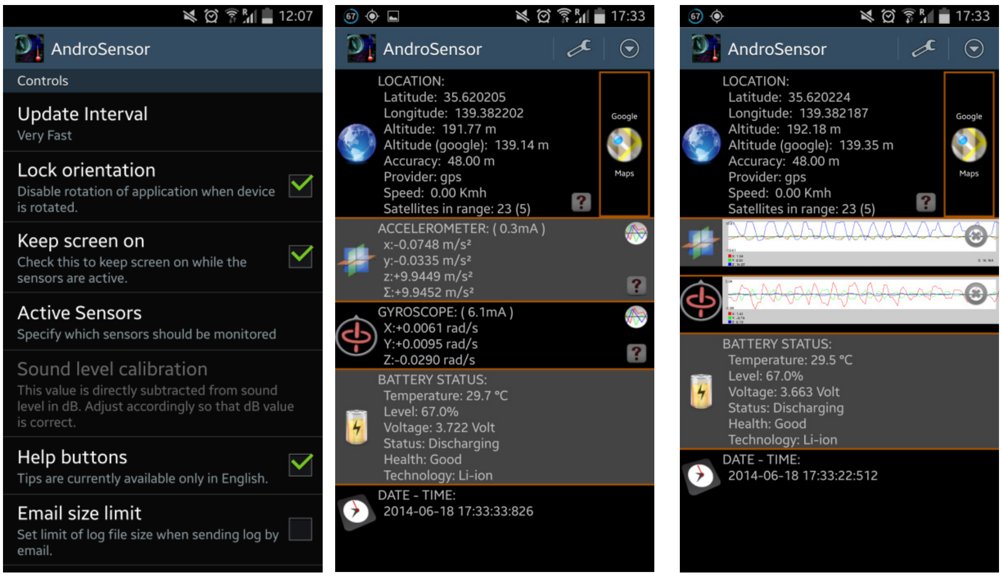


Figure 3-5: AndroSensor Screenshots

AndroidSensor can be configured to collect data from only selected or all sensors at the same time, set to save or upload data via email, set the rate of sampling and many more controls. The app can save all data into csv file formats on the smartphone internal memories and/or external drive such as a micro SD card depending on the setting. Screenshots and a sample data file (after converting to Microsoft Excel file format) of Androsensor are shown in Figure 3-5 and Table 3-4, respectively.

Table 3-4: Sample of AndroSensor data

ACCELEROMETER X (m/s^2)	ACCELEROMETER Y (m/s^2)	ACCELEROMETER Z (m/s^2)	GYROSCOPE X (rad/s)	GYROSCOPE Y (rad/s)	GYROSCOPE Z (rad/s)	LOCATION Latitude :	LOCATION Longitude :	LOCATION Altitude (m)	LOCATION Speed (Kmh)	LOCATION Accuracy (m)	Time since start in ms
-0.2107	7.1156	6.8187	0.0101	-0.066	-0.0308	35.62051	139.38179	189	7.7600527	12	10
-0.2107	7.1156	6.8187	0.0101	-0.066	-0.0308	35.62051	139.38179	189	7.7600527	12	20
-0.2107	7.1156	6.8187	0.0101	-0.066	-0.0308	35.62051	139.38179	189	7.7600527	12	30
-0.2107	7.1156	6.8187	0.0101	-0.066	-0.0308	35.62051	139.38179	189	7.7600527	12	40
-0.2107	7.1156	6.8187	0.0101	-0.066	-0.0308	35.62051	139.38179	189	7.7600527	12	50
-0.0287	7.1826	7.0773	-0.0507	-0.091	0.0177	35.62051	139.38179	189	7.7600527	12	60
-0.6225	7.3646	8.0445	-0.0333	-0.0086	-0.0027	35.62051	139.38179	189	7.7600527	12	70
-0.6225	7.3646	8.0445	-0.0333	-0.0086	-0.0027	35.62051	139.38179	189	7.7600527	12	80
-0.0958	7.8721	7.4795	0.0168	-0.0874	0.0464	35.62051	139.38179	189	7.7600527	12	90
-0.0958	7.8721	7.4795	0.0168	-0.0874	0.0464	35.62051	139.38179	189	7.7600527	12	100
-0.0958	7.8721	7.4795	0.0168	-0.0874	0.0464	35.62051	139.38179	189	7.7600527	12	110
-0.0958	7.8721	7.4795	0.0168	-0.0874	0.0464	35.62051	139.38179	189	7.7600527	12	120
1.063	7.7859	6.4548	0.0776	-0.0345	0.0977	35.62051	139.38179	189	7.7600527	12	130
1.063	7.7859	6.4548	0.0776	-0.0345	0.0977	35.62051	139.38179	189	7.7600527	12	140
1.063	7.7859	6.4548	0.0776	-0.0345	0.0977	35.62051	139.38179	189	7.7600527	12	150
1.063	7.7859	6.4548	0.0776	-0.0345	0.0977	35.62051	139.38179	189	7.7600527	12	160
1.063	7.7859	6.4548	0.0776	-0.0345	0.0977	35.62051	139.38179	189	7.7600527	12	170
1.245	6.8761	5.7748	0.0275	0.015	0.0348	35.62051	139.38179	189	7.7600527	12	180
1.245	6.8761	5.7748	0.0275	0.015	0.0348	35.62051	139.38179	189	7.7600527	12	190
0.7853	8.2456	7.5753	-0.0391	-0.0455	-0.0608	35.62051	139.38179	189	7.7600527	12	200
0.7853	8.2456	7.5753	-0.0391	-0.0455	-0.0608	35.62051	139.38179	189	7.7600527	12	210
0.7853	8.2456	7.5753	-0.0391	-0.0455	-0.0608	35.62051	139.38179	189	7.7600527	12	220
-0.2203	7.0102	5.9951	0.1042	0.026	-0.1539	35.62051	139.38179	189	7.7600527	12	230

AndroidSensor that is used for the experiments in this study is a special version obtained directly from the developer. This version can record at a very fast interval of more than 100Hz. For both experiments, only data from accelerometer (X, Y, Z); gyroscope (X, Y, Z) and location data (longitude, latitude, speed…) from GPS are needed. Data recording is done at an interval of 0.01 second or at a frequency rate of 100Hz. A simple calibration is done for all devices with AndroSensor before use, by setting the devices in different orientations to collect data; after that data from the devices is compared against each other to verify that they are working properly.

3.2.3. Referenced Road Roughness Condition Data

Referenced pavement condition data for this study is also obtained using VIMS. VIMS has been developed by Bridge and Structure Laboratory at the University of

Tokyo, Japan (Furukawa, 2005). The system is now being deployed for road management purpose in Laos.

VIMS deploys an accelerometer and a GPS on a vehicle. A driver then drives the vehicle on a road and calculates IRI based on acceleration response of the vehicle. Figure 4 shows the concept of VIMS approach.

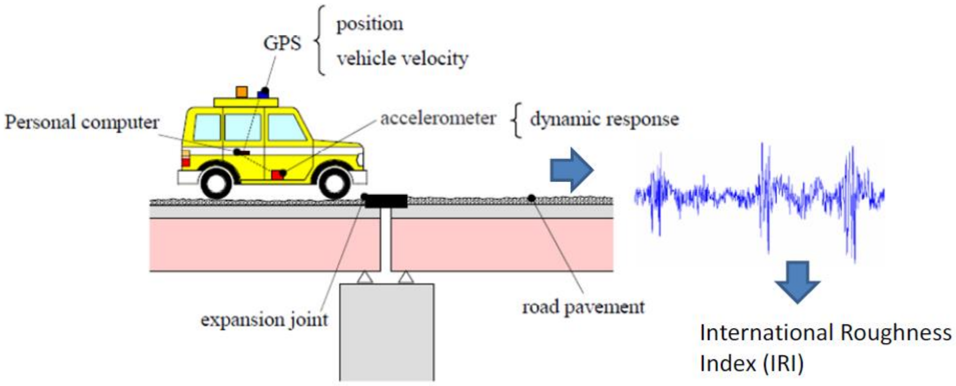


Figure 3-6: VIMS approach
Source: (Fujino et al., 2005; Nagayama et al., 2013; VIMS Manual, 2012)

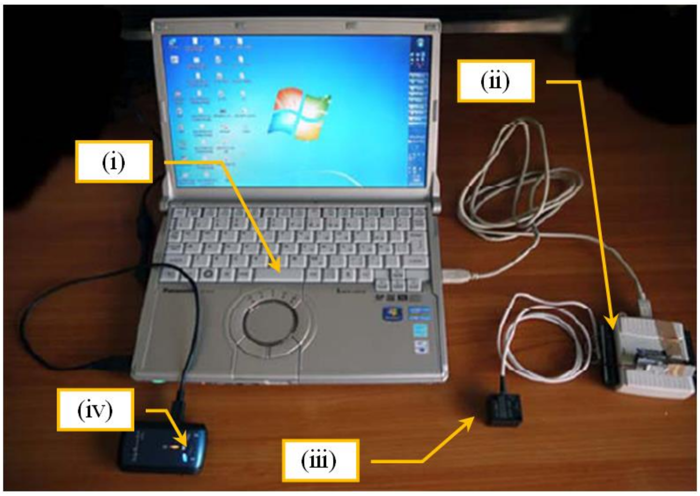


Figure 3-7: VIMS component
Source: (Nagayama et al., 2013)

VIMS comprises of both hardware and software (Fujino et al., 2005). The hardware includes (i) a laptop computer, (ii) a data acquisition module, (iii) an accelerometer and (iv) a GPS logger, see Figure 3-7. All the components are connected to each other via cables. For software, the system consists of two main programs, (1) An application for calibration and data collection, Figure 3-8; and (2) an application to carry out the analysis, Figure 3-9.

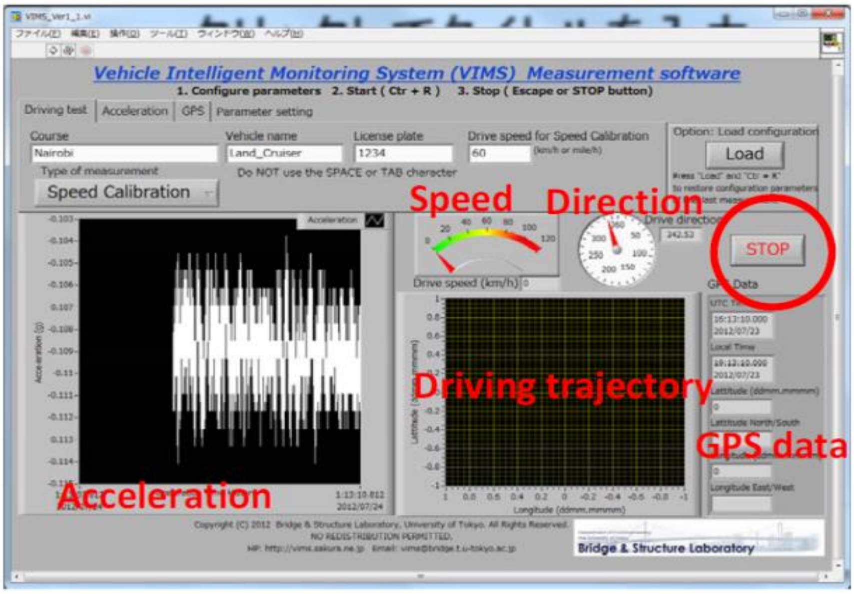


Figure 3-8: VIMS calibration and data collection software
Source: VIMS Manual, 2012

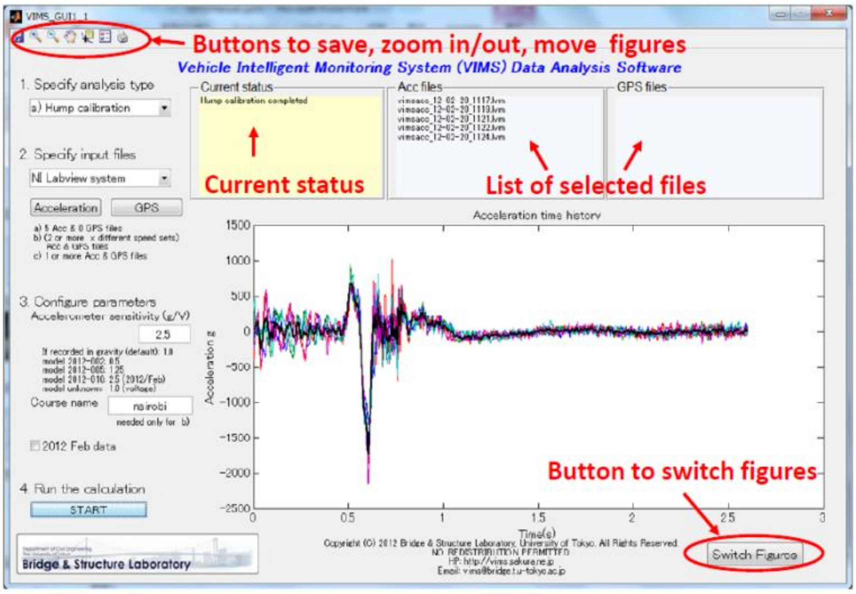


Figure 3-9: VIMS data analysis software
Source: VIMS Manual, 2012

The system calculates IRI for every 10 meter road section. The result can be put in Excel spreadsheet as well as visual presentation on Google Earth. VIMS can only calculate IRI when driving speed of the experiment vehicles is 20kph or faster. A sample of VIMS result is shown in Table 3-5.

Table 3-5: Example of VIMS result

VIMS	Date	IRI	Latitude	Longitude
	2012/12/10	8.46215	17.88805	102.6108
	2012/12/10	8.13753	17.88796	102.6108
	2012/12/10	7.808368	17.88788	102.6107
	2012/12/10	7.231083	17.8878	102.6107
	2012/12/10	6.931109	17.88772	102.6106
	2012/12/10	5.939928	17.88764	102.6106
	2012/12/10	6.177234	17.88756	102.6105
	2012/12/10	6.357153	17.88748	102.6105

For the experiments, VIMS is used with only two vehicles in the main experiment, and one vehicle in the additional experiment. To properly use VIMS, a calibration is required for each vehicle that VIMS will be used with. Each calibration consists of two parts, speed and hump calibrations, which takes half a day to complete (VIMS Consortium, 2012). VIMS data collection is carried out at the same time of the smartphone data collection.

3.2.4. Experiment Setting

For the main experiment, as mentioned earlier, a total of four smartphones are used. Two smartphones are glued closed to each other on the dashboard of the experiment vehicles with strong and thin adhesive tapes. The screens of the smartphones are facing up and the heads pointing towards the front of the vehicle. The orientation of these two smartphones are assumed to be fixed, therefore, the X, Y and Z axes of the smartphone reference frame represent the motion along left-right, front-rear and up-down of the vehicle, respectively. The remaining two smartphones are placed inside the driver's shirt front pocket and in the box near the gearshift, respectively. These smartphones are not glued or fixed, therefore their orientation is assumed to be free. See Figure 3-10.

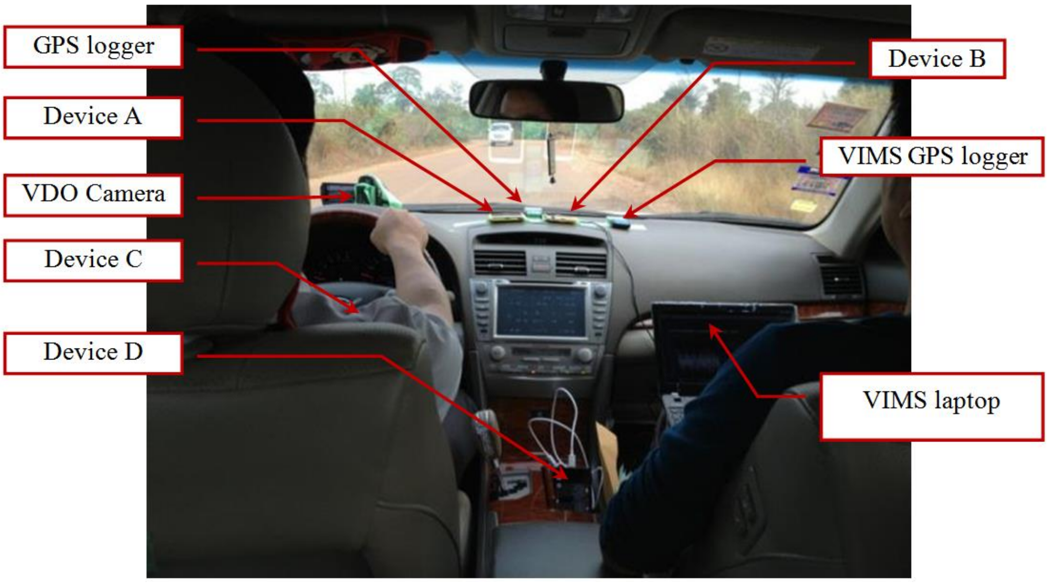


Figure 3-10: Experiment setting, the main experiment

For the additional experiment, all eleven smartphone are also placed at different locations inside the vehicle.

Details of the locations of the smartphones in the main experiments are indicated in the Table 3-6 below. Note that in Table 3-6, Device A is a Samsung Galaxy Note II (1), Device B is a Samsung Galaxy SIII, Device C is a Samsung Galaxy Note II (2), and Device D is a LG HDX. Locations of the smartphones used in the additional experiment and details of the smartphones are shown in Appendix B.

As indicated in Figure 3-10 above, a GPS logger and a video camera are also placed on the dash board of the vehicles. GPS logger records all the tracks of road section that the vehicles have passed through, while the video camera films road surface of the routes. The route tracks and road surface footage can be used to verify surface condition status against IRI measured by VIMS.

VIMS components are also installed in accordance to the VIMS manual (VIMS Consortium, 2012). For every vehicle that uses VIMS, two calibrations are carried out before data collection.

Table 3-6: Smartphone location for the main experiment

Experiment date	Vehicle and equipment	Location of smartphone
17-18 Nov 2012	Vehicle 1:	
	Device A	Dash board
	Device B	Dash board
	Device C	Pocket
	Device D	Near gearshift
19-20 Nov 2012	Vehicle 2:	
	Device A	Dash board
	Device B	Dash board
	Device C	Pocket
	Device D	Near gearshift
21 Nov 2012	Vehicle 1:	
	Device A	Dash board
	Device B	Dash board
	Device C	Near gearshift
	Device D	Pocket
22 Nov 2012	Vehicle 3:	
	Device A	Dash board
	Device B	Dash board
	Device C	Pocket
	Device D	Near gearshift
23 Nov 2012	Vehicle 4:	
	Device A	Dash board
	Device B	Dash board
	Device C	Pocket
	Device D	Near gearshift

3.2.5. Implementation

After setting and getting all the equipment ready, including calibrations of the vehicle for VIMS, the experiment vehicles will be driven along many selected roads to collect sensor data and actual IRI (from VIMS). The driving, in normal traffic condition, is done at different time of the day and shares the same routes for all vehicles and on different days. Driving on many road sections are also repeated more than once.

Speed controlled driving is carried out at the selected short sections. Three different speed ranges are applied for each short section, which the whole section has roughness condition of good or fair or poor and or bad, respectively. The speed ranges include approximately 20-30km/h, 40-50km/h, and 70-80km/h. 3 to 5 iterations for each speed range are done at each section depending on its roughness condition.

3.3. Data processing

Data from smartphones is uploaded into a desk top computer and converted to excel spreadsheets. The spreadsheets are carefully checked manually to select only road sections that have complete data sets, both data from smartphones and IRI data from VIMS. Sections with incomplete data set are the sections that have no data from VIMS, i.e. when the vehicle speed is too slow (<20kph) in traffic jam condition.

A simple high pass filter, a standard method used for Android devices, Android Developer Reference (2012), is applied to remove unrelated low frequency signal, which usually causes by the effect of vehicle maneuver such as changing speed and turning as well as the contribution of the force of gravity, from all axes (X, Y and Z) of the acceleration data.

Data matching by GPS coordinates is carried out. This process merges IRI data from VIMS with the acceleration data from smartphones for the same road sections. Then, the merged data files are cut into small 100 meter sections based on VIMS GPS coordinates. A 100 meter length of acceleration data is chosen as a unit for road surface estimation in this study. The reasons are (i) because Road Management System in Laos requires road surface condition to be estimated for every 100 meter section, therefore it would be more convenient to select the same unit so that it is compatible for future application; (ii) there is a concern on the accuracy of GPS position data, thus choosing a shorter section unit may cause some issues for data matching between VIMS and smartphone GPS data. In the sectioning process, road sections, where experiment vehicles have stopped (checking from speed and VIMS results) are excluded since data at these sections cannot be used to estimate road roughness condition. In addition, sections that are less than 100 meters are also ignored.

Sections that are qualified and selected for the analysis are summarized in Table 3-7 below.

Table 3-7: 100 meter sections resulted from sectioning, the main experiment

	Vehicle 1: Toyota VIGO 4WD Pick UP						Vehicle 2: Toyota Camry Sedan				Vehicle 3: Toyota VIGO 2WD Pick				Vehicle 4: Toyota Yaris Sedan			
	Device						Device				Device				Device			
	A	B	C	C	D	D	A	B	C	D	A	B	C	D	A	B	C	D
Number of sections selected for analysis	703	674	311	246	320	492	497	489	467	592	314	319	309	421	408	411	382	450
Location of smartphone	Dashboard	Dashboard	Pocket	Near gearshift	Pocket	Near gearshift	Dashboard	Dashboard	Pocket	Near gearshift	Dashboard	Dashboard	Pocket	Near gearshift	Dashboard	Dashboard	Pocket	Near gearshift

All selected data sections are converted to frequency domain and perform Fast Fourier Transform (FFT). FFT is an algorithm that is widely used in digital signal processing, engineering, science, mathematics and many other applications. It is one of the methods that are used to compute Discrete Fourier Transform (DFT). FFT is the most efficient and extremely fast, while giving the same results as other methods, to convert time domain signal into frequency domain signal (Smith, 1997).

Magnitude from FFT is the amplitude or strength of the associated frequency component. For a specific frequency window, it is assumed that the total sum of magnitudes represents the total strength of the vibration at that frequency window. Therefore, sum of magnitudes from FFT is studied to find out features, effect and relationship that the acceleration data might have in connection with road roughness condition.

Calculation of the sum of magnitudes from accelerometer data is done in 2 arrangements: (1) combining acceleration data from each X, Y, Z axis to get the sum of total acceleration vibration for a 100m section, before calculating the sum of magnitudes (the sum of magnitudes X, Y, Z of each 100m section), and (2) calculating the sum of magnitudes for each X, Y, Z axis separately (the sum of magnitudes X, sum of magnitudes Y and sum of magnitudes Z separately). However, since it does not make sense to combine gyroscope forces, sum of magnitudes from gyroscope is only calculated in one arrangement, which is the sum of magnitudes for each X, Y, Z axis separately.

Since the sampling rate of a waveform in time domain determines the maximum resolvable frequency, which is half the sampling rate (NI, 2013); therefore, for the sampling rate of 100Hz, magnitude of the frequency from 0-50Hz can be calculated using FFT.

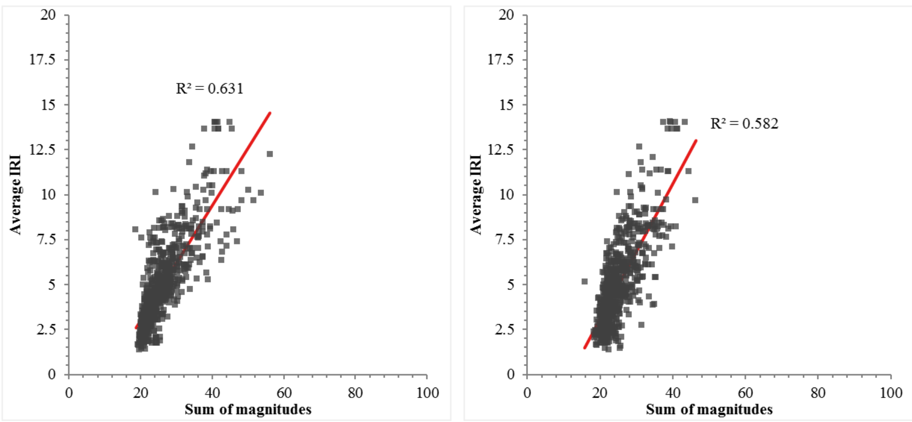
Simple program using VBA in Microsoft Excel is coded and applied to get all the process mentioned above done. The coding can be found in Appendix C.

3.4. Analysis results 1: Considering only accelerometer.

Note that analysis in this section is carried out using data from the main experiment, unless indicated otherwise. Only data from accelerometer is used. The relationships between the data from the accelerometer, sum of magnitudes, and the actual road roughness condition, average IRI, are analyzed. An average IRI is calculated from 10 VIMS IRI values (VIMS calculates IRI for every 10 meter road section) that comprises into a 100 meter road section. Sum of magnitudes is the total magnitude derived from FFT of the sum of acceleration X, Y and Z in 100 meter road sections (The sum of magnitudes X, Y, Z).

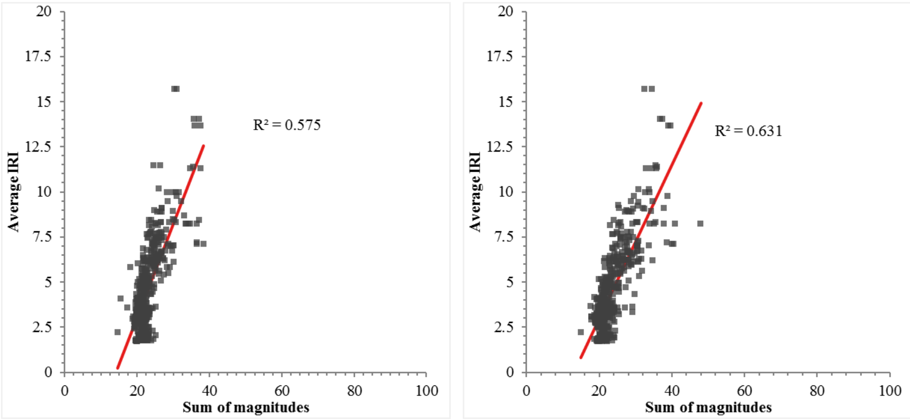
3.4.1. Fixed orientation smartphones

Fixed orientation smartphones are Device A and Device B, in the main experiment, which are glued on the dashboard of the vehicles. Figure 3-11 to Figure 3-14 below show linear relationship between sum of magnitudes of acceleration data and average road roughness (IRI) for fixed smartphones on all 4 vehicles, at the total frequency range of 0-50Hz.



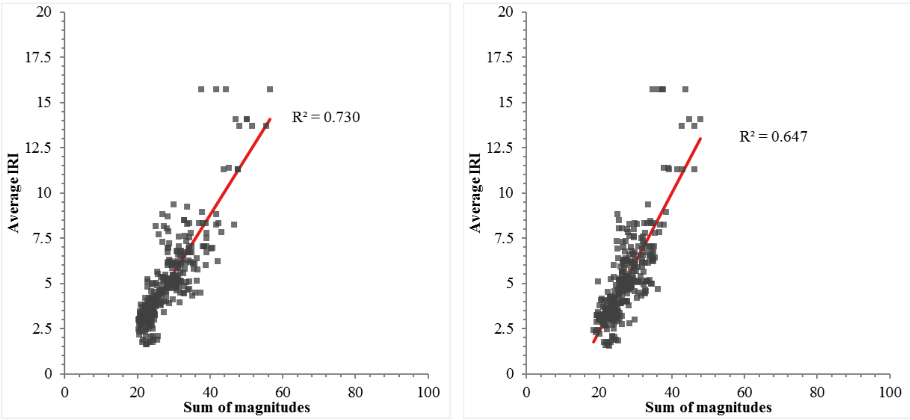
Device A Device B

Figure 3-11: Fixed orientation, Vehicle 1 (Device A and Device B)



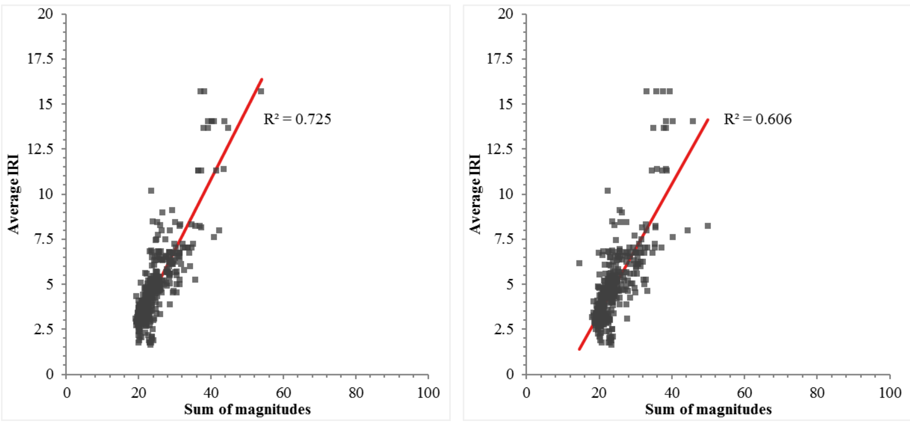
Device A Device B

Figure 3-12: Fixed orientation, Vehicle 2 (Device A and Device B)



Device A Device B

Figure 3-13: Fixed orientation, Vehicle 3 (Device A and Device B)



Device A Device B

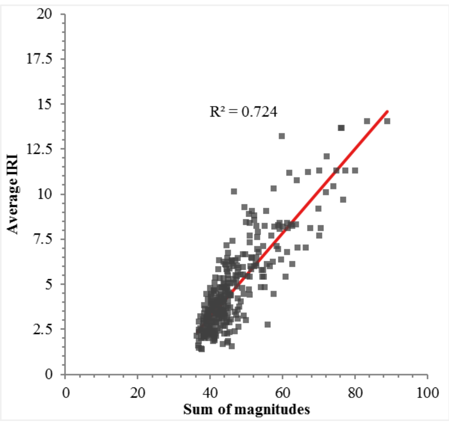
Figure 3-14: Fixed orientation, Vehicle 4 (Device A and Device B)

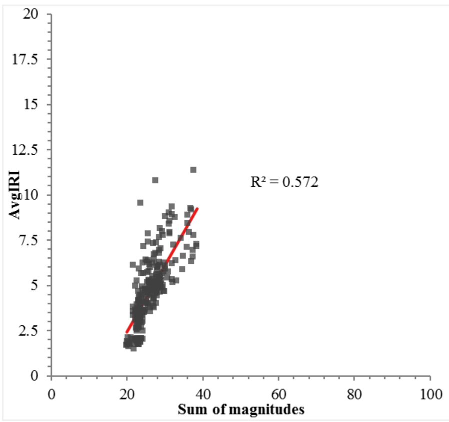
From the graphs above, it can be seen that there are linear relationships between the magnitudes of the acceleration vibration and IRI. The significant of the relationships is slightly different depending on the vehicles and smartphones. R^2 obtained from Device A tend to be greater than that of Device B in all vehicles, except in the case of Vehicle 2. The biggest R^2 obtained from fixed smartphones is 0.730, which is from Device A in Vehicle 3; while the smallest R^2 is also derived from Device A in Vehicle 2 (0.575).

3.4.2. Free orientation smartphones

Free orientation smartphones are Device C and Device D, in the main experiment, which are placed inside the driver's shirt pocket and inside the box near the gearshift, respectively. Device C and D have been switched their locations on one occasion during the Vehicle 1 experiment. To distinguish this switch, Device Cp and Device Db are used to represent Device C and Device D, when there are at their original locations; while Device Cb and Device Dp are used to represent the two smartphones, when their locations are switched.

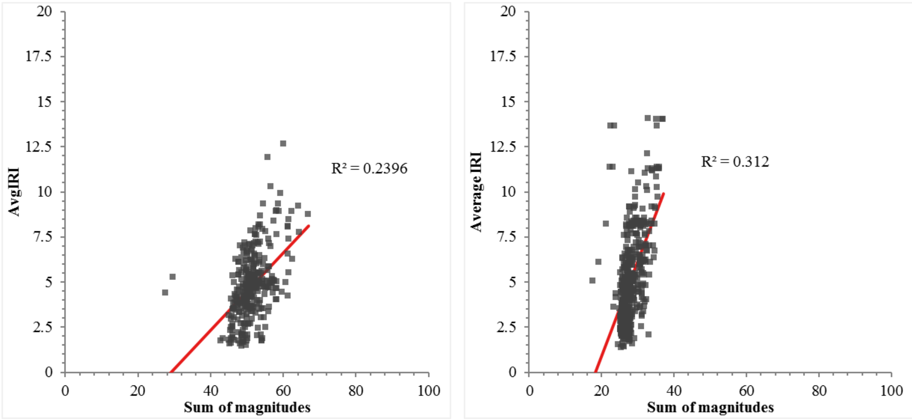
The linear relationship of the magnitudes and IRI for the cases of these free orientation smartphones, at the total frequency range of 0-50Hz, are presented in figures below.





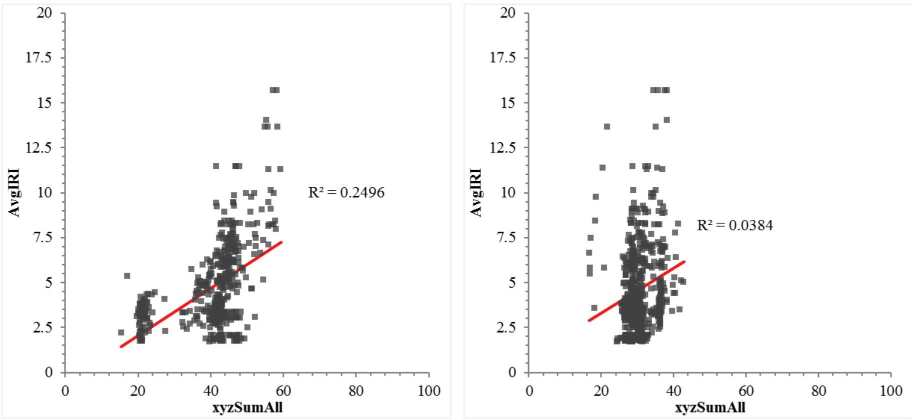
Device Cp Device Db

Figure 3-15: Free orientation, Vehicle 1 (Dev Cp and Device Db)



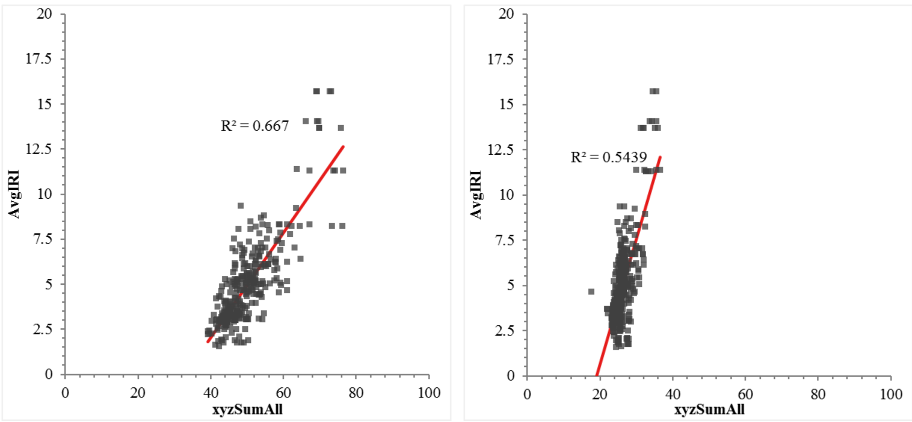
Device Dp Device Cb

Figure 3-16: Free orientation, Vehicle 1 (Device Dp and Device Cb)



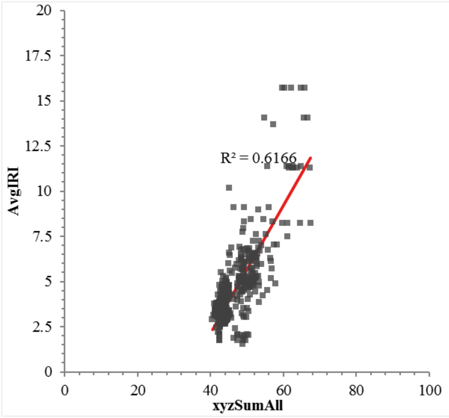
Device C Device D

Figure 3-17: Free orientation, Vehicle 2 (Device C and Device D)

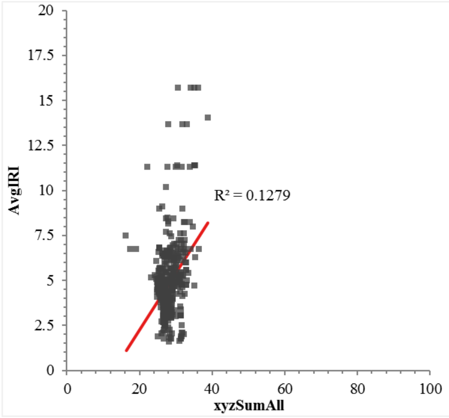


Device C Device D

Figure 3-18: Free orientation, Vehicle 3 (Device C and Device D)



Device C



Device D

Figure 3-19: Free orientation, Vehicle 4 (Device C and Device D)

Figure 3-15 to Figure 3-19 shows R^2 from smartphones that are placed inside the driver's shirt pocket (Device Cp, Device Dp and Device C), and smartphones that are place inside the box near the gearshift (Device Cb, Device Db, and Device D), in the Vehicle 1, 2, 3, and 4 respectively. By each vehicle, R^2 from the smartphones, which are placed inside the driver's pocket, tend to be better than R^2 from the smartphones that are placed inside the box near the gearshift. It could be said that, the smartphones inside the pocket may absorb the vibration, which is related to the roughness condition of the road surface, better than the one inside the box near the gearshift. Or the smartphones inside the box near the gearshift may absorb more noise than the smartphones that are placed inside the pocket.

The location switch between the two smartphones also indicates that regardless of the smartphones, the pocket is still better to capture the vibration from road surface roughness.

Figure 3-20 and Figure 3-21 show that, in general, R^2 from the smartphones, which are placed inside the driver's pocket are considerably good with many cases having the R^2 of more than 0.600 and as high as 0.724 (except in Vehicle 2 and Vehicle 1 Dp, where the value of R^2 is small, 0.250 and 0.240 respectively). In contrast, the R^2 of the smartphones that are placed inside the box near the gearshift, are relatively small (0.038, 0.128 and 0.312 for Vehicle 2, Vehicle 4 and Vehicle 1, respectively), while the highest value is 0.572 in Vehicle 1 Db and 0.544 in Vehicle 3 respectively.

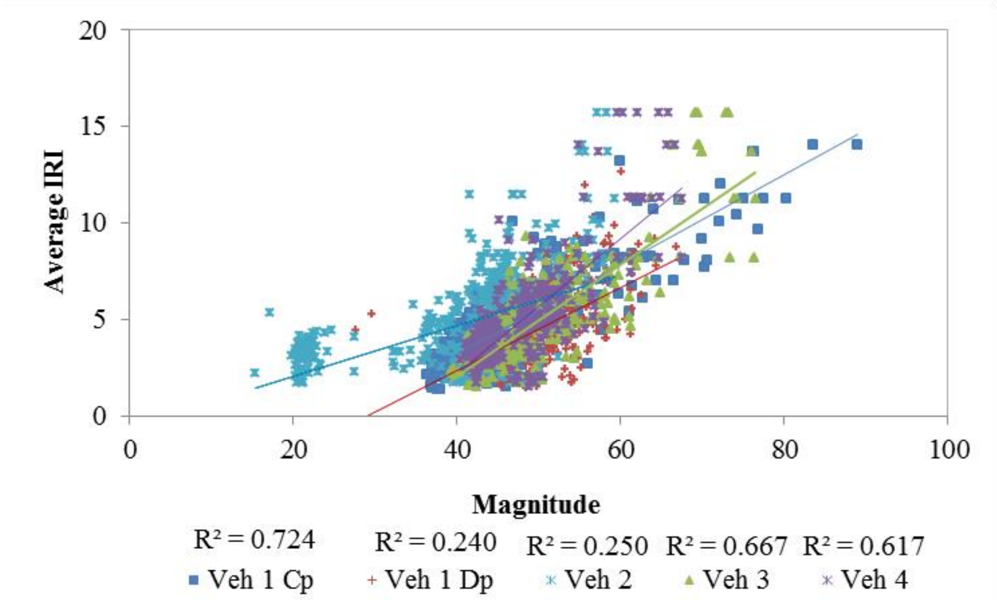


Figure 3-20: Free oreintation, all vehicles (Pocket)

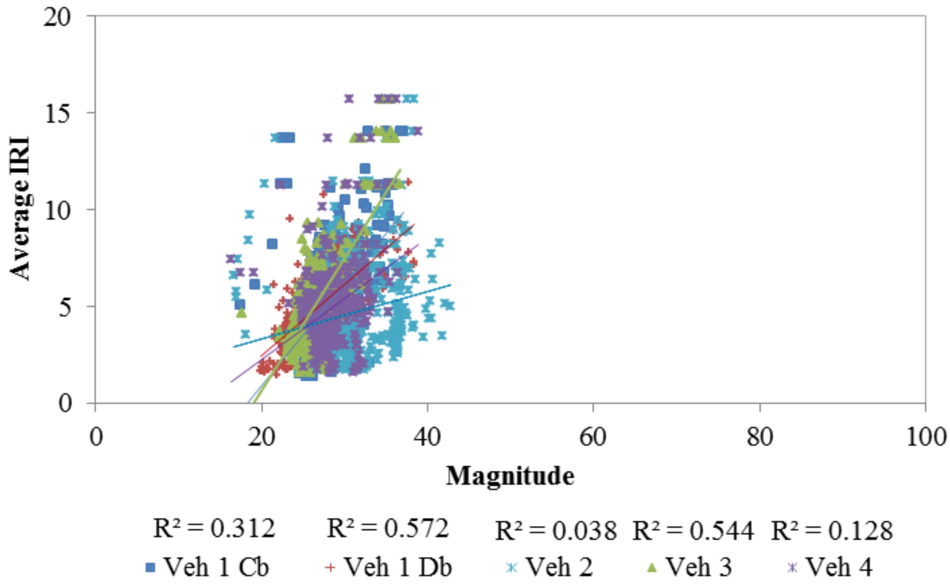


Figure 3-21: Free oreintation, all vehicles (Box)

Despite having found strong relationships between the magnitudes of acceleration and the average IRI, R^2 of the relationships vary particularly in cases of the free orientation smartphones. In the fixed orientation smartphones R^2 in all cases are considerably consistent. However, in the free orientation smartphones, a mix of strong and weak R^2 are observed. These smartphones may absorb some noise that may not be related to the vibration caused by road surface roughness (such as driver movement, vehicle engines, etc.), which may occur at some certain frequency ranges. To further investigate on this, frequency range and the effect of speed analysis are carried out. Details of the analysis are outlined in the following subsections.

3.4.3. The relationship at different ranges of frequency

To study the relationships between the magnitudes and IRI at different breakdown frequency ranges, for this study, the following breakdown frequency ranges are considered: the frequency range of 0-10Hz, 10-20Hz, 20-30Hz, 30-40Hz, 40-50Hz, 5-15Hz, 15-25Hz, 25-35Hz and 35-45Hz. The sum of magnitudes of the acceleration at these particular frequency ranges are identified from FFT and studied against IRI to find out their relationships.

Selected results are shown in the following Figure 3-22 to Figure 2-29:

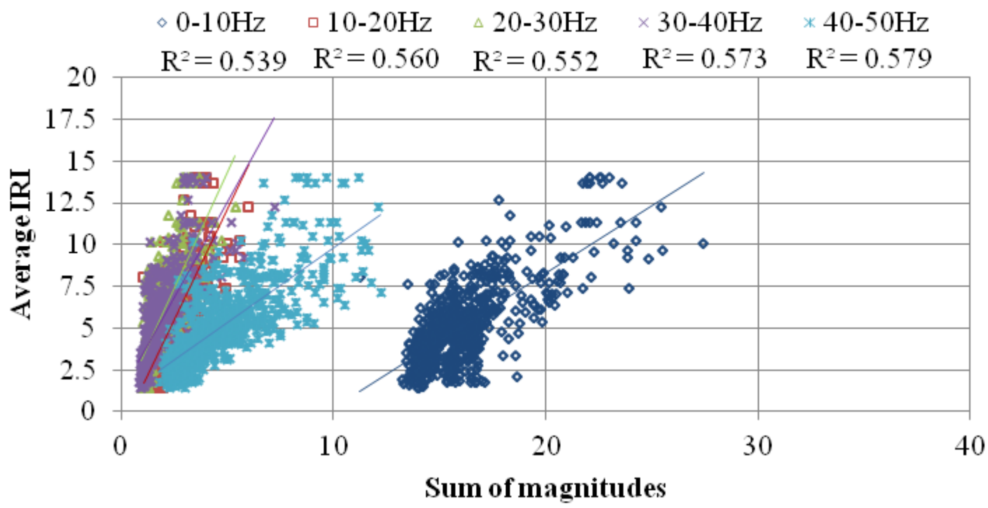


Figure 3-22: Breakdown frequency a (Vehicle 1, Device A)

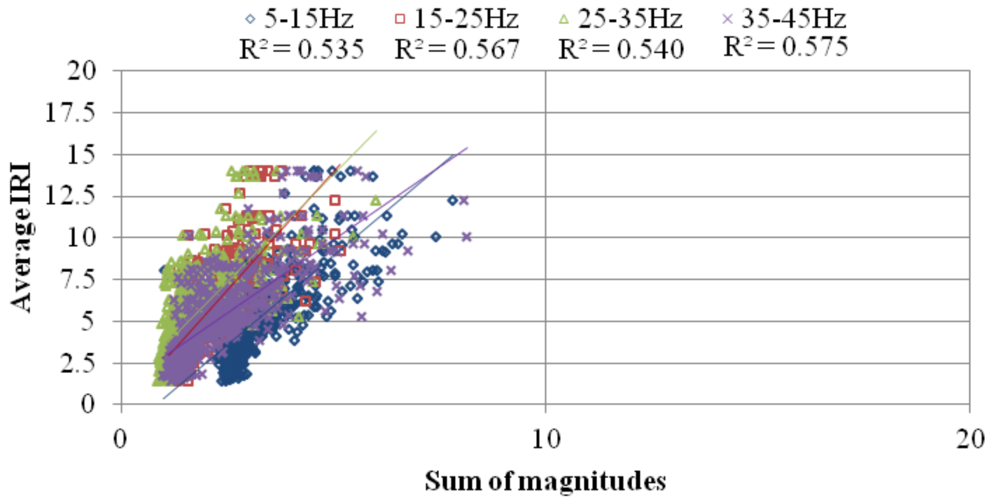


Figure 3-23: Breakdown frequency b (Vehicle 1, Device A)

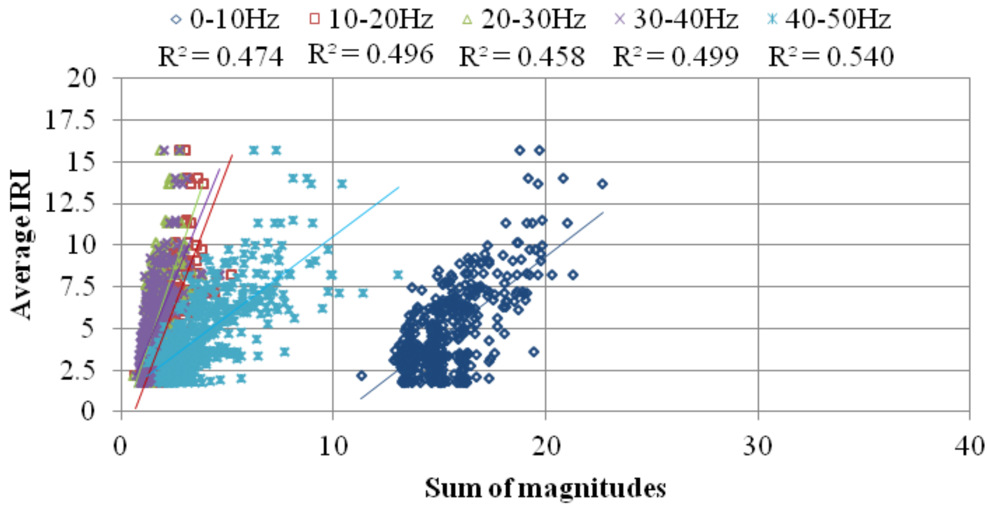


Figure 3-24: Breakdown frequency a (Vehicle 2, Device B)

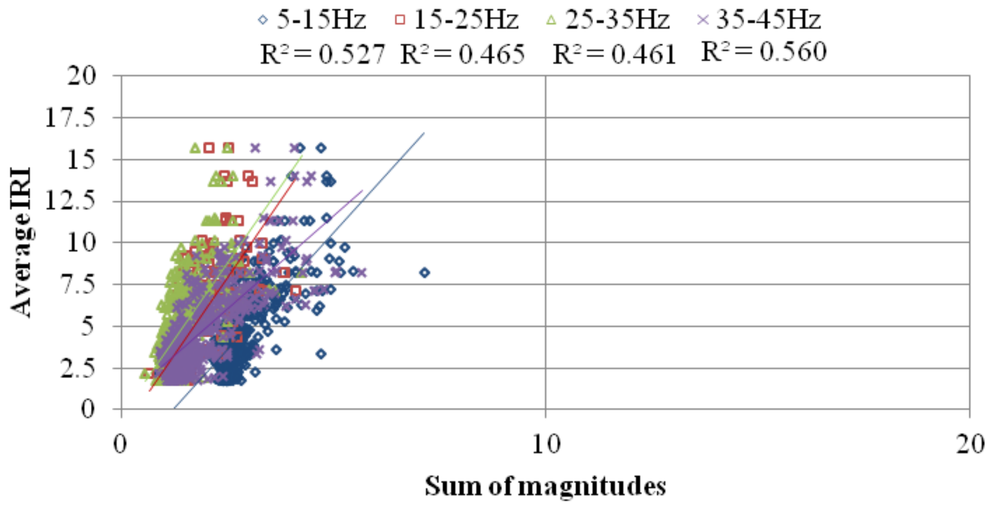


Figure 3-25: Breakdown frequency b (Vehicle 2, Device B)

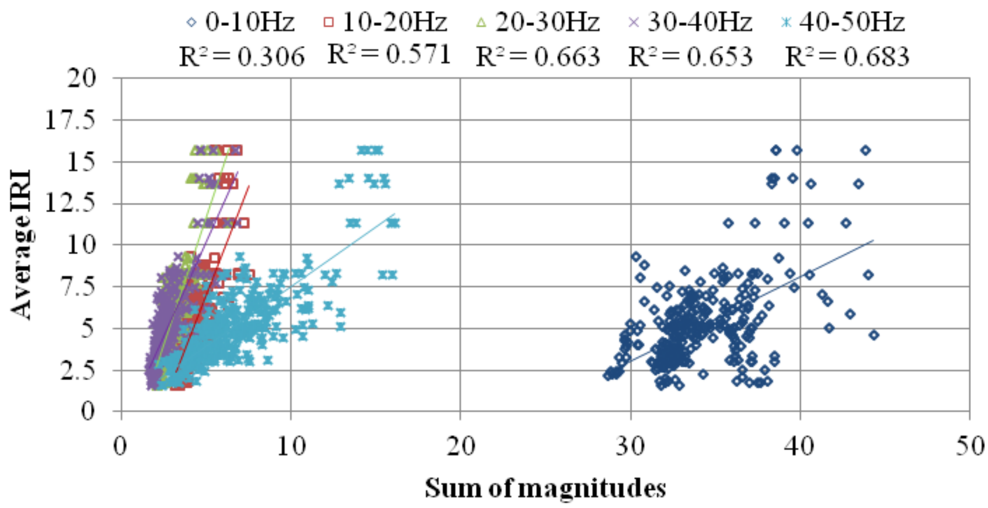


Figure 3-26: Breakdown frequency a (Vehicle 3, Device C)

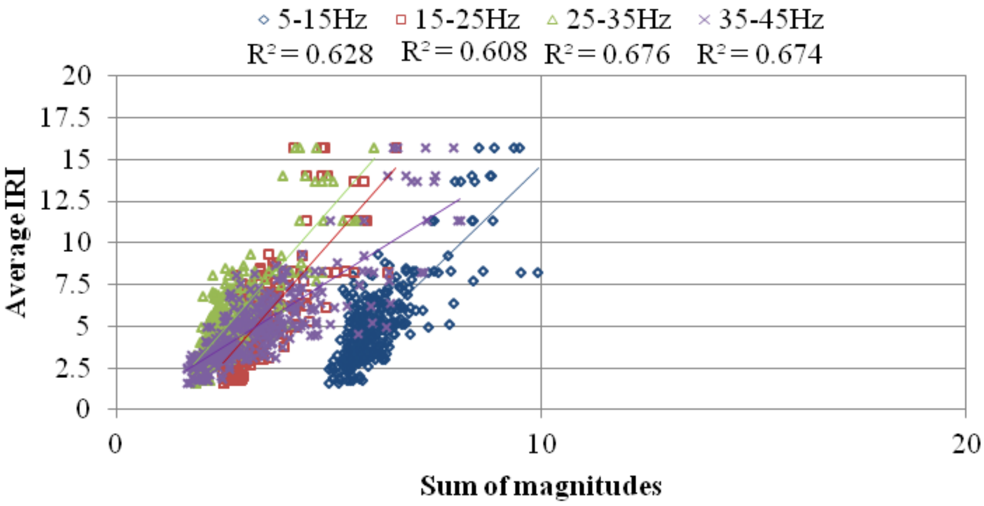


Figure 3-27: Breakdown frequency b (Vehicle 3, Device C)

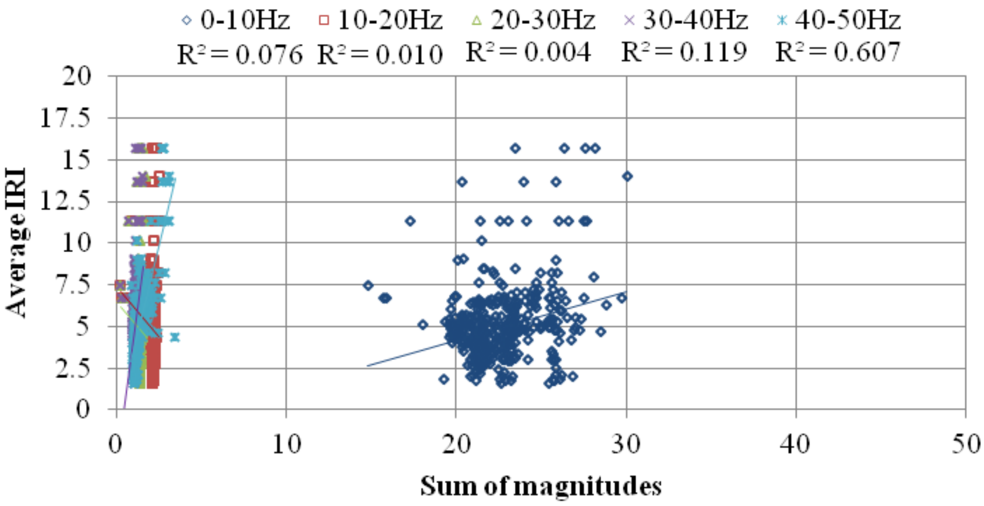


Figure 3-28: Breakdown frequency a (Vehicle 4, Device D)

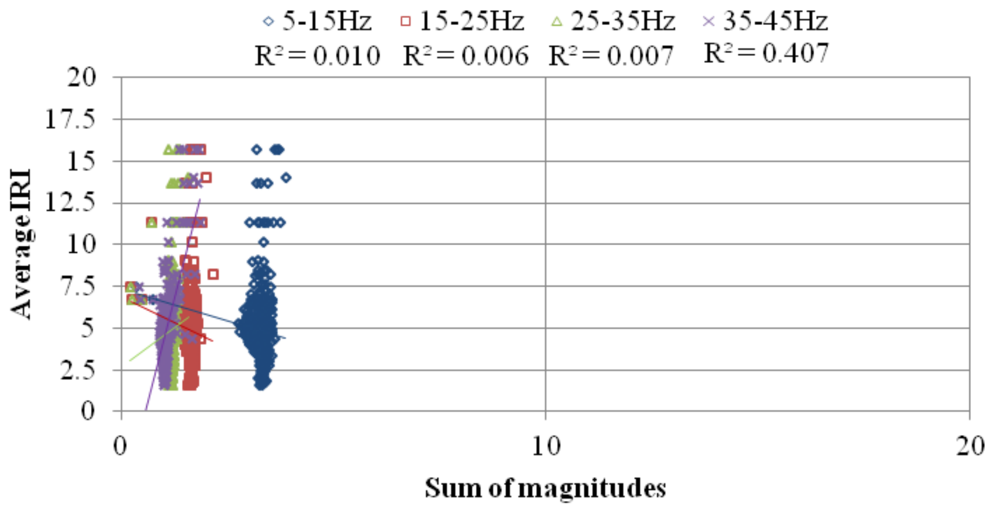


Figure 3-29: Breakdown frequency b (Vehicle 4, Device D)

It has been observed that at the breakdown frequency range of 40-50Hz, R^2 are highest for almost all of cases. While the R^2 at the range of 40-50Hz for Device A and Device B (the fixed orientation smartphones on the dashboard) improve slightly (see Figure 3-22 to Figure 3-25 for selected results), the R^2 for Device C and Device D (the free orientation smartphones inside the pocket and the box near the gearshift) improve significantly (see Figure 3-26 to Figure 3-29 for selected results). It is assumed that since Device C and Device D are free to move, thus they may absorb noise that may not relevant to the road roughness condition. The irrelevant noise may come from the movement of the driver, the maneuver of the vehicles, and the engine noise, for instances. From the breakdown frequency relationships, it is believed that the noise that Device C and Device D absorb may occur at low frequency ranges. Therefore, at the frequency range 40-50Hz the relationships of the magnitudes and IRI are strongest. The frequency range of 40-50Hz is believed to be the most relevant frequency range for the estimation of road roughness condition from the acceleration magnitudes.

Table 3-8 and Figure 3-30 summarize R^2 at all the breakdown frequency ranges for all devices in all vehicles.

Table 3-8: Summary of R^2 by breakdown frequency ranges

Vehicle	Device	R^2 by Frequency Ranges								
		0-10Hz	10-20Hz	20-30Hz	30-40Hz	40-50Hz	5-15Hz	15-25Hz	25-35Hz	35-45Hz
1	A	0.539	0.560	0.552	0.573	0.579	0.535	0.567	0.540	0.575
	B	0.517	0.426	0.484	0.460	0.459	0.423	0.461	0.478	0.439
	Cp	0.555	0.625	0.616	0.695	0.753	0.672	0.616	0.661	0.731
	Db	0.175	0.004	0.057	0.368	0.687	0.002	0.012	0.173	0.606
	Cb	0.074	0.120	0.176	0.372	0.589	0.143	0.146	0.266	0.484
	Dp	0.119	0.485	0.581	0.611	0.601	0.507	0.478	0.600	0.609
2	A	0.288	0.428	0.459	0.557	0.573	0.433	0.476	0.506	0.608
	B	0.474	0.496	0.458	0.499	0.540	0.527	0.465	0.461	0.560
	C	0.179	0.171	0.188	0.372	0.528	0.133	0.170	0.243	0.499
	D	0.040	0.018	0.009	0.0001	0.484	0.0001	0.484	0.013	0.016
3	A	0.659	0.671	0.692	0.698	0.632	0.619	0.700	0.691	0.681
	B	0.528	0.504	0.539	0.509	0.553	0.528	0.450	0.522	0.541
	C	0.306	0.571	0.663	0.653	0.683	0.628	0.608	0.676	0.674
	D	0.320	0.441	0.461	0.687	0.751	0.420	0.421	0.606	0.717
4	A	0.572	0.632	0.656	0.700	0.692	0.666	0.615	0.694	0.691
	B	0.461	0.499	0.473	0.579	0.604	0.562	0.511	0.498	0.614
	C	0.333	0.644	0.629	0.687	0.735	0.668	0.611	0.630	0.713
	D	0.076	0.010	0.004	0.119	0.607	0.010	0.006	0.007	0.407

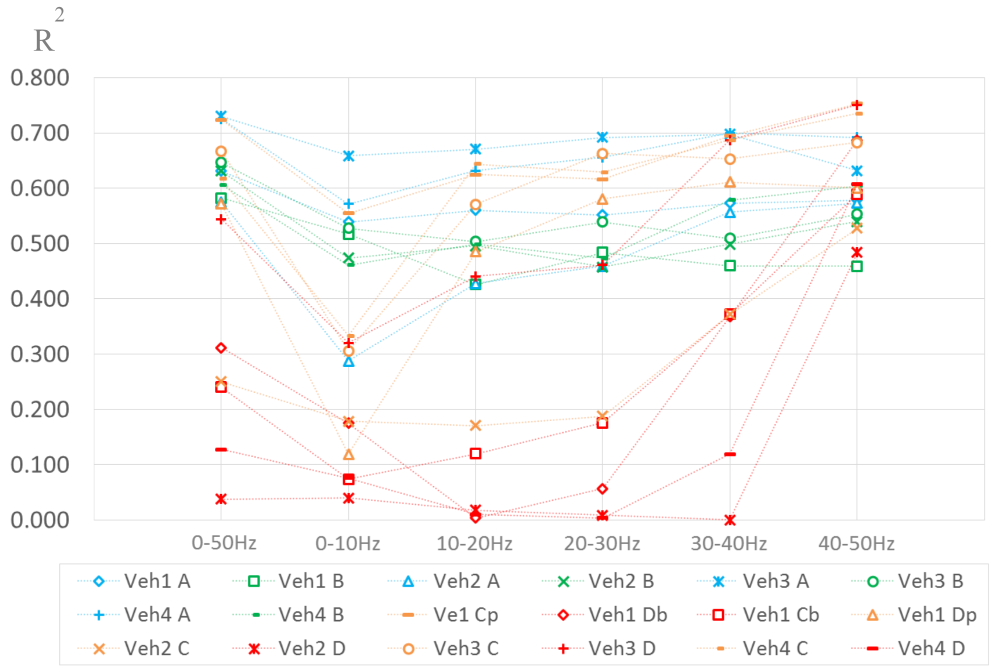


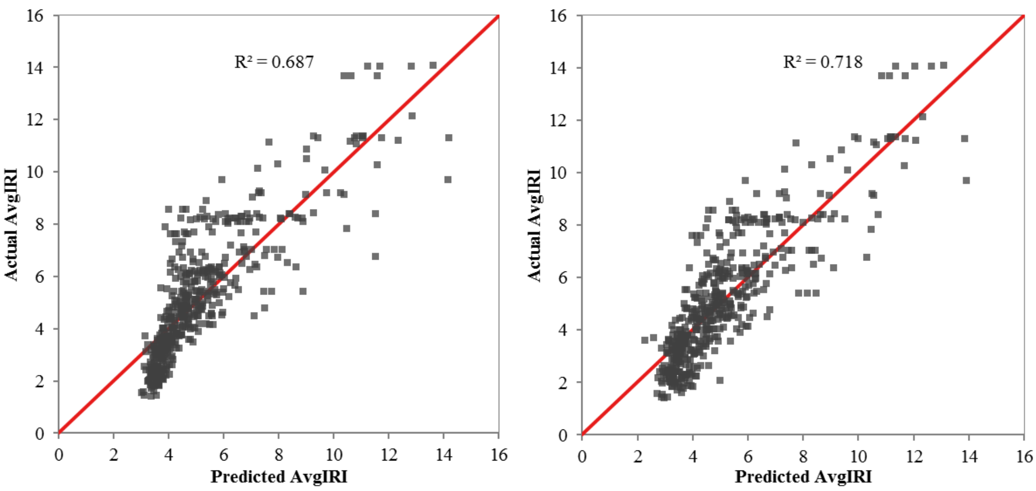
Figure 3-30: R^2 at different frequency ranges

3.4.4. Effect of speed

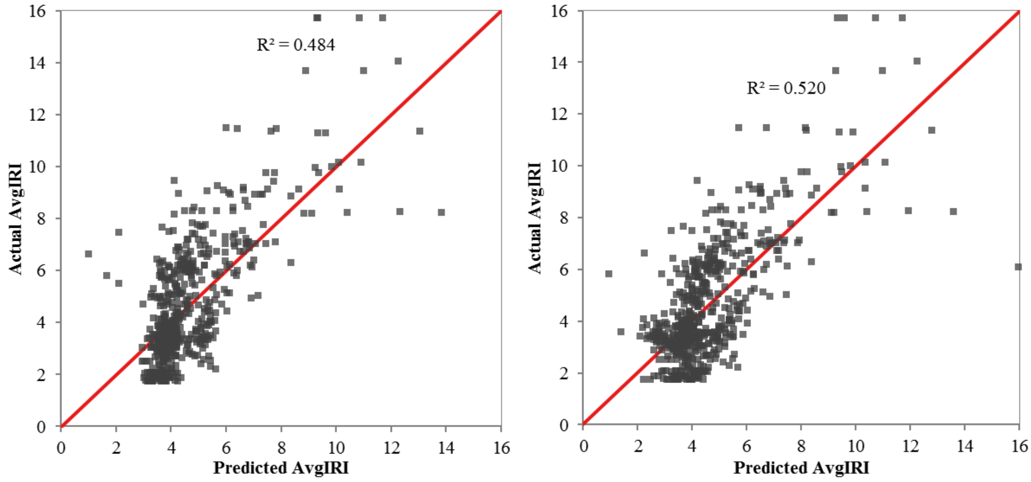
Speed may be one of the factors that affect the representation of acceleration vibration towards road roughness condition. To prove this, an investigation is carried out by implementing multiple regression analysis. IRI is set as the dependent variable, while the sum of magnitudes the average speed are set as the explanatory variables; assuming that IRI can be estimated as a function of the magnitude and the average speed. Below is a summary of multiple regressions for device D in each experiment vehicle (see Appendix D for more details of other devices). Statically, for all tests presented below, it is clear that speed does have some influence on the way acceleration vibration represent road roughness condition.

Table 3-9: Selected summary of multiple regression analysis (40-50Hz)

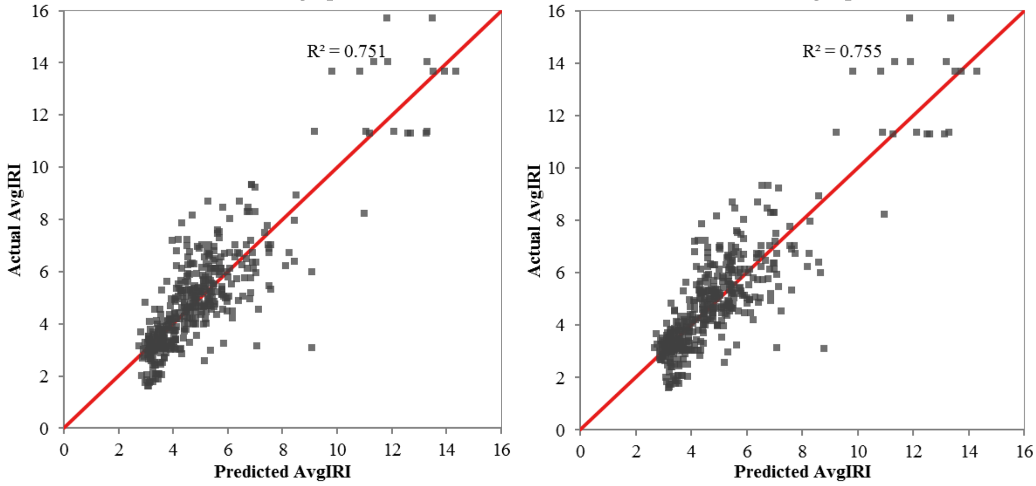
Device D (Box near gearshift)								
	Vehicle 1		Vehicle 2		Vehicle 3		Vehicle 4	
Observations	492		592		421		450	
Multiple R	0.847		0.721		0.869		0.786	
R Square	0.718		0.520		0.755		0.617	
Adjusted R Square	0.717		0.519		0.754		0.616	
F Stat	622.926		319.211		644.126		360.712	
	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat
Intercept	2.024	5.795	-1.390	-2.853	0.733	2.124	0.796	1.703
Magnitude	3.190	27.398	6.138	20.042	2.984	29.934	3.823	19.854
Avg. Speed	-0.038	-7.370	-0.030	-6.673	-0.013	-2.558	-0.021	-3.503



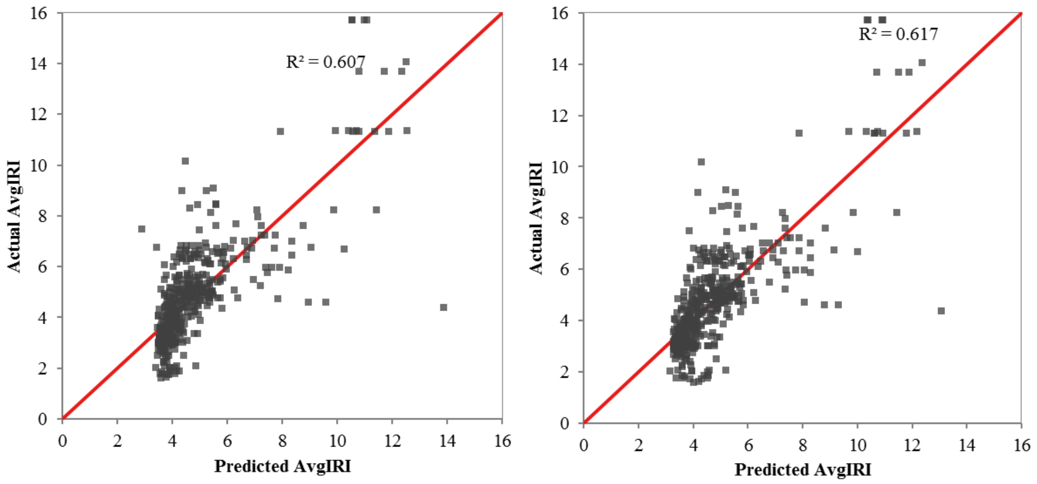
Not considering speed **Vehicle 1** Considering Speed



Not considering speed **Vehicle 2** Considering Speed



Not considering speed **Vehicle 3** Considering Speed



Not considering speed **Vehicle 4** Considering Speed

Figure 3-31: Actual and predicted IRI, multiple regressions (Device D)

See appendix E for more details.

It has been observed that the multiple regression yields a very good fit. A selected result (a result from Device D) summarized in Table 3-9 below, shows that the intercept and coefficient of the average IRI and average speed are statistically significant.

The coefficients of the magnitudes is positive, meaning that the worse the road surface condition is, the larger the sum of magnitudes of vibration. On the other hand, coefficient of the average speed is negative. This implies that a speed increase would mean a smaller sum of magnitudes, which could mean better road surface condition. One of the reasons could be, however, in general, drivers tend to drive at a higher speed on good roads; and at a much slower speed on road with bad surface condition. In addition, although the order of the coefficients is very similar for all devices and vehicle, the difference of coefficient by vehicle type and devices is observed.

3.4.5. Classification the magnitudes of vibration

To further understand the characteristics and trends of the acceleration magnitudes of different smartphones, the magnitudes are classified into roughness condition indexes. For this purpose, 4 condition indexes of road roughness, as summarized in Table 3-10, have been proposed.

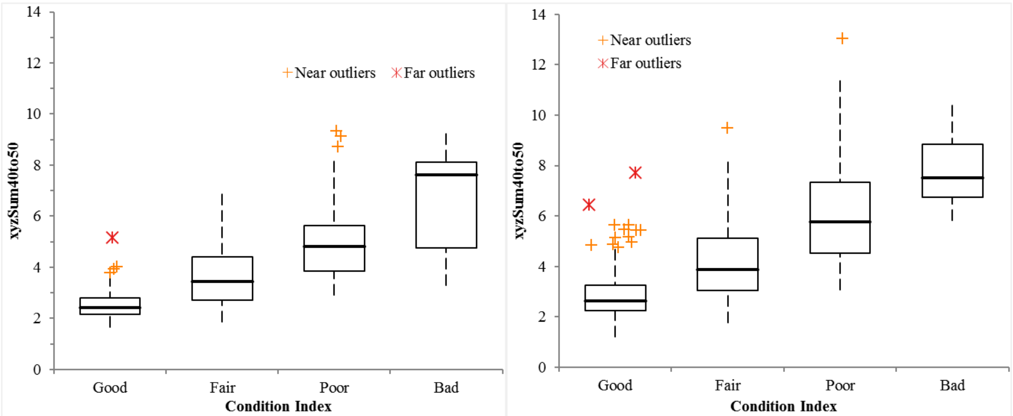
Table 3-10: Condition index

Index	Average IRI
Good	$0 \leq IRI < 4$
Fair	$4 \leq IRI < 7$
Poor	$7 \leq IRI < 10$
Bad	$IRI \geq 10$

The above indexes are adopted from road roughness condition bands used in Lao Road Management System (PTI, 2011b), where it uses 6 road condition bands: 1)

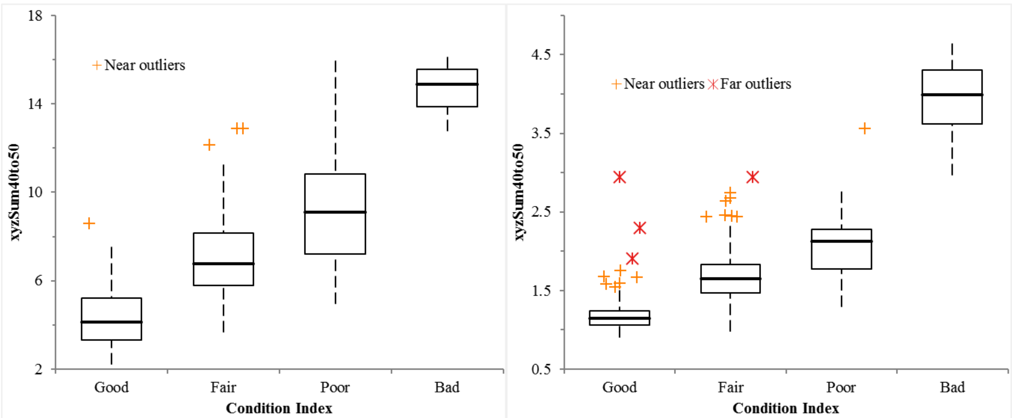
Excellent (0≤IRI<2), 2) Good (2≤IRI<4), 3) Fair (4≤IRI<7), Poor (7≤IRI<10), 5) Bad (10≤IRI<18), and Failed (IRI≥18).

Figure 3-32 and Figure 3-33 below show some selected results.



a. Device A b. Device B

Figure 3-32: Classification of magnitude by condition index, Vehicle 2



a. Device C b. Device D

Figure 3-33: Classification of magnitude by condition index, Vehicle 3

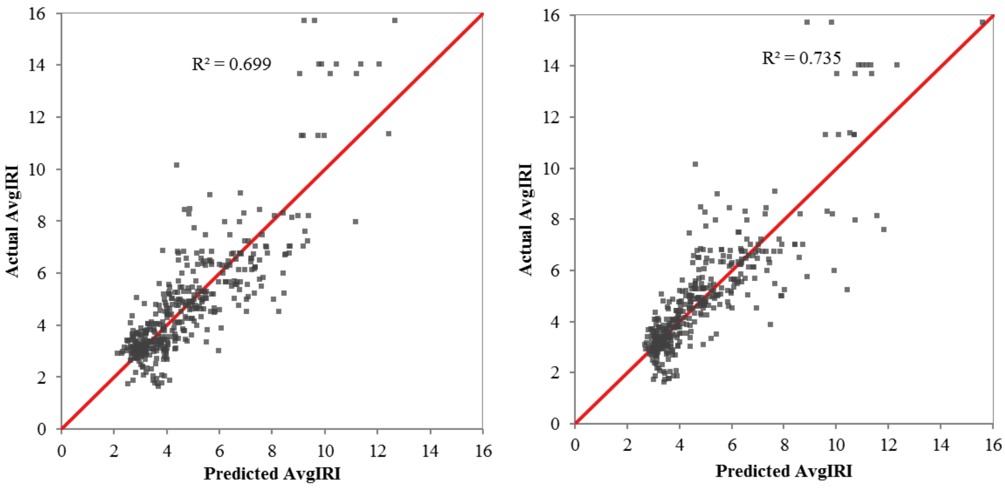
Figure 3-32 and 3-33 show quite clear classification of the sum of magnitudes in each road condition index, which indicates a very similar trend of the magnitudes increasing accordingly to the worsening of the condition. However, the range of magnitudes in each condition index is quite different for each device, which is located at a different location. An exception should be noted for Device A and

Device B, which are very similar, because they are both placed on the dashboard. In general, among the four devices, Device D has the biggest range of magnitudes in each condition index (a mean magnitudes of about 4 for good condition, 6.5 for fair, 9 for poor and 15 for bad), slightly bigger than that of Device A and Device B (which both have a mean of magnitudes of about 2.5 for good, 3.5 for fair, 5 for poor and 7 for bad); while Device C has the smallest range of magnitudes in each condition index (about 1 for good, 1.5 for fair, 2 for poor and 4 for bad condition). This implies that the estimation model for each vehicle or smartphone should be different depending on their parameters.

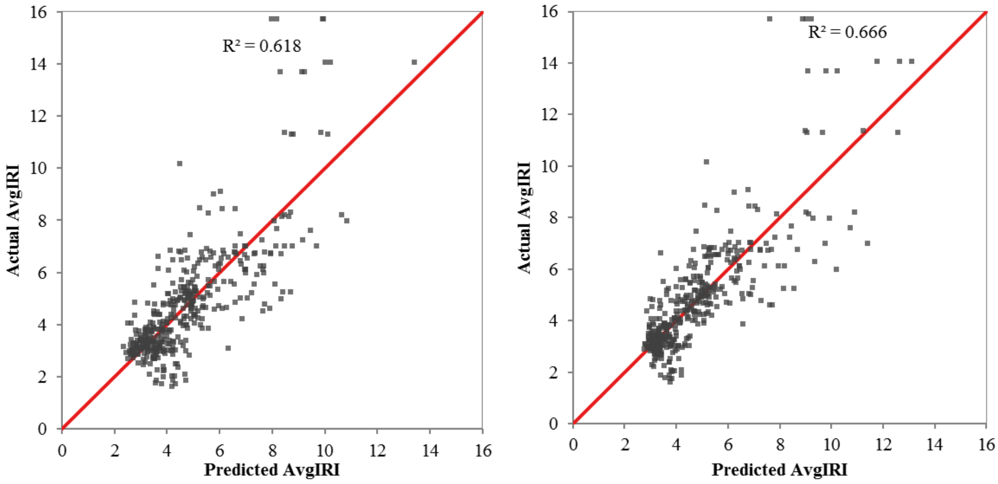
3.4.6. IRI as a linear function of the magnitudes and the average speed

From the above subsections, it is understood that IRI can be associated with a linear function of the magnitudes of the acceleration vibration and the average speed. This subsection attempts to further understand a few consideration of the function.

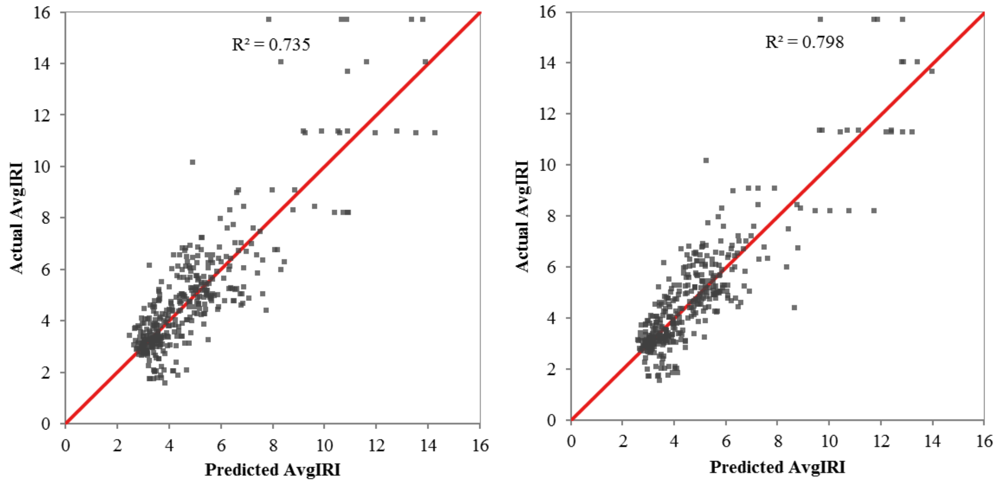
Two options of function are considered for comparison: (1) the magnitudes are calculated from the sum of all acceleration vibration axes combined, and (2) the magnitudes are calculated from each acceleration vibration axis separately. R^2 from the 2 cases can be compared as the following Figure 3-34. More details can be found in Appendix F.



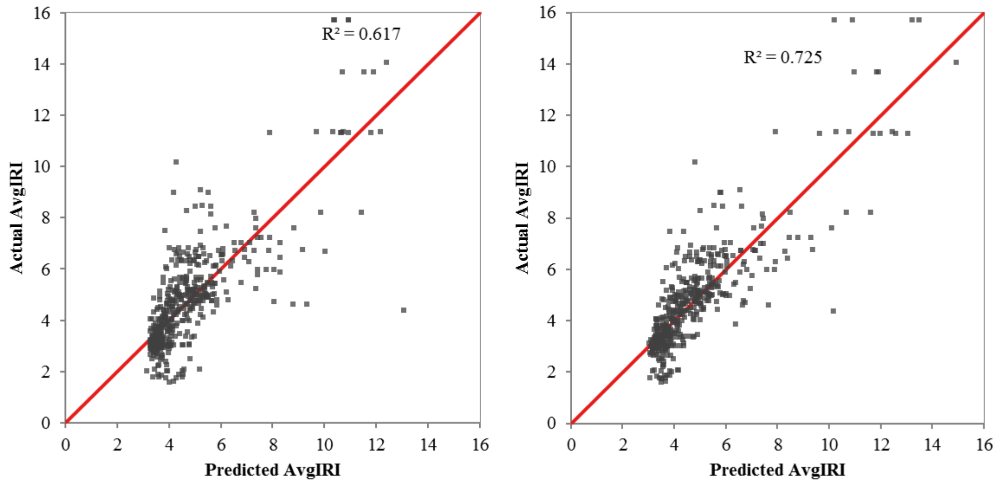
Consideration (1) **Device A** Consideration (2)



Consideration (1) **Device B** Consideration (2)



Consideration (1) **Device C** Consideration (2)



Consideration (1) **Device D** Consideration (2)

Figure 3-34: R^2 from different consideration of magnitudes, Vehicle 4

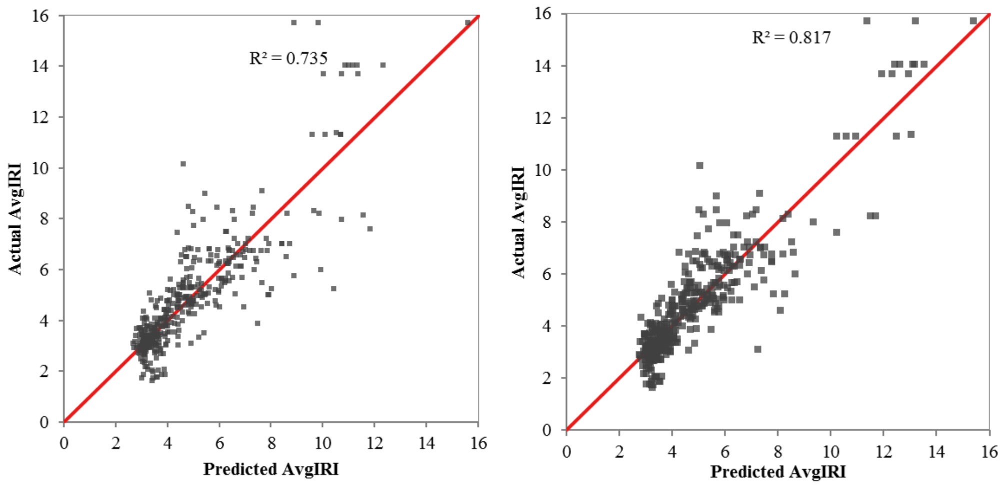
Generally, function 2, which considers the sun of magnitude for each axis separately, performs better than function 1, which considers the sum of magnitudes of all axes as one. The R^2 for Device C and Device D, estimated using function 2, are significantly bigger than that estimated using function 1.

3.5. Analysis results 2: Considering data from the accelerometers and the gyroscopes.

The previous analysis, presented in the above sections, suggests that there is a strong relationship between the magnitudes of the vibration from smartphone accelerometers, IRI, and the average speed. The strength of the relationship also differs at different frequency ranges; in which the strongest relationship is observed at the frequency range of 40-50Hz. Based on these findings, IRI can be roughly modeled as a linear function of the magnitudes, from accelerometers, and the average speed.

The main objective of this section is to explore whether adding gyroscope vibration magnitudes, in the linear function, would improve the estimation results, in comparison to the function that only takes into account the magnitudes from accelerometers and the average speed, which has been investigated in the previous section. This section focuses directly at the frequency range of 40-50 Hz.

The analysis shows that IRI can also be roughly modeled as a linear function of the magnitudes, calculated from both accelerometer and gyroscope data, and the average speed. By adding gyroscope vibration as an additional parameter in the function, significant improvement in the estimation of IRI is observed.



Function (1) **Device A** Function (2)

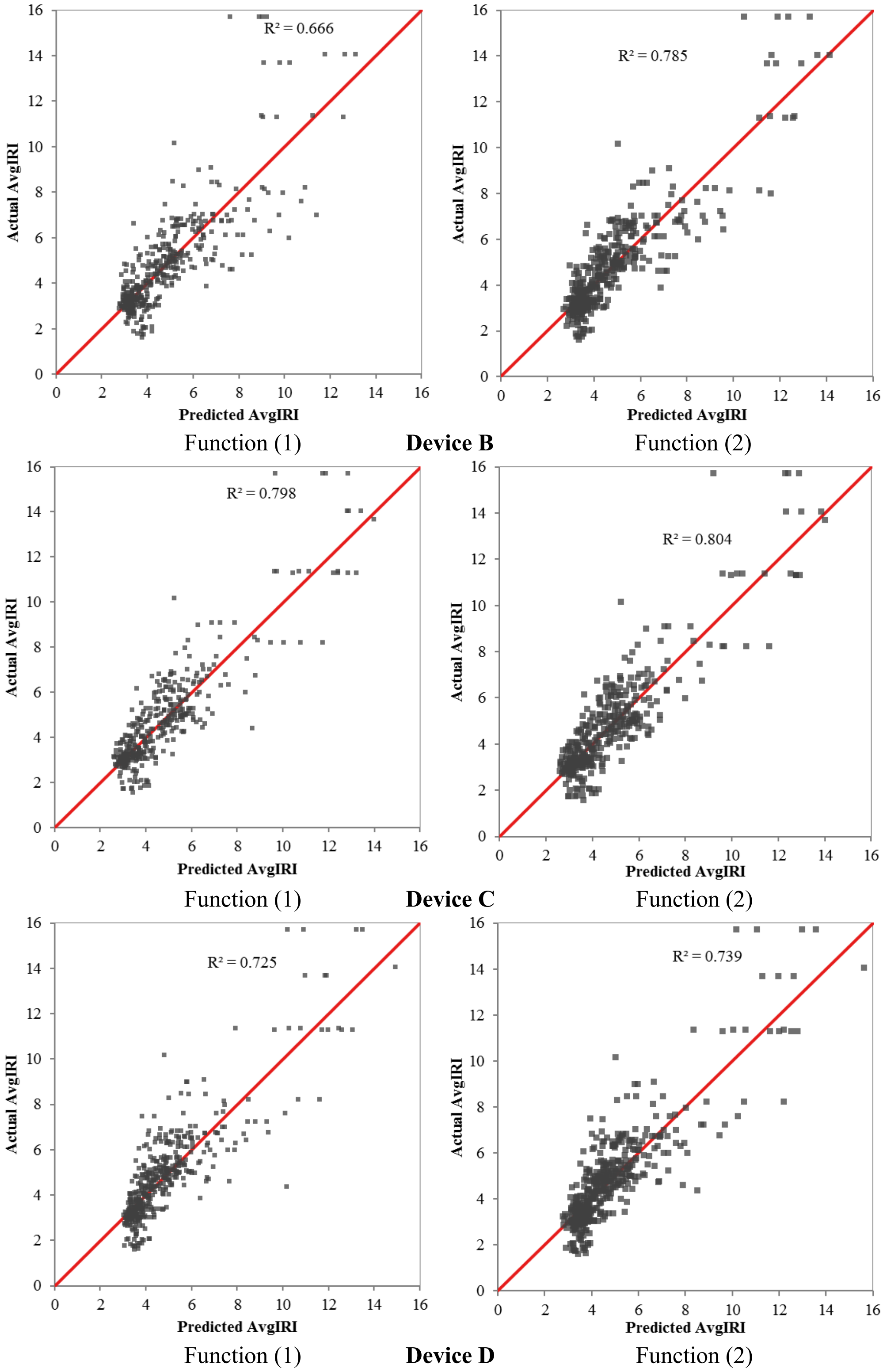


Figure 3-35: Comparison of estimation result, Vehicle 4

Figure 3-35 shows a selected result of a comparison of IRI estimation for the function that is taking into account only the average speed and the magnitudes, from accelerometer (Function 1); and the function that considers the average speed and the magnitudes from both accelerometers as well as gyroscopes (Function 2). More details can be found in Appendix G.

As the figure shows, for all smartphones in vehicle 4, the R^2 values in the right hand side graphs are greater than the R^2 values in the left hand side graphs. This indicates that Function 2 is better than Function 1. Smartphone B, for instance, the R^2 improves significantly from 0.575 to 0.766 of the estimation predicted by Function 1 and Function 2, respectively

Table 3-11: Summary of estimation results for both functions.

Vehicle	Smartphone	R^2 derived from the estimation function that takes intoaccount the average speed and magnitudes from:	
		Accelerometer (Function 1)	Accelerometer and Gyroscope (Function 2)
1	A	0.600	0.793
	B	0.545	0.736
	Cp	0.775	0.809
	Cb	0.602	0.618
	Db	0.718	0.806
	Dp	0.594	0.625
2	A	0.616	0.764
	B	0.620	0.758
	C	0.550	0.694
	D	0.520	0.736
3	A	0.658	0.790
	B	0.575	0.766
	C	0.696	0.793
	D	0.755	0.788
4	A	0.735	0.817
	B	0.666	0.735
	C	0.790	0.804
	D	0.725	0.739

Table 3-11 above summarizes R^2 that are derived from the estimation of Function 1 and Function 2 for all smartphones and all vehicles. In general, it can be concluded that R^2 that are estimated by Function 2 are greater than that estimated by Function 1. Almost all of R^2 estimated by Function 2 are greater than 0.74, while less than half of R^2 estimated by Function 1 reach that value. The greatest values of R^2 from Function 2 are as great as 0.8 in four cases (0.804, 0.806, 0.809, and 0.817 for Smartphone C Vehicle 4, Smartphone Db Vehicle 1, Smartphone Cp Vehicle 1, and Smartphone A Vehicle 4, respectively). In many cases, Smartphone B Vehicle 3, Smartphone D Vehicle 2, and Smartphone B Vehicle 1, for instances, there are significant differences between R^2 values estimated by the two functions (0.575 against 0.766, 0.520 against 0.736, and 0.545 against 0.736, respectively).

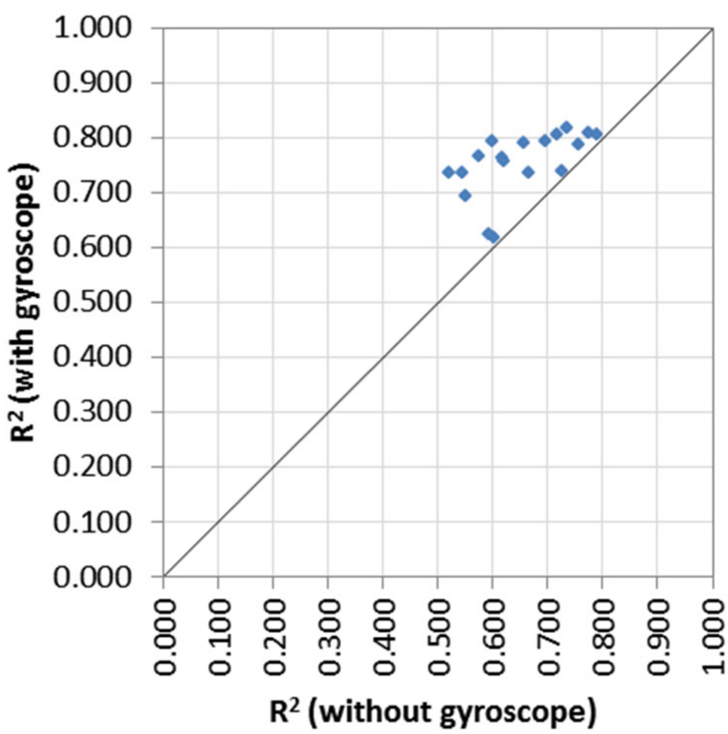


Figure 3-36: R^2 from the functions with and without gyroscope

3.6. Discussion and conclusions

To understand the relationship between smartphone sensor data and road roughness condition (IRI), two experiments have been carried out. A wide range of analysis has been conducted, in which it has been revealed that IRI can be expressed roughly as a linear function of magnitude of acceleration vibration and the average speed. Parameters (coefficients) of the linear function depend on individual vehicle or device.

It is also interesting to note that, from the breakdown frequency analysis, at high frequency range of 40-50 Hz the R^2 of the correlation are generally strong for the fixed orientation devices and strongest for the free orientation devices. It implies that at the high frequency range of 40-50 Hz, effects of irrelevant vibration, such as engine noise and movement of the driver, for instances, appear to be minimal. Therefore at this frequency range, vibration that is related to the road roughness condition can be observed efficiently.

The analysis also shows similar tendency in the classification of the sum of magnitudes by road condition indexes, suggesting that the same model for IRI estimation can be assumed as long as vehicle type and device do not change. However, in case vehicle type and device change, the parameters of the model should be calibrated.

A further analysis also indicates that by considering the magnitudes calculated for each axis of the acceleration vibration, better estimation accuracy can be achieved in comparison to the magnitudes calculated for a combination of all axes.

The best possible estimation accuracy can be achieved if both the sensors, accelerometer and gyroscope, are considered in the estimation function. However, the complexity of the function also increases.

Chapter 4: A STUDY ON THE FORMULATION OF A SIMPLE MODEL TO ESTIMATE ROAD ROUGHNESS CONDITION FROM NUMBERS OF ANONYMOUS SMARTPHONES

4.1. Introduction

The main objective of this chapter is to describe the development of a simple model that can be used to estimate road roughness condition (IRI) from many car drivers with smartphones. To achieve this, first of all, a model based on the function of the relationship in Chapter 3 is formulated. Next, a numerical example is undertaken to examine whether the model is working. Finally, real data sensor of the real road network in Vientiane, Laos is used in the simulation to confirm that the model can be used for the purpose.

Results of this chapter has been presented and submitted for international /domestic conferences and a journal: (DOUANGPHACHANH & ONEYAMA, 2013a), (DOUANGPHACHANH & ONEYAMA, 2014c), and (DOUANGPHACHANH & ONEYAMA, 2014a)

4.2. Background and concept of the proposed model

In the road network, there are many links, which comprise of many sections with certain roughness conditions. At each section or link there are probably many types of vehicles passing by. Suppose many of those anonymous drivers on those vehicles possess smartphones that are placed somewhere inside their vehicles; and some of them are acting as probe devices, which collect and process data for a purpose of analyzing the road surface condition of the mentioned road section. Being able to achieve this ambition would bring a great contribution to the maintenance and monitoring of the road infrastructure.

In order to realize this ambition, a tool or system that takes the advantage of the mentioned potential has to be in place. The final goal of this study is to propose a smartphone app as a tool to accomplish this objective. The app should considerably have a good estimation model, so that the accuracy of the estimation is acceptable for the use in road maintenance planning and monitoring.

As mentioned earlier in the previous chapters, as a basic foundation to achieve the development of the model, first of all, there is a need to study on the relationship between smartphone sensor data and the actual road surface roughness condition, which have been done and reported in Chapter 3. The study enables understanding on features, parameters and relationship function, which are very critical for the formulation of the estimation model.

Another most important consideration is to make the model that fits with the characteristics of this probe situation. The main characteristics of the situation include, also refer to Figure 4-1 below:

- There are many anonymous drivers with smartphones driving freely on the road network;
- The smartphones collect, store sensor data and process the estimation independently. Therefore, the smartphone sensor data, such as magnitudes and average speed are known variables;

- The objective is to estimate IRI of the road sections, therefore IRI of the road sections is a unknown variable;
- The coefficients of road roughness function for each vehicle will be different, depending on vehicle and/or smartphone locations and setting. Therefore, these coefficient parameters are also unknown and needed to be estimated.

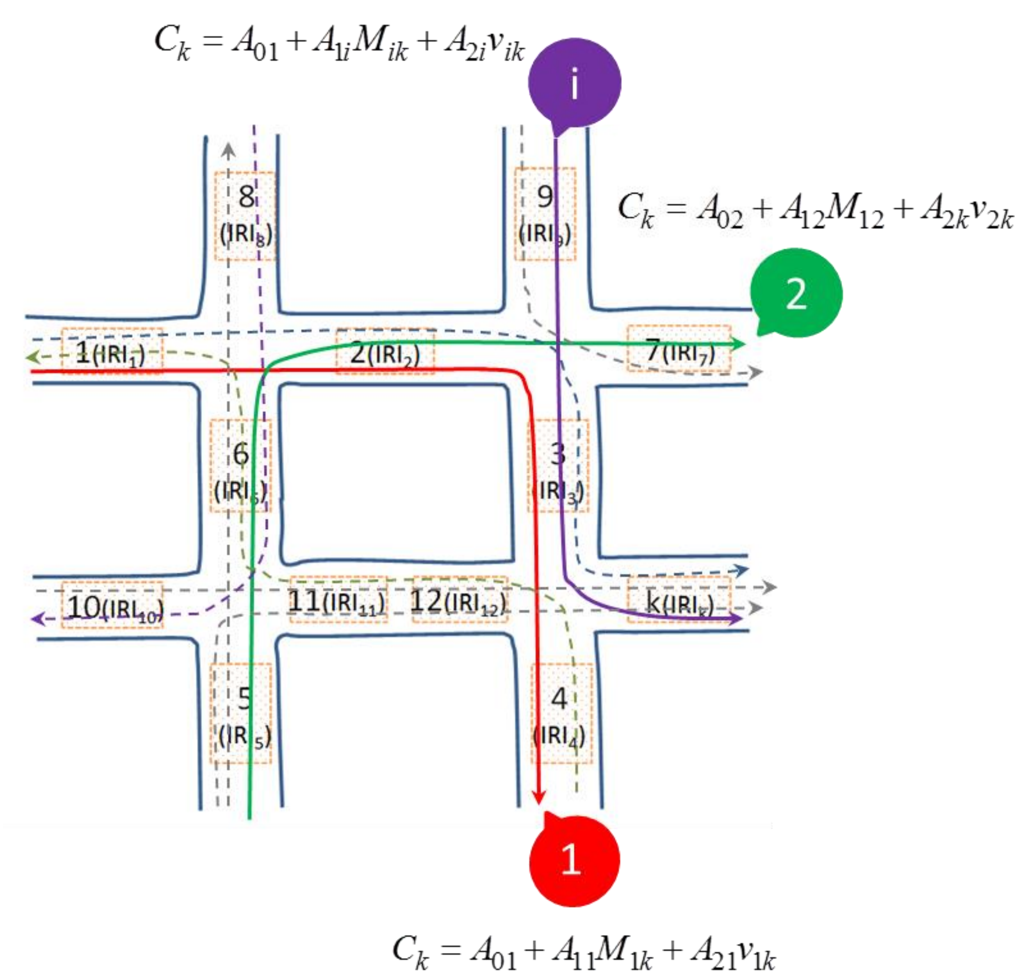


Figure 4-1: Characteristics of the approach

Note that detailed explanations of the variables can be found in the following subsection.

A solution to overcome or minimize the issues mentioned above is calibrations. In other words, all vehicles that will be used for the approach must be calibrated. This is to ensure that parameters of the model for each vehicle are correct. However, as each vehicle is treated as anonymous and there would be many vehicles, calibration of all anonymous vehicles is close to impossible. This issue is regarded as the main challenge, in which it has to be solved in order to realize this approach.

A possible solution is to estimate all parameters and the roughness condition (IRI) simultaneously; provided that the IRI does not change during the period of estimation. The parameters can be balanced out to match the IRI values for the same road sections, provided that a small number of real IRI of other sections is available. This process can also be regarded as an adjustment to calibrate relative IRI to the real IRI.

At this stage, a small number of road sections with real IRI are needed for the estimation of other sections. With the data or estimation being made available and accumulated, in the future development, the model could use these accumulated data and estimation (IRI) instead of the real IRI. The accumulated estimated IRI will also be useful as an indicator for the monitoring of the road network.

4.3. Model Formulation

For the first stage, to simplify the model that will be used in the smartphone app, only magnitudes from accelerometer and average speed will be considered in the function. Therefore, assuming we would like to estimate road roughness condition of road sections, within a road network, from acceleration and average speed data collected by anonymous drivers or smartphones, which are placed inside different vehicles (presumably running on the network randomly). From the conclusion that have been found in the experiment as mentioned in the previous chapter above, the model to estimate road roughness condition could be presented as:

$$C_k = A_{0i} + A_{1i} M_{ik} + A_{2i} v_{ik}, \qquad \textbf{Equation 1}$$

Where,

C_k : Road roughness condition (IRI) at section k,
M_{ik} : Magnitude of acceleration in frequency domain for vehicle i at section k,
v_{ik} : Average speed of vehicle i at section k,
A_{0i}, A_{1i} , A_{2i} : Coefficients of road roughness condition function for vehicle i.

Note that the parameter A_{0i}, A_{1i} , and A_{2i} represent the variation of parameters, which depend on vehicle type, smartphone type and smartphone setting.

The problem here is to estimate the unknown variables (C_k, A_{0i}, A_{1i}, and A_{2i}) by minimizing the error of the model. If considering least squared error regarding C_k, object function F can be formulated from the relationship in the equation (1):

$$F = \sum_i \sum_j \sum_k \delta_{ijk} \left\{ C_k - \left(A_{0i} + A_{1i} M_{ij}^{obs} + A_{2i} v_{ij}^{obs} \right) \right\}^2, \qquad \textbf{Equation 2}$$

where, j is the sequential data of vehicle i; and δ_{ijk} equals to 1 if the data j of vehicle i has passed through section k, while δ_{ijk} equals to 0 if the data j of vehicle i has not passed through section k. M_{ij}^{obs} and v_{ij}^{obs} are observed magnitudes and observed average speed, respectively.

Under this formulation, C_k, A_{0i}, A_{1i}, and A_{2i} can be estimated provided that we have observed IRI data (denoted by C_k^{obs}) at several observed sections $k \in K_{obs}$, where K_{obs} is a set of observed sections, obtaining from a more precise method (such as VIMS in this study). However, minimization of equation (2) under the constraint of $C_k = C_k^{obs}$ does not yield appropriate estimators, because, in the minimization, results are largely affected by the unobserved sections, where smaller values of C_k, A_{0i}, A_{1i}, and A_{2i} result in smaller value of equation (2).

Therefore, a method as the following steps is proposed:

1) First, a relative relationship of the road roughness condition is introduced.

$$c_k = a_{0i} + a_{1i} M_{ik} + a_{2i} v_{ik}, \qquad \textbf{Equation 3}$$

where, c_k is the relative road roughness condition at section k; a_{0i}, a_{1i}, and a_{2i} are coefficients of relative road roughness condition function for vehicle i. Note that equation (3) can be derived by dividing both sides of equation (1) by the same value.

2) Formulate objective function f, which is least square error regarding c_k under a constraint level of value for parameter a_{1i}:

$$\sum_i \sum_j \sum_k \delta_{ijk} \left\{ c_k - \left(a_{0i} + a_{1i} M_{ij}^{obs} + a_{2i} v_{ij}^{obs} \right) \right\}^2 \qquad \textbf{Equation 4}$$

$$\text{s.t. } \frac{1}{N} \sum_i a_{1i} = 1,$$

where, N is the number of vehicles.

3) Estimate c_k^{est}, a_{0i}^{est}, a_{1i}^{est} and a_{2i}^{est}, these are c_k, a_{0i}, a_{1i} and a_{2i}, respectively so as to minimize objective function f in equation (4) .

4) Assume $C_k = b_0 + b_1 c_k$, where b_0 and b_1 are parameters that would be derived from solving the regression of $C_k^{obs} = b_0 + b_1 c_k^{est}$ $(k \in K_{obs})$. In order words, b_0 and b_1 are calculated from observed road sections that have precise IRI values.

Then, road roughness condition C_k^{est} can be estimated applying the function $C_k^{est} = b_0 + b_1 c_k^{est}$ for all the remaining sections.

After that A_{0i}, A_{1i}, and A_{2i} can also be estimated by minimizing the following equation (5):

$$F = \sum_i \sum_j \sum_k \delta_{ijk} \left\{ C_k^{est} - \left(A_{0i} + A_{1i} M_{ij}^{obs} + A_{2i} v_{ij}^{obs} \right) \right\}^2 \quad \textbf{Equation 5}$$

Figure 4-2 summarizes the step of the estimation process.

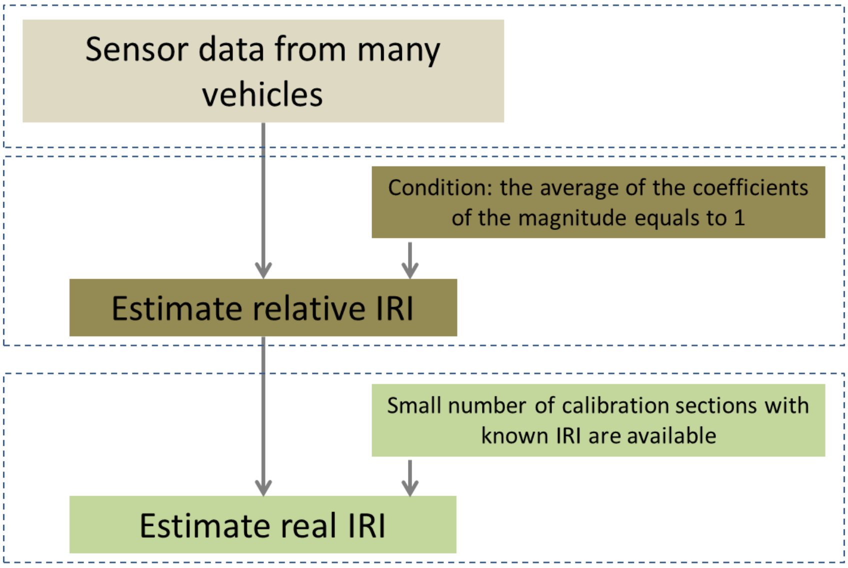


Figure 4-2: Estimation process

4.4. Numerical Examples

The main aim of the numerical examples is to validate the model performance in some simple cases, and to understand how to select a small number of sections as calibration sections.

The structure of the numerical e examples is shown in Figure 4-3.

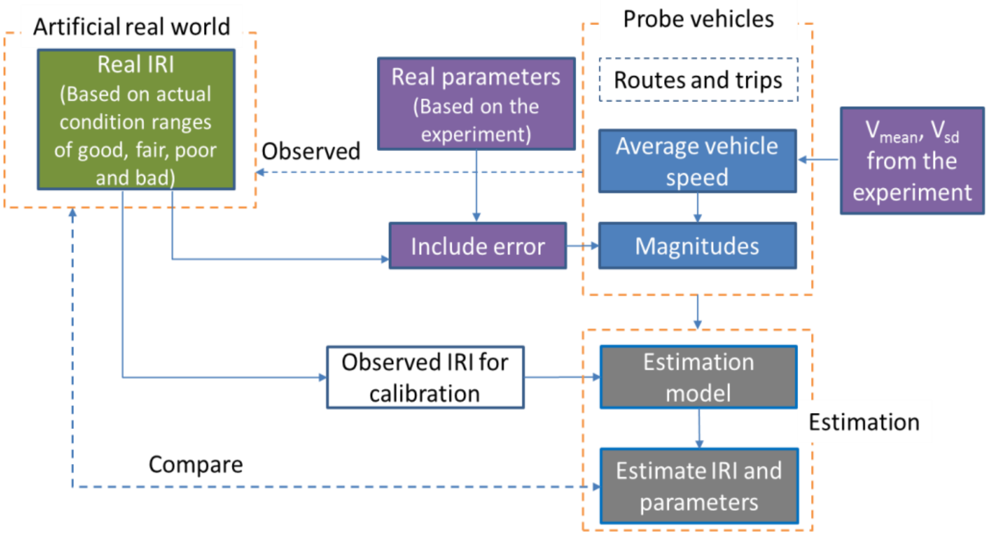


Figure 4-3: Structure of the numerical examples

4.4.1. Setting

In the numerical examples, an artificial real world road network that consists of 18 links (with identical length) is assumed. Each of the road links are set to have 20 sections (also with identical length), see Figure 4-4. Road roughness condition is set to be good for all sections in link 8 and 11; fair for all sections in link 3, 4, 5, 6, 13, 14, 15 and 16; poor for all sections in link 1, 2, 7, 10, 17 and 18; and finally, bad for all sections in link 9 and 12. In other words, IRI for each section is assigned randomly within an average IRI range corresponding to its condition index (good, fair, poor, and bad, respectively). Details of IRI ranges for each road condition index can be found in Table 4-1. Other settings include 6 running routes (Table 4-2 and Figure 4-5) and 10 vehicles (Figure 4-6).

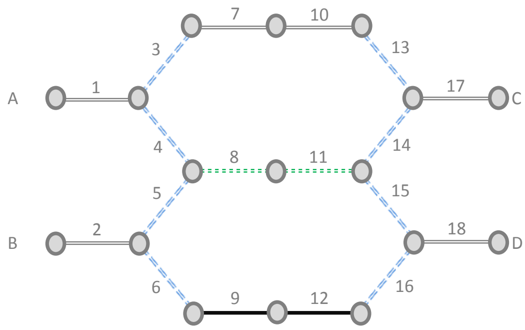


Figure 4-4: Road network

Table 4-1: Road condition index

Condition Index	Average IRI	Road Link	Legend
Good	0≤IRI<4	8, 11	
Fair	4≤IRI<7	3, 4, 5, 6, 13, 14, 15, 16	
Poor	7≤IRI<10	1, 2, 7, 10, 17, 18	
Bad	IRI≥10	9, 12	

The condition indexes of good, fair, poor, and bad are adopted from the condition indexes applied by the Lao RMS (PTI, 2011b).

Table 4-2: Route arrangement

Route	Via Links
A	1, 4, 8, 11, 14, and 17
B	1, 3, 7, 10, 13, and 17
C	2, 5, 8, 11, 15, and 18
D	2, 6, 9, 12, 16, and 18
E	1, 4, 8, 11, 15, and 18
F	2, 5, 8, 11, 14, and 17

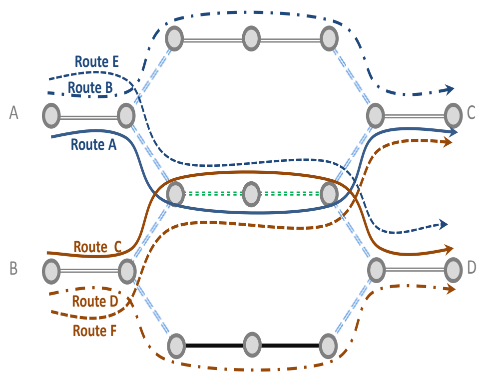


Figure 4-5: Map of route arrangement

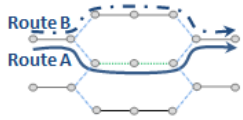
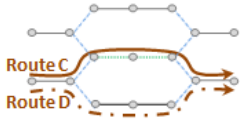
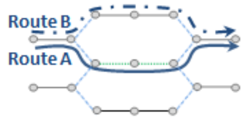
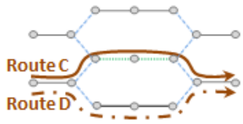
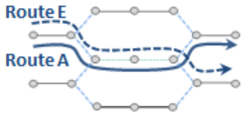
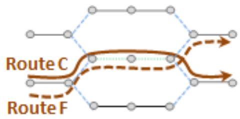
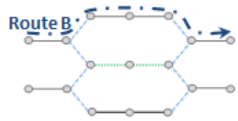
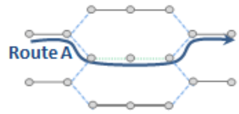
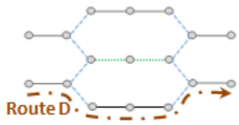
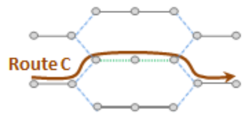
Vehicle	Route	Trips
1		Route A: 15 Trips Route B: 5 Trips Total Trips: 20
2		Route C: 15 Trips Route D: 5 Trips Total Trips: 20
3		Route A: 7 Trips Route B: 3 Trips Total Trips: 10
4		Route C: 7 Trips Route D: 3 Trips Total Trips: 10
5		Route A: 5 Trips Route E: 5 Trips Total Trips: 10
6		Route C: 5 Trips Route F: 5 Trips Total Trips: 10
7		Route B: 5 Trips Total Trips: 5
8		Route A: 5 Trips Total Trips: 5
9		Route D: 5 Trips Total Trips: 5
10		Route C: 5 Trips Total Trips: 5

Figure 4-6: Vehicle settings

4.4.2. Approach

The simulation processes are summarized in Figure 4-7.

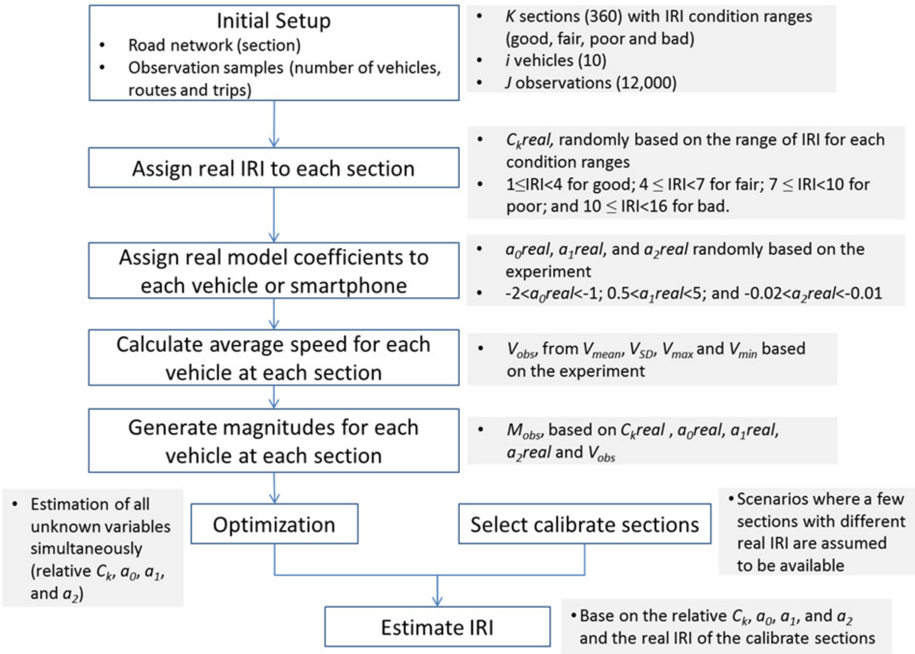


Figure 4-7: Simulation processes

The 5 scenarios include:

i. Only link 8 and 11 (all good condition) are observed precisely, the remaining links are observed roughly with errors;

ii. Only link 9 and 12 (all bad condition) are observed precisely, the remaining links are observed roughly with errors;

iii. Only link 8 and 9 (one good condition and one bad condition) are observed precisely, the remaining links are observed roughly with errors;

iv. Link 7, 8, 9 and 14 (good, fair, poor and bad; one link each) are observed precisely, the remaining links are observed roughly with errors;

v. Link 1, 5, 11 and 12 (good, fair, poor and bad; one link each) are observed precisely, the remaining links are observed roughly with errors.

Coding is written using R Stats programming package. Details of the coding can be found in Appendix H.

4.4.3. Results

After running the simulations for 5 cases as mentioned above, the performance of the model can be summarized in the following figures:

a) Only link 8 and 11 (all good condition links) are observed precisely.

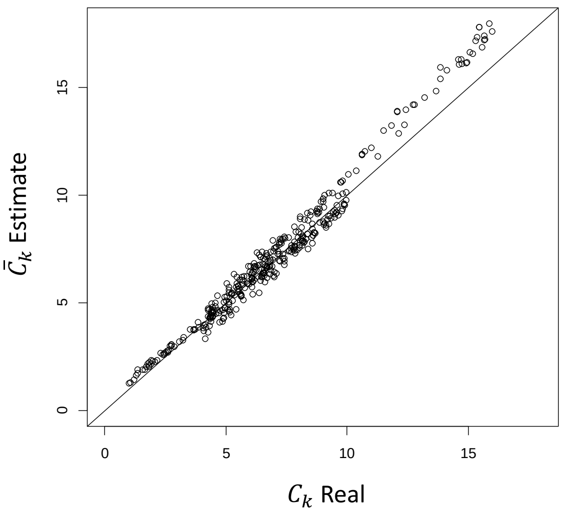


Figure 4-8: Real and estimated IRI (Scenario 1)

b) Only link 9 and 12 (all bad condition links) are observed precisely.

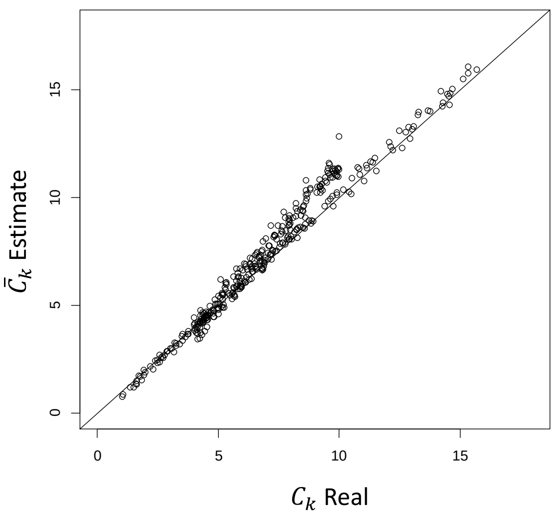


Figure 4-9: Real and estimated IRI (Scenario 2)

c) Only link 8 and 9 (one good condition link and one bad condition link) are observed precisely.

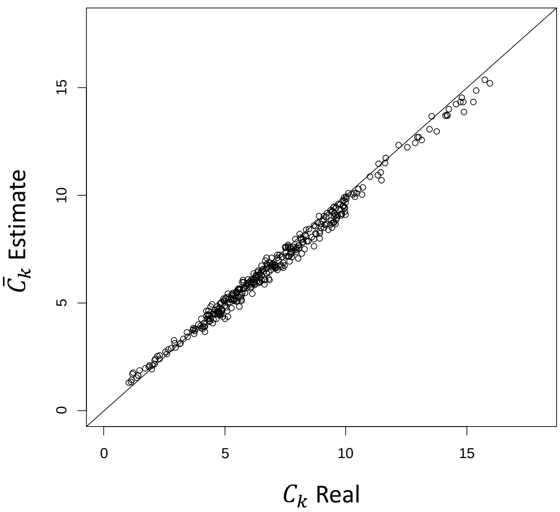


Figure 4-10: Real and estimated IRI (Scenario 3)

d) Link 7, 8, 9 and 14 (good, fair, poor and bad; one link each) are observed precisely.

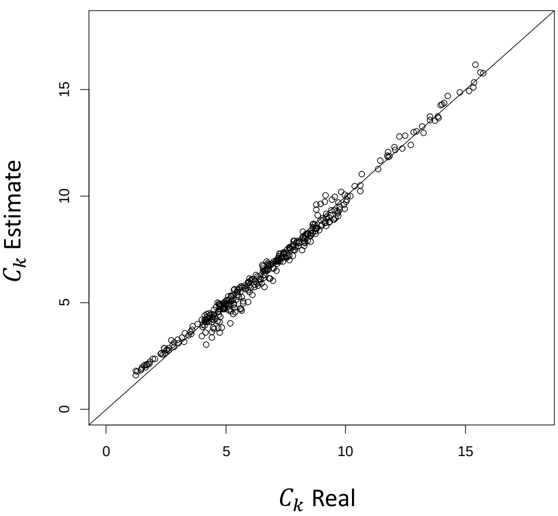


Figure 4-11: Real and estimated IRI (Scenario 4)

e) Link 1, 5, 11 and 12 (good, fair, poor and bad; one link each) are observed precisely.

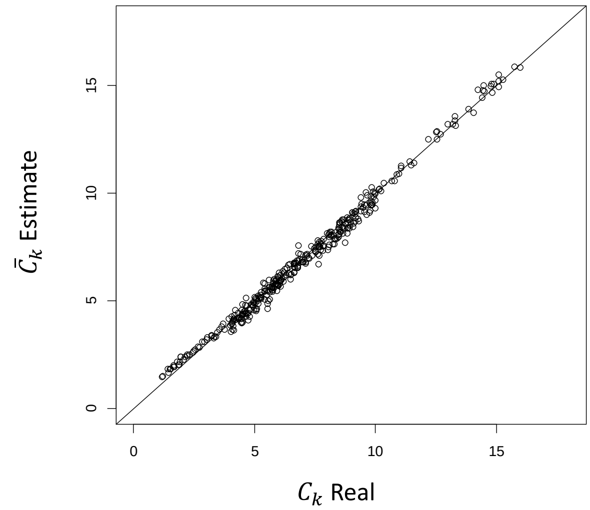


Figure 4-12: Real and estimated IRI (Scenario 5)

In general, the model performs considerably good as it yields very good fitting for all the example cases. Moreover, the model obviously perform better, as shown in Figure.4-10, Figure 4-11 and Figure 4-12, if two or more different type of road roughness conditions. Figure 4-11 and Figure 4-12 show the best results, because calibration sections of each good, fair, poor and bad condition are considered as the observed road roughness condition (IRI).

4.5. Simulation using real life data

To further validate that the model, formulated and tested in the numerical simulations above, is actually sufficient to be used for road surface roughness estimation from smartphone sensor data, an example using real sensor data from the experiments are carried out.

4.4.1. Setting

From the experiment, 18 unique combinations of vehicle/device setting are available (the combinations of four vehicles and four devices setting), however due to some technical issues concerning the GPS data and time constraint, data of one device (Device B) have been excluded, therefore only 14 unique combinations are selected for the analysis in this example.

Table 4-3: Vehicle/Device setting combinations

Combination Number	Combination Code	Description	Remarks
1	AV1	Device A (dash board) Vehicle 1	Selected
2	AV2	Device A (dash board) Vehicle 2	Selected
3	AV3	Device A (dash board) Vehicle 3	Selected
4	AV4	Device A (dash board) Vehicle 4	Selected
5	BV1	Device B (dash board) Vehicle 1	Excluded
6	BV2	Device B (dash board) Vehicle 2	Excluded
7	BV3	Device B (dash board) Vehicle 3	Excluded
8	BV4	Device B (dash board) Vehicle 4	Excluded
9	CV1a	Device C (inside pocket) Vehicle 1	Selected
10	CV1b	Device C (box near gear handle) Vehicle 1	Selected
11	CV2	Device C (inside pocket) Vehicle 2	Selected
12	CV3	Device C (inside pocket) Vehicle 3	Selected
13	CV4	Device C (inside pocket) Vehicle 4	Selected
14	DV1a	Device D (inside pocket) Vehicle 1	Selected
15	DV1b	Device D (box near gear handle) Vehicle 1	Selected
16	DV2	Device D (inside pocket) Vehicle 2	Selected
17	DV3	Device D (inside pocket) Vehicle 3	Selected
18	DV4	Device D (inside pocket) Vehicle 4	Selected

A total of 1,865 of road sections have been selected from the experiment. At each of the total 1,865 road sections, at least 1 or more unique combinations of vehicle/device setting have passed through once or multiple times. At some sections, there are more than one combination and repetitions. For each combination, average speed, magnitudes from FFT and average IRI at each section are known. Totally there are 5,685 observations for this example.

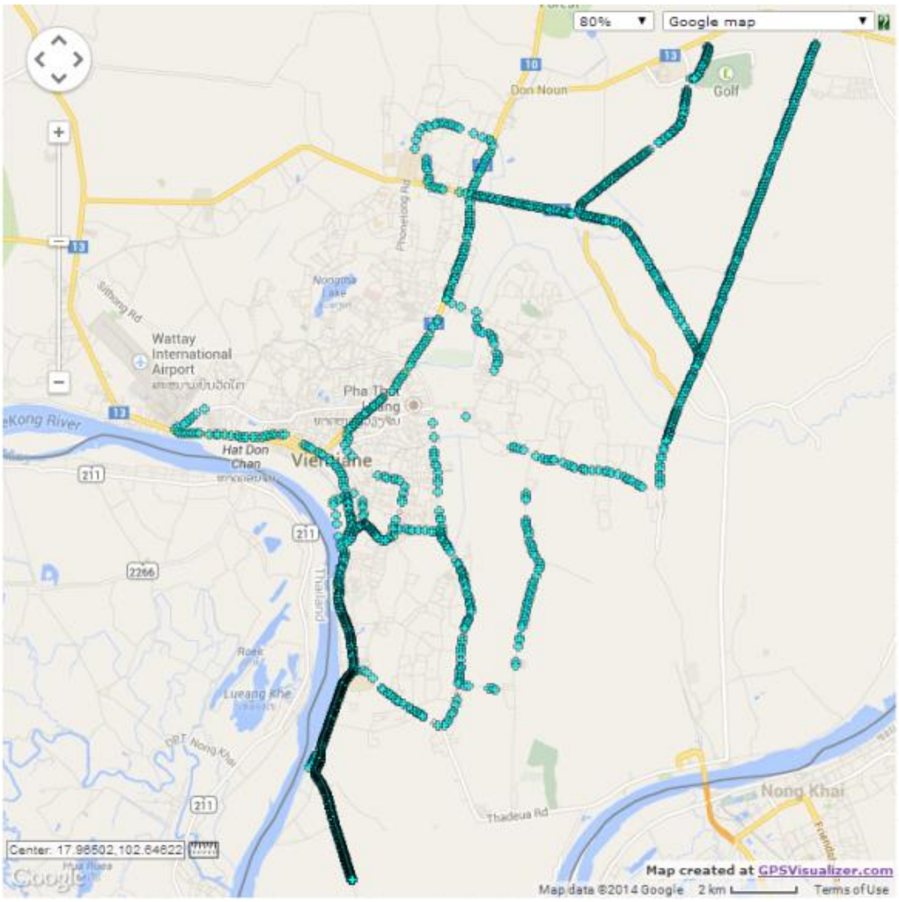


Figure 4-13: Selected road sections

In the numerical simulations above, as it has been discussed that selecting a mix of different road section with different conditions would allow us to predict road roughness condition more accurately and reliable. Therefore, in this example 37 different road sections, which equal to approximately 2% of the total road sections, with different road conditions as observed sections with known IRI values, are selected. These observed sections are used to estimate the parameter coefficients where they will be then used in the model, also discussed above, to estimate IRI for other sections.

Coding is also written using R Stats programming package. Detail of the coding can be found in Appendix I.

4.4.2. Result

After running the simulation, the result of this example shows that by using 2% of the total number of road sections, the estimate model can predict IRI of the remaining road sections with approximately 29% of errors (PRMSE of 0.290).

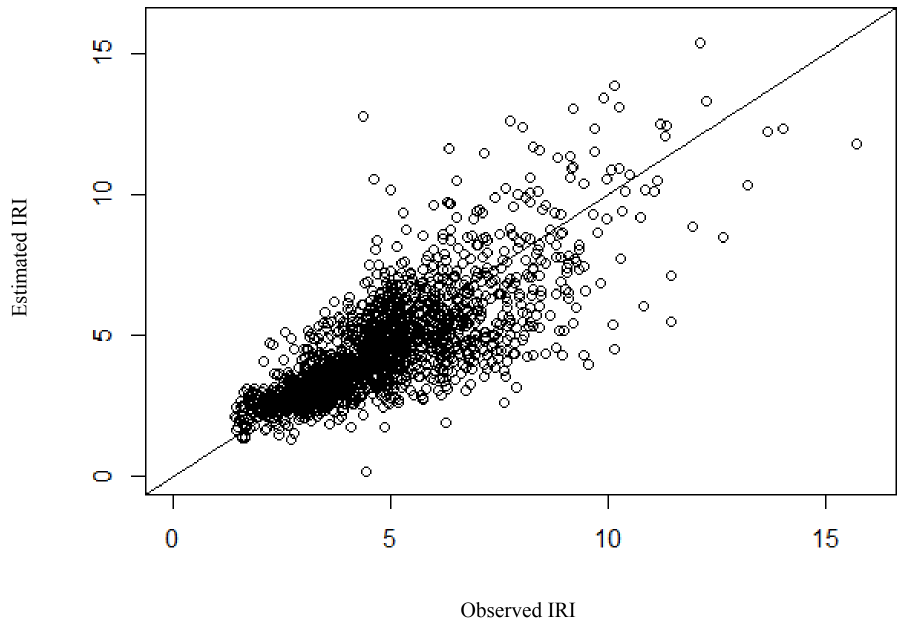


Figure 4-14: Observed and estimate IRI, Real Data Example

4.4.3. Discussion and conclusions

In this chapter, the main purpose is to develop a model to estimate road roughness condition (IRI). In order to realize the model, it is necessary to understand the relationship between road roughness condition and the data to be obtained using smartphone devices. As already reported in Chapter 3, experiments to collect the data (acceleration and speed) using Android smartphones have been carried out. The analysis, which includes matching of data with reference data and investigation in frequency domain, proves that road roughness condition can be roughly modeled as a linear function of magnitude of acceleration and average speed.

The model formulation is based on the concept that it will be used in a smartphone app to estimate road roughness condition by anonymous drivers. After model formulation, numerical examples have been simulated. The simulation results show that the model performs promisingly, particularly in cases, where observed road roughness condition consists of different IRI values spreading across different road condition indexes. Additionally an example using real sensor data is also performed. The result of the example confirms that the developed simple model can be used to predict IRI of road surface from many anonymous smartphone sensor data with certain level of accuracy.

Chapter 5: THE DEVELOPMENT OF A SMARTPHONE APP

5.1. Introduction

This chapter introduces an Android smartphone app called “IRI Sensing”. IRI Sensing has been developed based on the model that has been formulated and examined in Chapter 4. Concept, structure and user interface of the app are presented in the following sections. Furthermore, two initial test runs of the app have also been carried out and reported in this chapter.

5.2. Concept

The main idea of the development is focused on the building of a simple app that is easy to use and operate for all users. It also should be resource efficient so that it does not affect the battery life, data packets, as well as the overall performance of the smartphones while using the app.

The app should be able to calculate magnitudes of the acceleration vibration for every 100m road section, which later can be relate to road roughness condition (IRI) with the accuracy that is acceptable for the purpose of road maintenance planning and continuous monitoring. The main attractive feature of the app is that it estimates the condition of the road roughness from smartphone sensor data being obtained by participating drivers in the real traffic, who agree to download and install the app onto their smartphones.

To achieve the above mentioned objectives, in the first step of the development, Android Operating System (OS) has been chosen as a platform for the app development, simply because Android OS is an open source environment, which is convenient for the first stage. The OS is also very popular and used by many smartphone users. App for other smartphone OS may be developed in the near future.

Due to time constraint, coding of the app has been outsourced to private consultants.

5.3. Structure and calculation process

The structure of IRI sensing can be summarized into 3 main modules: (1) data collection module, which gathers data from sensors, (2) FFT calculation module, and (3) IRI estimation modules.

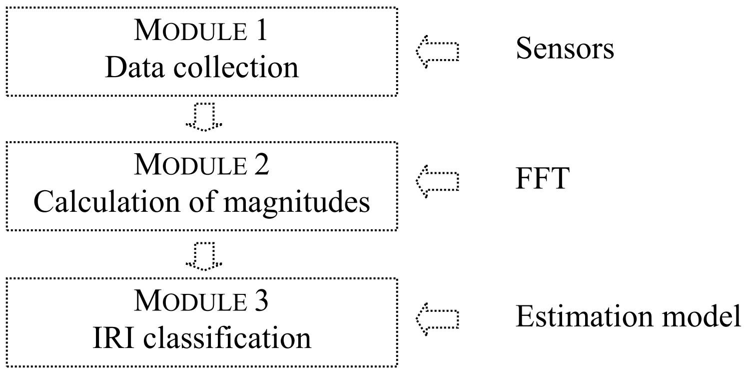


Figure 5-1: IRI Sensing structure

Data collection module is implemented in accordance with the application programming interface (API) guidelines of Android OS. The module collects 3 axis acceleration data from accelerometer and various positioning/location information from GPS such as latitude, longitude and speed. The sampling rates of 100Hz and 1Hz are selected for the accelerometer and the GPS, respectively.

FFT module is a set of coding that use FFT algorithm to calculate the magnitudes from acceleration vibration. To reduce calculation time and resource consumption in the smartphone OS, a 64 bins of FFT is selected. FFT of 64 bins is considered to produce sufficient resolution for a sampling rate of 100Hz of the vibration signal. The sum of magnitudes selected is defined as the sum of magnitudes XYZ of all acceleration vibration axes combined. This sum of magnitudes is calculated for every 100m section.

IRI estimation module uses the estimation model, which has been formulated and examined in Chapter 4 above, to classify road surface condition. The sum of magnitudes at the frequency range of 40-50Hz will extracted from FFT calculation before being use in the model.

The processing procedure of the app is outlined in the Figure 5-2 below:

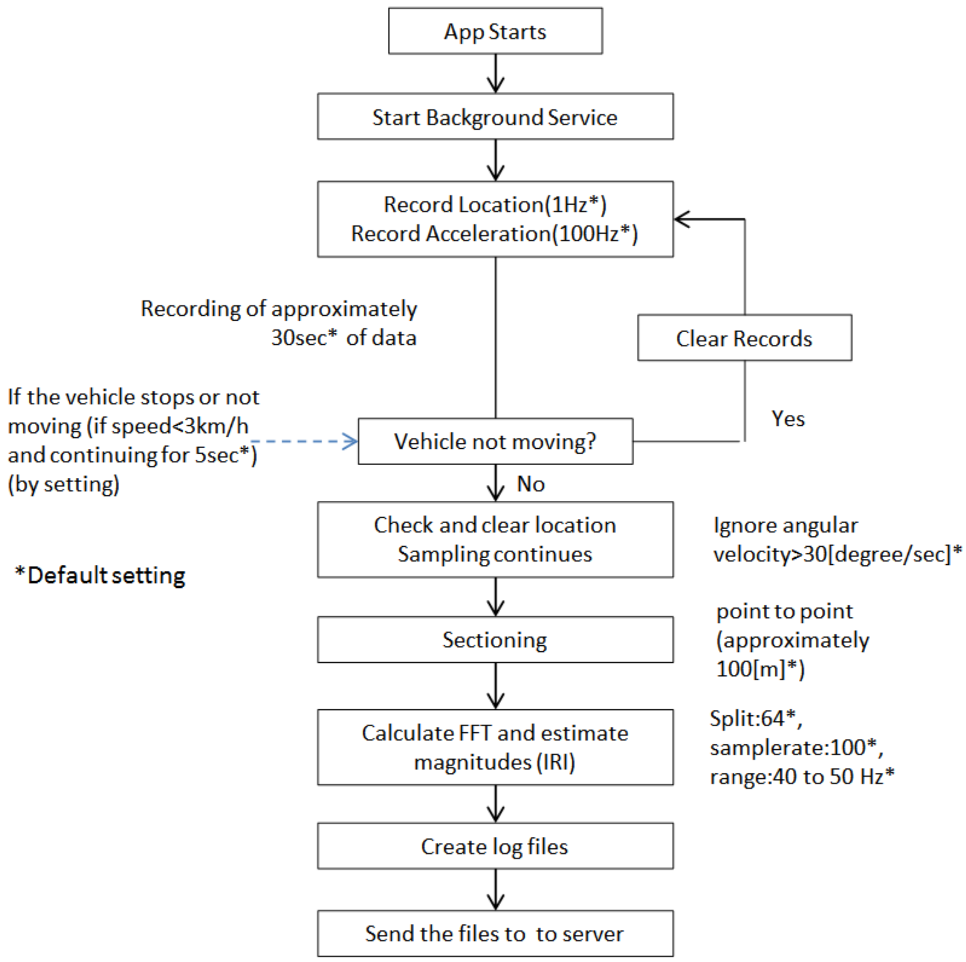


Figure 5-2: Processing flowchart of IRI Sensing

Basically, upon starting the process in the app, sensors will start logging data according to the default sampling rates. Data will be cut after every 100m (calculating from GPS data) to make a section. A section will also be made if the vehicle stops (also checking from GPS data) before the distance of the driving has yet to reach 100m. This loop will repeat until it has been stopped or paused. At the same time data that have already been sectioned will be sent to the second module, in which it will be going through high-pass filter and FFT. FFT results will be sent to the next module to for the estimation of IRI based on the estimation model.

Sample of IRI Sensing file are shown in Table 5-1.

Table 5-1: Sample of IRI sensing data

Section ID	Smartphone ID	SectionStartTime	StartLatitude	StartLongitude	SectionEndTime	EndLatitude	EndLongitude	SectionMidTime	MidLatitude	MidLongitude	Length	Speed	Magnitudes
344002:1350043:344003:1350050	CC3A6166AA6C	20140610110440.7	34.66714	135.01183	20140610110443.8	34.667507	135.01381	20140610110440.7	34.66714	135.01183	186.0986	223.31833	0.78831
344003:1350050:344004:1350054	CC3A6166AA6C	20140610110443.8	34.667507	135.01381	20140610110445.7	34.66773	135.01512	20140610110443.8	34.667507	135.01381	123.13483	443.28537	0.47223
344004:1350054:344005:1350059	CC3A6166AA6C	20140610110445.7	34.66773	135.01512	20140610110447.8	34.66797	135.0164	20140610110445.7	34.66773	135.01512	120.03105	216.0559	0.95625
344005:1350059:344006:1350104	CC3A6166AA6C	20140610110447.8	34.66797	135.0164	20140610110449.8	34.66821	135.01772	20140610110447.8	34.66797	135.0164	123.332	221.9976	0.63613
344006:1350104:344006:1350108	CC3A6166AA6C	20140610110449.8	34.66821	135.01772	20140610110451.8	34.668438	135.01901	20140610110449.8	34.66821	135.01772	121.782486	219.20848	1.02853
344006:1350108:344007:1350113	CC3A6166AA6C	20140610110451.8	34.668438	135.01901	20140610110453.8	34.66862	135.02026	20140610110451.8	34.668438	135.01901	116.404366	209.52786	1.44979
344007:1350113:344008:1350118	CC3A6166AA6C	20140610110453.8	34.66862	135.02026	20140610110455.8	34.66885	135.02153	20140610110453.8	34.66862	135.02026	119.24528	214.6415	0.38063
344008:1350118:344009:1350122	CC3A6166AA6C	20140610110455.8	34.66885	135.02153	20140610110457.8	34.6691	135.02281	20140610110455.8	34.66885	135.02153	119.86557	215.75803	0.51779
344009:1350122:344010:1350127	CC3A6166AA6C	20140610110457.8	34.6691	135.02281	20140610110459.8	34.66933	135.02406	20140610110457.8	34.6691	135.02281	117.405556	211.33	0.4215
344010:1350127:344011:1350131	CC3A6166AA6C	20140610110459.8	34.66933	135.02406	20140610110501.8	34.669586	135.02533	20140610110459.8	34.66933	135.02406	119.286514	214.71573	0.62808
344011:1350131:344012:1350136	CC3A6166AA6C	20140610110501.8	34.669586	135.02533	20140610110503.8	34.669872	135.02661	20140610110501.8	34.669586	135.02533	122.67331	220.81195	0.76497
344012:1350136:344013:1350140	CC3A6166AA6C	20140610110503.8	34.669872	135.02661	20140610110505.8	34.67014	135.02785	20140610110503.8	34.669872	135.02661	116.221245	209.19824	0.75536
344013:1350140:344014:1350147	CC3A6166AA6C	20140610110505.8	34.67014	135.02785	20140610110508.8	34.67049	135.02975	20140610110505.8	34.67014	135.02785	179.34206	215.21046	1.13245
344014:1350147:344015:1350154	CC3A6166AA6C	20140610110508.8	34.67049	135.02975	20140610110511.8	34.670948	135.0316	20140610110508.8	34.67049	135.02975	177.34563	319.22214	1.01492
344015:1350154:344017:1350158	CC3A6166AA6C	20140610110511.8	34.670948	135.0316	20140610110513.8	34.671253	135.03284	20140610110511.8	34.670948	135.0316	118.14281	212.65706	0.68037
344017:1350158:344024:1350234	CC3A6166AA6C	20140610110513.8	34.671253	135.03284	20140610110529.8	34.673428	135.04276	20140610110513.8	34.671253	135.03284	939.67755	211.42744	1.92621

5.4. User interface of IRI Sensing

The app user interface consists of 4 main parts:

5.4.1. Setting and configuration

After installing the app (APK file) on a smartphone, the app icon will be shown on the smartphone application menu. Clicking on the icon will initiate the app interface. For the first use, the app will ask the user to set an initial configuration. This configuration can be changed at any time by clicking on the smartphone setup menu while the app is in use. After the initial configuration the user will be navigated to the app main screen.

The app main screen shows information of activating sensors, which include accelerometer and gyroscope as well as GPS. The information is real-time status of the sensors. User must press on "Start Sensing" button to start recording data and estimating magnitudes.

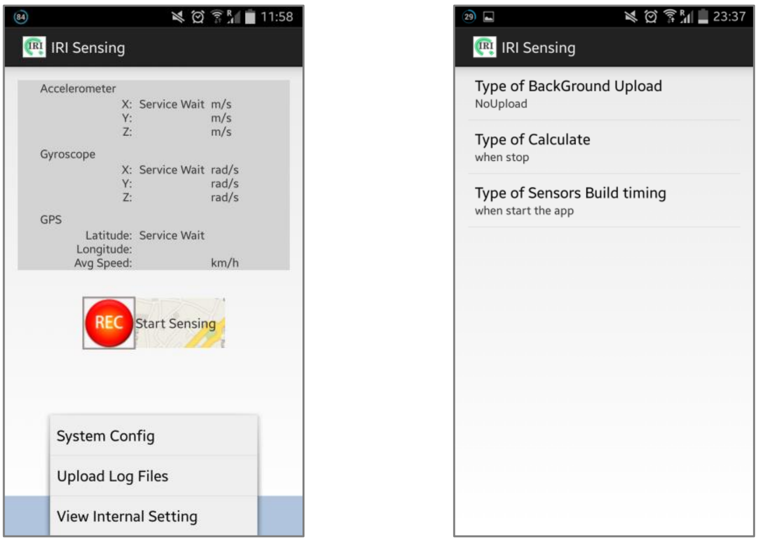
IRI sensing icon

Main screen

Figure 5-3: IRI Sensing icon and main screen

The app configuration includes: system configuration "System Config", data files uploading setting "UpLoad Log Files", and checking current configuration

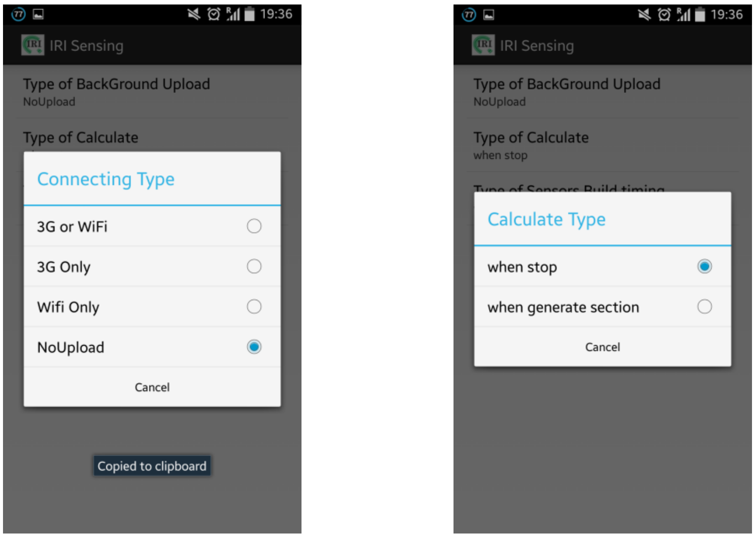
"View Internal Setting".



Configuration menu "System Config"

Figure 5-4: IRI Sensing Configuration menu 1

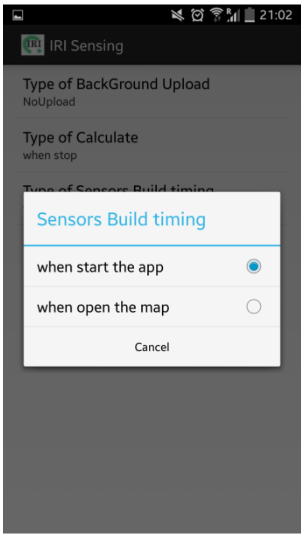
"System Config" allows users to change 3 main important procedures of the app, which are (1) the connection options for uploading the data files "Type of Background Upload", calculation approach "Type of Calculation", and options to activate sensors "Type of Sensors Build Timing".



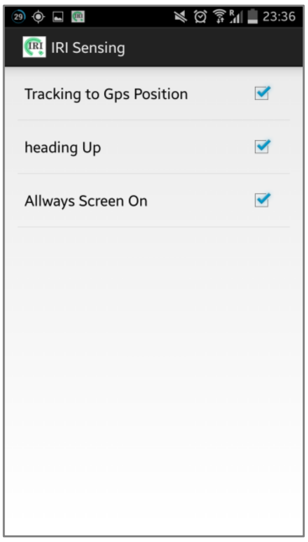
"Type of background upload" "Type of calculation"

Figure 5-5: IRI Sensing Configuration menu 2

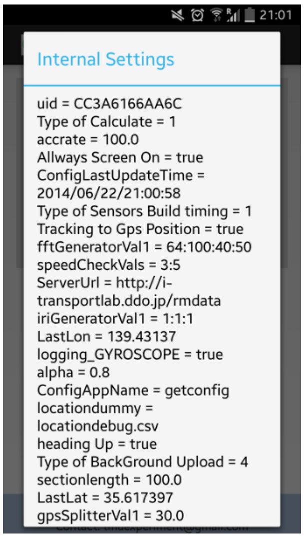
By clicking on "Type of Background Upload" users can choose how the data can be uploaded to the server. The options include: upload via 3G (cellular network) or WiFi, 3G only, WiFi only, or no upload. "Type of Calculation" allows users to choose how the app estimates or calculates results such as to estimate at once at the end when the vehicles already stop "When Stop", or to estimate real-time while the vehicles are running "When generate section"



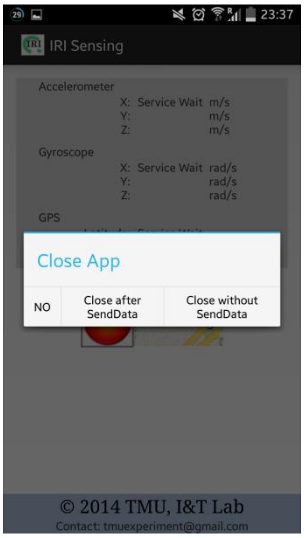
"Type of sensor build timing"



"Map Config"



Configuration file



App warning

Figure 5-6: IRI Sensing Configuration menu 3

While on recording screen, users can also setup some other settings such as tracking the route of trip by selecting “Tracking to GPS Position”, show preferred the direction of the trip by checking “Heading Up”, and a setting that would leave the screen on all the time “Always Screen On”

5.4.2. Data collecting and estimation

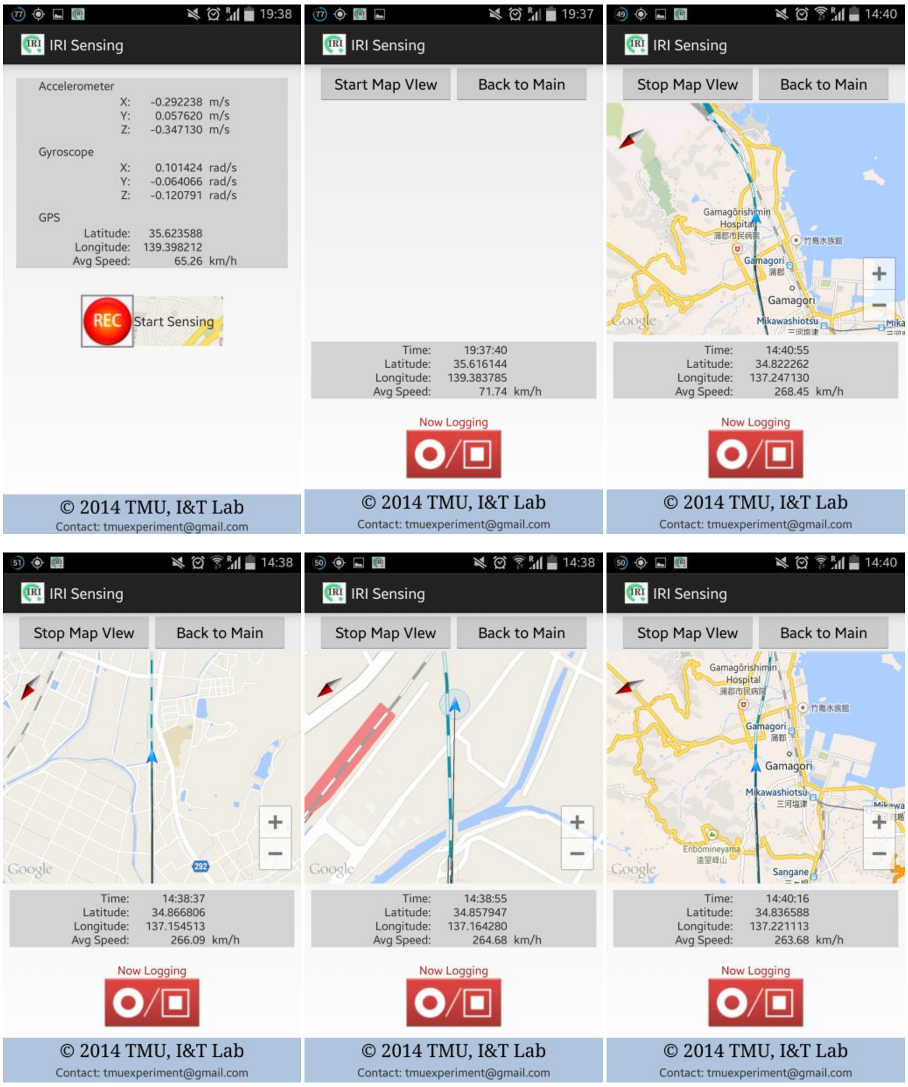


Figure 5-7: Data collection screens

Users can start the recording and estimation process by simply pressing the record button, which will bring the users to data recording screen. On the screen, users can choose to turn on or off the displaying of the route on a map. Going back to the main screen is also possible without interrupting to the process.

5.4.3. Data uploading

Data uploading will be done automatically, if the users select to do so. The automatic data uploading will be carried out every time the app starts. Manual data uploading can also be done by going to the setting menu and selecting data upload.

At the moment, data will be uploaded to a server configured as a default server. This setting can be changed but the system admin.

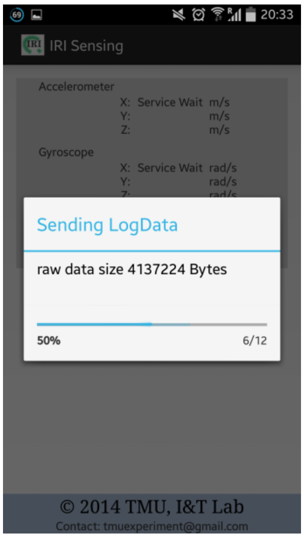


Figure 5-8: Data uploading

5.4.4. Visualization

Currently the visualization of the app is only limited to route tracking and map viewing. In the future, results of the estimation will also be indicated by condition index on the map.

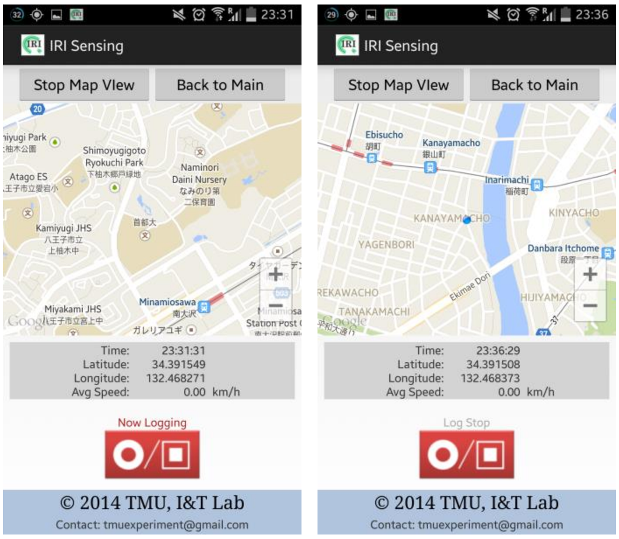


Figure 5-9: Map viewing and route tracking

5.5. Pilot use

5.5.1. Test run 1

A few simplified tests on the use of IRI Sensing have been carried out on a road in Tama-shi, Tokyo, Japan, from June 21 to July 4, 2014. Due to some constraints the test is only limited to:

- A selected road with a total length of approximately 3 km (see Figure 5-10);
- The selected road with one surface condition. The condition of the road is good (judging from visual inspection because real IRI of the road is not available). Roads with other surface conditions are not available nearby;
- Using one smartphone (a Samsung Galaxy S4); and
- The vehicle is public bus;

Figure 5-10: Route of test run 1

In the tests, the smartphone is place on a deck above the left hand side front wheel of the bus. IRI Sensing is operated while the bus is moving in normal operational condition. For each day of the tests, the bus is not the same. The location, where the smartphone has been placed, is shown in Figure 5-11. Figure 5-11 indicates the different of the deck on two selected buses.

Figure 5-11: Location of the smartphone for IRI Sensing test run

After running the test, and checking IRI Sensing results, only 9 sections or approximately 900m of the road can be estimated. The remaining length of the road cannot be estimated by IRI Sensing mainly because the buses stop very often at intersections and bus stops, which lead to some estimation sections being much shorter than 100m. A few sections with length of much longer than 100m, due to the inaccuracy of the GPS, are also observed. Sections that are much shorter and much longer than 100m will be omitted from the estimation.

Figure 5-12: Nine sections estimated by IRI Sensing

In Figure 5-12, S1 to S9 are section 1 to section 9, respectively. The colored markings or icons represent IRI Sensing estimations for the respective sections.

IRI Sensing results are summarized in Table 5-2. Note that because the real IRI of the testing road is not available, only magnitudes of the vibration are indicated in Table 5-2 for comparison purposes.

Table 5-2 IRI Sensing results

Run ID	Section No.	Section Coordinate (Mid point)		Section Length	Average Speed	Acceleration magnitudes
		Latitude	Longitude			
g19	S1	35.62074	139.43274	112.2	57.7	1.015
f2		35.62078	139.43277	100.8	51.8	4.011
c2		35.62071	139.43268	111.2	44.5	0.856
a3	S2	35.621918	139.43214	102.4	36.9	1.593
d36		35.62193	139.43233	113.5	45.4	1.770
c3		35.621655	139.43234	103.5	41.4	1.231
d17	S3	35.62265	139.4319	101.6	40.6	1.692
g21		35.622517	139.43196	101.6	45.7	1.578
g33		35.62258	139.432	101.9	11.1	1.056
d55	S4	35.625053	139.43105	108.2	38.9	2.419
d9		35.625	139.43109	105.3	31.6	1.280
a17		35.625057	139.43105	103.2	31.0	1.608
d10	S5	35.624138	139.43149	104.2	34.1	1.100
d28		35.62402	139.43144	106.4	34.8	0.842
d56		35.62413	139.43146	103.5	37.3	2.597
a18		35.62412	139.43146	103.2	31.0	1.287
a19	S6	35.622753	139.43211	103.1	8.4	0.745
b21		35.62267	139.4321	108.1	7.6	0.751
d29		35.622765	139.43207	108.7	10.0	1.125
a20	S7	35.62187	139.43253	105.3	34.5	0.876
d12		35.621887	139.4326	100.5	15.7	0.651
d30		35.621872	139.43253	102.6	36.9	1.067
g32		35.621765	139.43254	100.6	36.2	0.896
d13	S8	35.62108	139.4329	107.3	38.6	0.727
d31		35.62099	139.43288	104.5	41.8	0.558
d35		35.62093	139.43289	101.9	52.4	0.923
g31		35.62086	139.4328	103.6	41.4	1.250
e1	S9	35.619297	139.43306	100.1	36.0	1.213
d15		35.619167	139.43314	103.3	37.2	1.099
d33		35.61909	139.43309	101.8	40.7	1.123
d61		35.619526	139.43309	105.7	18.1	1.123

The estimations of the app for many road sections, in the initial tests, are generally consistent. As shown in Table 5-2, the estimations obtained from separate occasions show slight differences of the magnitudes, particularly for section S2, S3, S6, S7, S8, and S9. In each of the section S1, S4, and S5, despite having one large estimated magnitude, the remaining two, two and three estimations, in S1, S4 and S5 respectively, are relatively consistent.

5.5.2. Test run 2

This test run has been carried out in Laos on 29th July 2014. Also due to some constraints this test is limited to:

- A selected road with a total length of approximately 5 km (Figure 5-13);
- The selected road has surface condition of good, a mix of poor and bad, and bad sections;
- Using one smartphone (a Samsung Galaxy S4, the same device used in test run 1); and
- One vehicle, which is a Toyota VIGO 4WD;

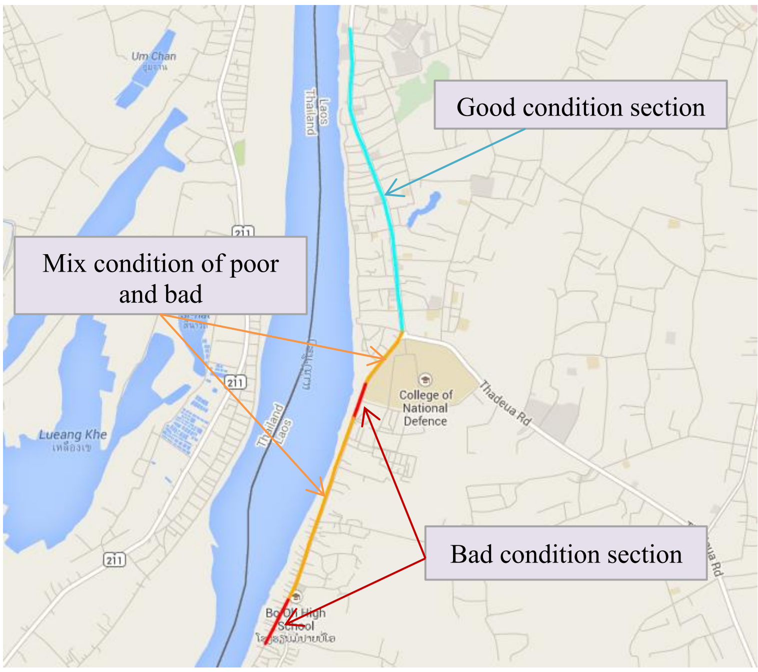


Figure 5-13: Route of test run 2

The smartphone has been placed on the dashboard of the vehicle, which is driven normally on the selected road for two rounds with IRI Sensing in operation.

The results are visualized in the figures below, which show considerably consistent estimation. The estimation results for the good condition section indicate that almost all of the acceleration magnitudes are in between 0.5 to 1.7 (cyan icons) with only 4 inconsistencies having the magnitudes of between 2 to 3 (orange icons). Figure 5-14.

Figure 5-14: IRI Sensing results for the good condition section

Figure 5-15: Results for the mixed condition (poor and bad) section 1

Figure 5-16: Results for the mixed condition (poor and bad) section 2

Figure 5-15 and Figure 5-16, which show the results of the estimation for the road sections with a mixed condition (between poor and bad conditions), also indicate consistent magnitudes (orange and red icons showing magnitudes that are corresponding to poor and bad sections, respectively) with some distortions by having some cyan icons, which are corresponding to good road condition. It is interesting to note that, however, all the five cyan icons in Figure 5-16 have their values very close to 2, which is the minimum value of magnitudes corresponding to a poor road condition.

Figure 5-17: Results for the bad condition section 1

Figure 5-18: Results for the bad condition section 2

Similarly, the estimation for bad sections is also very consistent. The magnitudes estimated are generally 4 to 6, with a few estimated magnitudes with values slightly smaller than 4.

5.6 Conclusions

The development of a smartphone app to estimate road roughness condition is one of the main and final goals of this dissertation. The app has been developed based on Android to take the advantage of it open source environment. The proposed app is believed to be simple, user friendly and easy to use with many basic functions.

From some initial tests, the app tends to be working with promising estimation results. It is important to note that the number of estimation in these tests is still relatively small; therefore to properly evaluate the performance of the app, more tests would be necessary. In addition, more roads with different surface condition, observed IRI, and vehicle selections would also be important for future tests and enhancement.

Chapter 6: CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

The objective of this study is to develop a method to estimate road roughness condition using smartphones with the following main original focuses: 1) the method that is simple and easy to implement with certain accuracy that is acceptable for road maintenance planning and monitoring; and 2) the method that is taking advantages of huge data being made available by anonymous road and smartphone users. With this objective in mind, the study could be a significant contribution in the field of road infrastructure monitoring and management, because it could lead to a practicable measuring tool that could be used to collect data more frequently and regularly, which is very difficult to achieve in the current practice.

To realize this goal, the smartphone application must be proposed and put in place (details in Chapter 5), and it must have a considerably good estimation model, so that the accuracy of the estimation is acceptable for the use in road maintenance planning and monitoring.

To achieve this, first of all, there is a need to study on the relationship between smartphone sensor data and the actual road surface roughness condition (details in Chapter 3). The study would enable the understanding on features, parameters and relationship function, which are very critical for the formulation of the estimation model.

After obtaining prospective function for the estimation model, the model will be formulated, investigated and tested to ensure that it works for the purpose. The most important point in the model formulation is that the model must be able to estimate road surface roughness condition from anonymous drivers (detail in Chapter 4)

To sum up, from the analysis, it is clear that IRI can be expressed roughly as a linear function of magnitude of acceleration vibration and average speed. However, parameters (coefficients) of linear function are different depending on individual vehicle or smartphone. Another interesting and important finding includes: from the breakdown frequency analysis, at high frequency range of 40-50 Hz the R^2 of the correlation are generally strongest. The analysis also shows similar tendency in the classification of the sum of magnitudes by road condition indexes, suggesting that the same model for IRI estimation can be assumed as long as vehicle type and device do not change. However, in case vehicle type and device change, the parameters of the model should be calibrated.

A further analysis also indicates that by considering the magnitudes calculated for each axis of the acceleration vibration, better estimation accuracy can be achieved in comparison to the magnitudes calculated for a combination of all axes. The best possible estimation accuracy can be achieved if both the sensors are considered in the estimation function.

In real use, it is very difficult to calibrate the parameters within solo data. However, by gathering so many data sets from so many vehicles and devices, the parameters might be estimated based on the commonality of road roughness for different vehicle types and devices. This is the advantage of the proposed approach.

The next step, model to estimate road roughness condition (IRI) has been proposed. The analysis from the previous chapters is a crucial foundation for the development of the model.

After model formulation, numerical examples have been simulated. The simulation results show that the model performs promisingly, particularly in cases, where observed road roughness condition consists of different IRI values spreading across different road condition indexes. Additionally an example using real sensor data is also performed. The result of the example confirms that the simple model can be used to predict IRI of road surface from smartphone sensor data with promising accuracy.

After obtaining the model, it has been incorporated into the development of a smartphone app in Android environment. The app has a simple user interface and a set of basic functionalities. The main feature of the app is that it can be installed on

Android smartphones and then used to estimate road roughness condition with ease of use.

Due to some constraints, the tests of the app are carried out using only one smartphone, on some public buses and a pick-up, and with limited conditions of roads. The purpose is to test whether the app is working and the estimation results are potentially practical. The test results indicate that the app is considerably practical with generally consistent estimation outcomes.

Recommendations for future work may include the following areas:

- Focus on the improvement of the estimation model to consider a more accurate function, such as the addition of gyroscope data or the consideration of each vibration axis separately.
- Another area of improvement maybe also focused on the app user interface and functionality.

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APPENDIX A: COSTS OF ROAD CONDITION SURVEY, LAOS

Average annual costs of network survey, National roads and bridges

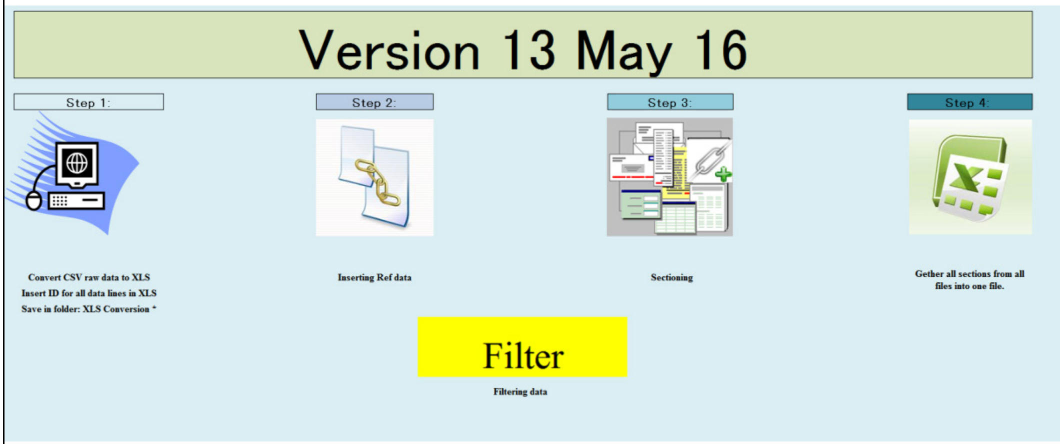
Activity	Unit	Quantity	Unit cost	Cycle	Amount
			USD	Years	USD
Referencing and inventories	**km**	**200**	**30**	**1**	**6,000**
Paved road condition	**km**	**4,000**	**5**	**2**	**10,000**
Unpaved road condition	**km**	**3,200**	**5**	**1**	**16,000**
Roughness	**km**	**4,000**	**11**	**2**	**22,000**
Bridge condition	**Bridge**	**1,300**	**13**	**1**	**16,900**
Traffic	**Link**	**240**	**82**	**5**	**3,936**
Socio-economic parameters	**Link**	**240**	**40**	**5**	**1,920**
Supervision and logistics					**15,000**
Total					***91,756***

Source: (PTI, 2009)

Appendix B: Smartphone location for the additional experiment

Date	Vehicle	Locations of the smartphones								
		Dashboard	Center Panel Box	Box Near Gear Shift	Front Passenger Seat	Rear Seat	Wind Shield	Driver Shirt Pocket	Driver Trouser Pocket	Other
3-Mar-14	1		1 and 3	7	2, 6 and 11	5, 8, 9 and 10				4 (Not in use)
4-Mar-14			2 and 3	7	5 and 8	1, 9 and 11				4, 6 and 10 (Participants)
5-Mar-14		9 and 11	2 and 3	7		8		1		5 (Not in use); 4, 6 and 10 (Participants)
6-Mar-14		9 and 11	2 and 3	7		8	5		1	4, 6 and 10 (Participants)
7-Mar-14			2 and 3	7		8	5	1		4, 6 and 10 (Participants); 9 and 11 (Used for IRISensing)
8-Mar-14 (1)		1, 2 and 10	7 and 8	5			3		11	4, 6 and 10 (Participants)
8-Mar-14 (2)		3 and 5		1, 2, 10 and 11			9	8	7	4 and 6 (Participants)
10-Mar-14 (1)	2	8 and 11		1 and 5	7	2 and 10	9	4	3	6 (Participant)
10-Mar-14 (2)		1, 2 and 10		4	9		3	8 and 11	7	5 (Not in use); 6 (Participant)
10-Mar-14 (3)		4, 7 and 9		3, 8 and 11			5	2	1 and 10	6 (Participant)
10-Mar-14 (4)		5	2 and 7			9	8	10	11	6 (Participant); 1, 3 and 4 (Used for IRISensing)

APPENDIX C: VBA CODES FOR DATA PROCESSING




```
Option Explicit

Sub VNDAnalysis()

Dim fPathResult, fPathSum As String
Dim sPath, fPathDone, RFolder As String
Dim sFile As String
Dim sDir As String
Dim oWB As Workbook
Dim Fname, WBName, WBName1 As String
Dim Alfa, Interval As Variant
Dim ExecFile As Variant
Dim ExecFileNumber As Long

Application.ScreenUpdating = False
Application.EnableEvents = False
Application.DisplayAlerts = False

Alfa = Application.InputBox(Prompt:="Input Alpha for High Pass Filter (0.1~0.9; Or 1 for no
filter)", Type:=1) 'Input Alfa for High Pass Filter
If Alfa <> 1 Then
    If Alfa = False Then
        If MsgBox("No value, Abort? Yes to abort; No to use default value", vbYesNo) = vbYes
        Then
            Exit Sub
        Else
            MsgBox "Default value of 0.1 will be selected"
            Alfa = 0.1
        End If
    Else
        If Alfa < 0.1 Or Alfa > 0.9 Then
            Do
              Alfa = Application.InputBox(Prompt:="Invalid value (0.1~0.9 or 1 for no filter)",
              Type:=1)
```

```
            Loop Until Alfa >= 0.1 And Alfa <= 0.9 Or Alfa = 1 Or Alfa = False
        End If
        If Alfa = False Then
          If MsgBox("No value, Abort? Yes to abort; No to use default value", vbYesNo) = vbYes
          Then
                Exit Sub
            Else
                MsgBox "Default value of 0.1 will be selected"
                Alfa = 0.1
            End If
        End If
    End If
End If

If MsgBox("Execute all files in a folder? [Yes]All files, [No]Only selected file", vbYesNo) = vbYes
Then

    MsgBox "Please select a folder with files to execute" 'Promt to select path by user
    Do
        With Application.FileDialog(msoFileDialogFolderPicker)
            .InitialFileName = ActiveWorkbook.Path & "¥"
            .AllowMultiSelect = False
            .Show
            If .SelectedItems.Count > 0 Then
                sPath = .SelectedItems(1) & "¥"
                Exit Do
            Else
              If MsgBox("No folder chose, do you wish to abort?", vbYesNo) = vbYes Then Exit
              Sub
            End If
        End With
    Loop

    On Error GoTo Err_Clk

    RFolder = Format(Now(), "yyyymmdd_hhmmss")
    fPathDone = sPath & "Result" & RFolder & "¥"
    On Error Resume Next
    MkDir fPathDone
    On Error GoTo 0

    sDir = Dir$(sPath & "*.xls", vbNormal)
    Do Until Len(sDir) = 0
        If sDir <> ThisWorkbook.Name Then
            Set oWB = Workbooks.Open(sPath & sDir)
            WBName = Left(oWB.Name, InStr(oWB.Name, ".") - 1)
            WBName1 = Right(WBName, 1)
            If WBName1 <> "R" Then

                Call AzimuthX
                Call HighPassFilter(Alfa)
                Call SectioningV11
```

```
                Fname = Left(WBName, Len(WBName) - 5)
                ActiveWorkbook.CheckCompatibility = False
                oWB.SaveAs fPathDone & Fname & " R"
                ActiveWorkbook.CheckCompatibility = True
                oWB.Close False
                Else
                    oWB.Close False
                End If
        End If
        sDir = Dir$
    Loop

Else
    sPath = ActiveWorkbook.Path & "¥"
    MsgBox "Please select file(s) to execute"
    ExecFile = Application.GetOpenFilename("Excel Files (*.xls*), *.xls*", Title:="Select File(s)",
    MultiSelect:=True)

    If IsArray(ExecFile) Then
        On Error GoTo Err_Clk
        RFolder = Format(Now(), "yyyymmdd_hhmmss")
        fPathDone = sPath & "Result" & RFolder & "¥"
        On Error Resume Next
        MkDir fPathDone
        On Error GoTo 0

            For ExecFileNumber = LBound(ExecFile) To UBound(ExecFile)
            Set oWB = Workbooks.Open(Filename:=ExecFile(ExecFileNumber))
            WBName = Left(oWB.Name, InStr(oWB.Name, ".") - 1)
            WBName1 = Right(WBName, 1)
            If WBName1 <> "R" Then

                Call AzimuthX
                Call HighPassFilter(Alfa)
                Call SectioningV11

                Fname = Left(WBName, Len(WBName) - 5)
                ActiveWorkbook.CheckCompatibility = False
                oWB.SaveAs fPathDone & Fname & " R"
                ActiveWorkbook.CheckCompatibility = True
                oWB.Close False
            Else
                oWB.Close False
            End If
        Next ExecFileNumber
    Else
        If ExecFile = False Then GoTo Cancel
    End If
End If

Err_Clk:
```

```
If Err <> 0 Then
      Err.Clear
      Resume Next
End If

ErrorExit:
Cancel:

ActiveSheet.Columns.AutoFit
Application.DisplayAlerts = True
Application.EnableEvents = True
Application.ScreenUpdating = True
End Sub
Sub HighPassFilter(Alfa)
Dim i, LR As Long
Dim Alpha1 As Variant

Alpha1 = Alfa

Sheets("Sheet2").Select
Cells(2, 18).Value = Cells(2, 2)
Cells(2, 19).Value = Cells(2, 3)
Cells(2, 20).Value = Cells(2, 4)
Cells(2, 21).Value = Cells(2, 5)
Cells(2, 22).Value = Cells(2, 6)
Cells(2, 23).Value = Cells(2, 7)

LR = Range("B" & Rows.Count).End(xlUp).Row

If Alpha1 <> 1 Then ' Alfa = 1 for no filter
For i = 3 To LR
     Cells(i, 18).Value = Cells(i, 2).Value - ((Alpha1 * Cells(i, 2).Value) + ((1 - Alpha1) * Cells(i - 1,
     18).Value))
     Cells(i, 19).Value = Cells(i, 3).Value - ((Alpha1 * Cells(i, 3).Value) + ((1 - Alpha1) * Cells(i - 1,
     19).Value))
     Cells(i, 20).Value = Cells(i, 4).Value - ((Alpha1 * Cells(i, 4).Value) + ((1 - Alpha1) * Cells(i - 1,
     20).Value))
     Cells(i, 21).Value = Cells(i, 5).Value - ((Alpha1 * Cells(i, 5).Value) + ((1 - Alpha1) * Cells(i - 1,
     21).Value))
     Cells(i, 22).Value = Cells(i, 6).Value - ((Alpha1 * Cells(i, 6).Value) + ((1 - Alpha1) * Cells(i - 1,
     22).Value))
     Cells(i, 23).Value = Cells(i, 7).Value - ((Alpha1 * Cells(i, 7).Value) + ((1 - Alpha1) * Cells(i - 1,
     23).Value))

Next i
Range("R2", "W" & LR).Copy
ActiveSheet.Paste Destination:=Range("B2", "G" & LR)
End If
End Sub
Sub SectioningV11()

Dim LatLSL(999), LatUSL(999), RowCntGRP(999) As Variant
```

```
Dim LongLSL(999), LongUSL(999), SectID(999) As Variant
Dim Z, S, U, t, lr1, lr2, XX, blankrow, targetrow, MyCounter As Long
Dim W1, W2, IRIAvg, StartCell, GRP1stRow, lrTemp As Long
Dim StartRowValueLat, EndRowValueLat, RowLat, Temp3StartR, SumIRI, AvgIRI As Single
Dim StartRowValueLong, EndRowValueLong, RowLong, StartR, EndR, StartRTemp, StartRx As
Single
Dim GRP, RowCnt, J, V, K, r As Single
Dim Lat1, Lat2, Lon1, Lon2 As Double
Dim Sht As Worksheet
Dim FindRow As Range

blankrow = 1
targetrow = 2
MyCounter = 1
GRP = 1
SumIRI = 0
AvgIRI = 0
RowCnt = 0

For Each Sht In ActiveWorkbook.Worksheets
        If Sht.Visible = xlSheetVeryHidden Then
            Sht.Visible = xlSheetVisible
            If Sht.Name <> "Sheet1" And Sht.Name <> "Sheet2" Then
                'Application.DisplayAlerts = False
                Sht.Delete
            Else
                Sht.Visible = xlSheetVeryHidden
            End If
        Else
            If Sht.Name <> "Sheet1" And Sht.Name <> "Sheet2" Then
                'Application.DisplayAlerts = False
                Sht.Delete
            End If
        End If
Next Sht

Sheets("Sheet1").Select ' Sectioning VIMS IRI and Location data
lr1 = Range("F" & Rows.Count).End(xlUp).Row
Columns("H:AV").Delete
For Z = 2 To lr1
    If MyCounter <= 10 Then
        If Cells(Z, 6) <= 8 Or Cells(Z, 6) >= 12 Then
            Z = Z
            MyCounter = 1
            targetrow = targetrow + 1
            GRP = GRP + 1
            SumIRI = 0
        Else
            Cells(targetrow, 8) = Cells(Z, 1)
            Cells(targetrow, 9) = Cells(Z, 3)
            Cells(targetrow, 11) = Cells(Z, 4)
            Cells(targetrow, 12) = Cells(Z, 5)
```

```
                Cells(targetrow, 13) = Cells(Z, 6)
                    If MyCounter = 1 Then
                        LatLSL(GRP) = Cells(Z, 4).Value
                        LongLSL(GRP) = Cells(Z, 5).Value
                        SectID(GRP) = Cells(Z, 2).Value
                        GRP1stRow = targetrow
                    End If
                LatUSL(GRP) = Cells(targetrow, 11).Value
                LongUSL(GRP) = Cells(targetrow, 12).Value
                SumIRI = Cells(Z, 3).Value + SumIRI
                AvgIRI = SumIRI / MyCounter
                Cells(GRP1stRow, 10) = AvgIRI
                MyCounter = MyCounter + 1
                targetrow = targetrow + 1
            End If
        Else
                targetrow = targetrow + 1
                Z = Z - 2
                MyCounter = 1
                GRP = GRP + 1
                SumIRI = 0
        End If
RowCntGRP(GRP) = MyCounter - 1
Next Z
Cells(1, 8) = Cells(1, 1)
Cells(1, 9) = "IRI"
Cells(1, 10) = "AvgIRI"
Cells(1, 11) = "Lat"
Cells(1, 12) = "Long"
Cells(1, 13) = "Dist"

Sheets.Add after:=Sheets(Sheets.Count)
ActiveSheet.Name = "Temp1"
Sheets.Add after:=Sheets(Sheets.Count)
ActiveSheet.Name = "Temp2"
Sheets.Add after:=Sheets(Sheets.Count)
ActiveSheet.Name = "Temp3"

Sheets("Sheet2").Select
StartCell = 2

Columns("N:AS").Delete
lrTemp = Range("F" & Rows.Count).End(xlUp).Row

U = 1
For t = 3 To lrTemp
RowLat = Abs(Cells(t, 8) - Cells(t - 1, 8))
RowLong = Abs(Cells(t, 9) - Cells(t - 1, 9))
    If RowLat <> 0 And RowLong <> 0 Then
        StartRTemp = Mid((Cells(t - 1, 8).Address), 4, 8)
        Range(Cells(t, 8), Cells(t, 9)).Copy
        Sheets("Temp3").Select
```

```
        U = U + 1
        ActiveSheet.Paste Destination:=Range("B" & U, "C" & U)
        Cells(U, 1) = StartRTemp
    End If
    Sheets("Sheet2").Select
Next t

Call AzimuthY
Call SectArr

Sheets("Temp3").Select
lr2 = Range("A" & Rows.Count).End(xlUp).Row
K = 2
For S = 1 To GRP - 1
        J = 0
        V = 0
        For W1 = K To lr2 '(K + 15)
            Sheets("Temp3").Select
            StartRowValueLat = Abs(Cells(W1, 2) - LatLSL(S))
            StartRowValueLong = Abs(Cells(W1, 3) - LongLSL(S))
            Temp3StartR = Mid((Cells(W1, 2).Address), 4, 8)
            StartR = Cells(W1, 1).Value
            If Cells(W1, 6).Value = SectID(S) Then
                Sheets("Temp1").Select
                J = J + 1
                Cells(J, 1) = StartR
                Cells(J, 2) = StartRowValueLat
                Cells(J, 3) = StartRowValueLong
                Cells(J, 4) = StartRowValueLat + StartRowValueLong
                Cells(J, 5) = Temp3StartR
            End If
        Next W1

        Sheets("Temp1").Select
        Range("E1").Select
        Application.CutCopyMode = False
        ActiveWorkbook.Worksheets("Temp1").Sort.SortFields.Clear
        ActiveWorkbook.Worksheets("Temp1").Sort.SortFields.Add Key:=Range("D1"), _
        SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
        With ActiveWorkbook.Worksheets("Temp1").Sort
            .SetRange Range("A1", "E" & J)
            .Header = xlNo
            .MatchCase = False
            .Orientation = xlTopToBottom
            .SortMethod = xlPinYin
            .Apply
        End With
        StartR = Cells(1, 1).Value
        StartRx = Cells(1, 5).Value

        XX = StartRx
        For W2 = XX To lr2
```

```
        Sheets("Temp3").Select
        EndRowValueLat = Abs(Cells(W2, 2) - LatUSL(S))
        EndRowValueLong = Abs(Cells(W2, 3) - LongUSL(S))
        EndR = Cells(W2, 1).Value
        If Cells(W2, 6) = SectID(S) Then
            Sheets("Temp2").Select
            V = V + 1
            Cells(V, 1) = EndR
            Cells(V, 2) = EndRowValueLat
            Cells(V, 3) = EndRowValueLong
            Cells(V, 4) = EndRowValueLat + EndRowValueLong
        End If
    Next W2

    Sheets("Temp2").Select
    Range("D1").Select
    Application.CutCopyMode = False
    ActiveWorkbook.Worksheets("Temp2").Sort.SortFields.Clear
    ActiveWorkbook.Worksheets("Temp2").Sort.SortFields.Add Key:=Range("D1"), _
    SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal
    With ActiveWorkbook.Worksheets("Temp2").Sort
        .SetRange Range("A1", "D" & V)
        .Header = xlNo
        .MatchCase = False
        .Orientation = xlTopToBottom
        .SortMethod = xlPinYin
        .Apply
    End With
    EndR = Cells(1, 1).Value

    Sheets("Sheet2").Select

    For r = StartR + 1 To EndR + 1
        Cells(StartCell, 14) = Cells(r, 1).Value
        Cells(StartCell, 15) = Cells(r, 2).Value
        Cells(StartCell, 19) = Cells(r, 3).Value
        Cells(StartCell, 23) = Cells(r, 4).Value - 9.81
        Cells(StartCell, 27) = Cells(r, 5).Value
        Cells(StartCell, 31) = Cells(r, 6).Value
        Cells(StartCell, 35) = Cells(r, 7).Value
        Cells(StartCell, 39) = Cells(r, 8).Value
        Cells(StartCell, 40) = Cells(r, 9).Value
        Cells(StartCell, 41) = Cells(r, 11).Value
        Cells(StartCell, 43).FormulaR1C1 = "=SQRT(RC[-28]^2+RC[-24]^2+RC[-20]^2)"

        StartCell = StartCell + 1
    Next r
    Cells(StartCell - EndR + StartR - 1, 42).Value = RowCntGRP(S)
    Lat1 = Cells(StartR + 1, 8).Value
    Lon1 = Cells(StartR + 1, 9).Value
    Lat2 = Cells(EndR + 1, 8).Value
    Lon2 = Cells(EndR + 1, 9).Value
```

```
        Cells(StartCell - EndR + StartR - 1, 44).Value = Distance(Lat1, Lon1, Lat2, Lon2)

        StartCell = StartCell + 1
        K = XX - 1
        Sheets("Temp1").Range("A1", "E" & J).Clear
        Sheets("Temp2").Range("A1", "D" & V).Clear
Next S
Cells(1, 14) = "#"
Cells(1, 15) = "ax"
Cells(1, 16) = "axFFTFrq"
Cells(1, 17) = "axFFTMag"
Cells(1, 18) = "axFFTCpx"
Cells(1, 19) = "ay"
Cells(1, 20) = "ayFFTFrq"
Cells(1, 21) = "ayFFTMag"
Cells(1, 22) = "ayFFTCpx"
Cells(1, 23) = "az"
Cells(1, 24) = "azFFTFrq"
Cells(1, 25) = "azFFTMag"
Cells(1, 26) = "azFFTCpx"
Cells(1, 27) = "gx"
Cells(1, 28) = "gxFFTFrq"
Cells(1, 29) = "gxFFTMag"
Cells(1, 30) = "gxFFTCpx"
Cells(1, 31) = "gy"
Cells(1, 32) = "gyFFTFrq"
Cells(1, 33) = "gyFFTMag"
Cells(1, 34) = "gyFFTCpx"
Cells(1, 35) = "gz"
Cells(1, 36) = "gzFFTFrq"
Cells(1, 37) = "gzFFTMag"
Cells(1, 38) = "gzFFTCpx"
Cells(1, 39) = "Lat"
Cells(1, 40) = "Long"
Cells(1, 41) = "Speed"
Cells(1, 42) = "VIMSSect#"
Cells(1, 43) = "xyzLength"
Cells(1, 44) = "SectDist"

Call Move2NewSheet

End Sub
Sub SectArr()
Dim lrtemp3, xtemp3, ytemp3, dupli, col As Single

Sheets("Temp3").Select
lrtemp3 = Range("E" & Rows.Count).End(xlUp).Row

col = 5
xtemp3 = Cells(lrtemp3, col).Value
For ytemp3 = 1 To xtemp3
```

```
    dupli = Application.WorksheetFunction.CountIf(Range("E1:E" & lrtemp3), ytemp3)
    If dupli <= 10 Then

        Call DelSomeRows(ytemp3, col)

    End If
Next ytemp3

Call Rearr

End Sub
Sub DelSomeRows(ytemp3, col)
    Dim colNo As Long:        colNo = col
    Dim ws      As Worksheet: Set ws = ActiveSheet

    Dim rgCol As Range
    Set rgCol = ws.Columns(colNo)
    Set rgCol = Application.Intersect(ws.UsedRange, rgCol)
    Dim rgZeroCells As Range
    Dim rgCell        As Range
    For Each rgCell In rgCol.Cells
        If Not IsError(rgCell) Then
            If rgCell.Value = ytemp3 Then
                If rgZeroCells Is Nothing Then
                    Set rgZeroCells = rgCell
                Else
                    Set rgZeroCells = Union(rgZeroCells, rgCell)
                End If
            End If
        End If
    Next rgCell
    If Not rgZeroCells Is Nothing Then
        rgZeroCells.EntireRow.Delete
    End If
End Sub
Sub Rearr()
Dim temp3lr, temp3x, temp3y As Single

Sheets("Temp3").Select
temp3lr = Range("E" & Rows.Count).End(xlUp).Row

temp3y = 1
For temp3x = 2 To temp3lr
    If temp3x > 2 Then
        If Abs(Cells(temp3x, 4).Value - Cells(temp3x - 1, 4).Value) > 40 Then
            If Cells(temp3x, 5).Value <> Cells(temp3x - 1, 5).Value Then
                temp3y = temp3y + 1
                Cells(temp3x, 6).Value = temp3y
            End If
        End If
    End If
    Cells(temp3x, 6).Value = temp3y
```

```
Next temp3x

End Sub
Function Distance(Lat1, Lon1, Lat2, Lon2) As Double
Dim Rad1, Rad2, Rad3, Rad4 As Double

Rad1 = CDbl(Application.WorksheetFunction.Radians(90 - Lat1))
Rad2 = CDbl(Application.WorksheetFunction.Radians(90 - Lat2))
Rad3 = CDbl(Application.WorksheetFunction.Radians(Lon1 - Lon2))
Rad4 = Cos(Rad1) * Cos(Rad2) + Sin(Rad1) * Sin(Rad2) * Cos(Rad3)

If Rad4 < -1 Then Rad4 = -1
If Rad4 > 1 Then Rad4 = 1

Distance = CDbl(Application.WorksheetFunction.Acos(Rad4)) * 6371 * 1000

End Function
Sub Move2NewSheet()
Dim lr4, lr5 As Long
Dim Cnta, Cntb, StartCell, EndCell, x As Single
Dim MyName As String

Sheets("Sheet1").Select
lr4 = Range("H" & Rows.Count).End(xlUp).Row
Cnta = 1
StartCell = 2
EndCell = 1
MyName = "a" & Cnta

    For x = 2 To lr4 + 1
        If Cells(x, 8) = "" Then
            EndCell = x
            Range(Cells(StartCell, 8), Cells(EndCell, 13)).Copy
            Sheets.Add after:=Sheets(Sheets.Count)
            ActiveSheet.Paste Destination:=Range("A2", "I14")
            Cells(1, 1) = "#"
            Cells(1, 2) = "IRI"
            Cells(1, 3) = "AvgIRI"
            Cells(1, 4) = "Lat"
            Cells(1, 5) = "Long"
            Cells(1, 6) = "Dist"
            ActiveSheet.Name = MyName
            Sheets("Sheet1").Select
            x = x + 1
            StartCell = EndCell + 1
            Cnta = Cnta + 1
            MyName = "a" & Cnta
        End If
    Next x

Sheets("Sheet2").Select
lr5 = Range("N" & Rows.Count).End(xlUp).Row
```

```
Cntb = 1
StartCell = 2
EndCell = 1
MyName = "b" & Cntb

    For x = 2 To lr5 + 1
        If Cells(x, 14) = "" Then
            EndCell = x
            Range(Cells(StartCell, 14), Cells(EndCell, 44)).Copy
            Sheets.Add after:=Sheets(Sheets.Count)
            ActiveSheet.Paste Destination:=Range("A2", "AI3000")
            Cells(1, 1) = "#"
            Cells(1, 2) = "ax"
            Cells(1, 3) = "axFFTFrq"
            Cells(1, 4) = "axFFTMag"
            Cells(1, 5) = "axFFTCpx"
            Cells(1, 6) = "ay"
            Cells(1, 7) = "ayFFTFrq"
            Cells(1, 8) = "ayFFTMag"
            Cells(1, 9) = "ayFFTCpx"
            Cells(1, 10) = "az"
            Cells(1, 11) = "azFFTFrq"
            Cells(1, 12) = "azFFTMag"
            Cells(1, 13) = "azFFTCpx"
            Cells(1, 14) = "gx"
            Cells(1, 15) = "gxFFTFrq"
            Cells(1, 16) = "gxFFTMag"
            Cells(1, 17) = "gxFFTCpx"
            Cells(1, 18) = "gy"
            Cells(1, 19) = "gyFFTFrq"
            Cells(1, 20) = "gyFFTMag"
            Cells(1, 21) = "gyFFTCpx"
            Cells(1, 22) = "gz"
            Cells(1, 23) = "gzFFTFrq"
            Cells(1, 24) = "gzFFTMag"
            Cells(1, 25) = "gzFFTCpx"
            Cells(1, 26) = "Lat"
            Cells(1, 27) = "Long"
            Cells(1, 28) = "Speed"
            Cells(1, 29) = "VIMSSect#"
            Cells(1, 30) = "xyzLenght"
            Cells(1, 31) = "xyzFFTFrq"
            Cells(1, 32) = "xyzFFTMag"
            Cells(1, 33) = "xyzFFTCpx"
            Cells(1, 34) = "SectDist"
            Cells(2, 34).Value = Cells(2, 31).Value

            Call GoToManual

            ActiveSheet.Name = MyName
            Sheets("Sheet2").Select
            x = x + 1
```

```
            StartCell = EndCell + 1
            Cntb = Cntb + 1
            MyName = "b" & Cntb

        End If
    Next x
    Sheets("Sheet1").Select
    Range("O1").Value = Cntb - 1

    Call Summary

End Sub

Sub FillEmptyCells()
Dim EmptyCells As Range
Dim EmptyCells1 As Range


Range("B2", "Y1025").Select
For Each EmptyCells In Selection
If IsEmpty(EmptyCells) Then EmptyCells.Value = "0"
Next

Range("AD2", "AG1025").Select
For Each EmptyCells1 In Selection
If IsEmpty(EmptyCells1) Then EmptyCells1.Value = "0"
Next

End Sub

Sub FFTCal()
    Range("C2", "E1025").Clear
    Application.Run "ATPVBAEN.XLAM!Fourier", ActiveSheet.Range("B2", "B1025"),
    ActiveSheet.Range("E2"), _False, False

    Range("D2", "D1025").FormulaR1C1 = "=2/1024*IMABS(RC[1])"
    Range("C2") = 0
    Range("C3") = 100 / 1024
    Range("C3").Select
    Selection.DataSeries Rowcol:=xlColumns, Type:=xlLinear, Date:=xlDay, _
    Step:=0.097656, Stop:=100, Trend:=False

    Range("G2", "I1025").Clear
    Application.Run "ATPVBAEN.XLAM!Fourier", ActiveSheet.Range("F2", "F1025"),
    ActiveSheet.Range("I2"), _False, False

    Range("H2", "H1025").FormulaR1C1 = "=2/1024*IMABS(RC[1])"

    Range("G2", "G1025") = Range("C2", "C1025").Value

    Range("K2", "M1025").Clear
    Application.Run "ATPVBAEN.XLAM!Fourier", ActiveSheet.Range("J2", "J1025"),
```

```
    ActiveSheet.Range("M2"), _False, False

    Range("L2", "L1025").FormulaR1C1 = "=2/1024*IMABS(RC[1])"

    Range("K2", "K1025") = Range("C2", "C1025").Value

    Range("O2", "Q1025").Clear
    Application.Run "ATPVBAEN.XLAM!Fourier", ActiveSheet.Range("N2", "N1025"),
    ActiveSheet.Range("Q2"), _False, False

    Range("P2", "P1025").FormulaR1C1 = "=2/1024*IMABS(RC[1])"

    Range("O2", "O1025") = Range("C2", "C1025").Value

    Range("S2", "U1025").Clear
    Application.Run "ATPVBAEN.XLAM!Fourier", ActiveSheet.Range("R2", "R1025"),
    ActiveSheet.Range("U2"), _False, False

    Range("T2", "T1025").FormulaR1C1 = "=2/1024*IMABS(RC[1])"

    Range("S2", "S1025") = Range("C2", "C1025").Value

    Range("W2", "Y1025").Clear
    Application.Run "ATPVBAEN.XLAM!Fourier", ActiveSheet.Range("V2", "V1025"),
    ActiveSheet.Range("Y2"), _False, False

    Range("X2", "X1025").FormulaR1C1 = "=2/1024*IMABS(RC[1])"

    Range("W2", "W1025") = Range("C2", "C1025").Value

    Range("AE2", "AG1025").Clear
    Application.Run "ATPVBAEN.XLAM!Fourier", ActiveSheet.Range("AD2", "AD1025"),
    ActiveSheet.Range("AG2"), _False, False

    Range("AF2", "AF1025").FormulaR1C1 = "=2/1024*IMABS(RC[1])"

    Range("AE2", "AE1025") = Range("C2", "C1025").Value

End Sub

Sub Summary()

Dim axSum0to10, axSum10to20, axSum20to30, axSum30to40, axSum40to50 As Single
Dim axSum5to15, axSum15to25, axSum25to35, axSum35to45 As Single
Dim aySum0to10, aySum10to20, aySum20to30, aySum30to40, aySum40to50 As Single
Dim aySum5to15, aySum15to25, aySum25to35, aySum35to45 As Single
Dim azSum0to10, azSum10to20, azSum20to30, azSum30to40, azSum40to50 As Single
Dim azSum5to15, azSum15to25, azSum25to35, azSum35to45 As Single
Dim gxSum0to10, gxSum10to20, gxSum20to30, gxSum30to40, gxSum40to50 As Single
Dim gxSum5to15, gxSum15to25, gxSum25to35, gxSum35to45 As Single
Dim gySum0to10, gySum10to20, gySum20to30, gySum30to40, gySum40to50 As Single
Dim gySum5to15, gySum15to25, gySum25to35, gySum35to45 As Single
```

```
Dim gzSum0to10, gzSum10to20, gzSum20to30, gzSum30to40, gzSum40to50 As Single
Dim gzSum5to15, gzSum15to25, gzSum25to35, gzSum35to45 As Single
Dim xyzSum0to10, xyzSum10to20, xyzSum20to30, xyzSum30to40, xyzSum40to50 As Single
Dim xyzSum5to15, xyzSum15to25, xyzSum25to35, xyzSum35to45 As Single
Dim AvgSpd, Cnt, q As Single


Sheets.Add after:=Sheets(Sheets.Count)
ActiveSheet.Name = "Summary"

Sheets("Sheet1").Select
Cnt = Range("O1").Value

For q = 1 To Cnt
Sheets("a" & q).Select
Range("C2").Copy
Sheets("Summary").Select
Cells(q + 1, 1) = WBName
Cells(q + 1, 2) = q
ActiveSheet.Paste Destination:=Cells(q + 1, 3)
Sheets("b" & q).Select
    axSum0to10 = Application.Sum(Range("D2", "D104"))
    axSum10to20 = Application.Sum(Range("D105", "D206"))
    axSum20to30 = Application.Sum(Range("D207", "D309"))
    axSum30to40 = Application.Sum(Range("D310", "D411"))
    axSum40to50 = Application.Sum(Range("D412", "D514"))
    axSum5to15 = Application.Sum(Range("D54", "D155"))
    axSum15to25 = Application.Sum(Range("D156", "D258"))
    axSum25to35 = Application.Sum(Range("D259", "D360"))
    axSum35to45 = Application.Sum(Range("D361", "D462"))

    aySum0to10 = Application.Sum(Range("H2", "H104"))
    aySum10to20 = Application.Sum(Range("H105", "H206"))
    aySum20to30 = Application.Sum(Range("H207", "H309"))
    aySum30to40 = Application.Sum(Range("H310", "H411"))
    aySum40to50 = Application.Sum(Range("H412", "H514"))
    aySum5to15 = Application.Sum(Range("H54", "H155"))
    aySum15to25 = Application.Sum(Range("H156", "H258"))
    aySum25to35 = Application.Sum(Range("H259", "H360"))
    aySum35to45 = Application.Sum(Range("H361", "H462"))

    azSum0to10 = Application.Sum(Range("L2", "L104"))
    azSum10to20 = Application.Sum(Range("L105", "L206"))
    azSum20to30 = Application.Sum(Range("L207", "L309"))
    azSum30to40 = Application.Sum(Range("L310", "L411"))
    azSum40to50 = Application.Sum(Range("L412", "L514"))
    azSum5to15 = Application.Sum(Range("L54", "L155"))
    azSum15to25 = Application.Sum(Range("L156", "L258"))
    azSum25to35 = Application.Sum(Range("L259", "L360"))
    azSum35to45 = Application.Sum(Range("L361", "L462"))

    gxSum0to10 = Application.Sum(Range("P2", "P104"))
```

```
gxSum10to20 = Application.Sum(Range("P105", "P206"))
gxSum20to30 = Application.Sum(Range("P207", "P309"))
gxSum30to40 = Application.Sum(Range("P310", "P411"))
gxSum40to50 = Application.Sum(Range("P412", "P514"))
gxSum5to15 = Application.Sum(Range("P54", "P155"))
gxSum15to25 = Application.Sum(Range("P156", "P258"))
gxSum25to35 = Application.Sum(Range("P259", "P360"))
gxSum35to45 = Application.Sum(Range("P361", "P462"))

gySum0to10 = Application.Sum(Range("T2", "T104"))
gySum10to20 = Application.Sum(Range("T105", "T206"))
gySum20to30 = Application.Sum(Range("T207", "T309"))
gySum30to40 = Application.Sum(Range("T310", "T411"))
gySum40to50 = Application.Sum(Range("T412", "T514"))
gySum5to15 = Application.Sum(Range("T54", "T155"))
gySum15to25 = Application.Sum(Range("T156", "T258"))
gySum25to35 = Application.Sum(Range("T259", "T360"))
gySum35to45 = Application.Sum(Range("T361", "T462"))

gzSum0to10 = Application.Sum(Range("X2", "X104"))
gzSum10to20 = Application.Sum(Range("X105", "X206"))
gzSum20to30 = Application.Sum(Range("X207", "X309"))
gzSum30to40 = Application.Sum(Range("X310", "X411"))
gzSum40to50 = Application.Sum(Range("X412", "X514"))
gzSum5to15 = Application.Sum(Range("X54", "X155"))
gzSum15to25 = Application.Sum(Range("X156", "X258"))
gzSum25to35 = Application.Sum(Range("X259", "X360"))
gzSum35to45 = Application.Sum(Range("X361", "X462"))

xyzSum0to10 = Application.Sum(Range("AF2", "AF104"))
xyzSum10to20 = Application.Sum(Range("AF105", "AF206"))
xyzSum20to30 = Application.Sum(Range("AF207", "AF309"))
xyzSum30to40 = Application.Sum(Range("AF310", "AF411"))
xyzSum40to50 = Application.Sum(Range("AF412", "AF514"))
xyzSum5to15 = Application.Sum(Range("AF54", "AF155"))
xyzSum15to25 = Application.Sum(Range("AF156", "AF258"))
xyzSum25to35 = Application.Sum(Range("AF259", "AF360"))
xyzSum35to45 = Application.Sum(Range("AF361", "AF462"))

AvgSpd = Application.Average(Range("AB2", "AB1100"))

Sheets("Summary").Select
Cells(q + 1, 4).Value = axSum0to10
Cells(q + 1, 5).Value = aySum0to10
Cells(q + 1, 6).Value = azSum0to10
Cells(q + 1, 7).Value = gxSum0to10
Cells(q + 1, 8).Value = gySum0to10
Cells(q + 1, 9).Value = gzSum0to10

Cells(q + 1, 11).Value = axSum10to20
Cells(q + 1, 12).Value = aySum10to20
Cells(q + 1, 13).Value = azSum10to20
```

```
Cells(q + 1, 14).Value = gxSum10to20
Cells(q + 1, 15).Value = gySum10to20
Cells(q + 1, 16).Value = gzSum10to20

Cells(q + 1, 18).Value = axSum20to30
Cells(q + 1, 19).Value = aySum20to30
Cells(q + 1, 20).Value = azSum20to30
Cells(q + 1, 21).Value = gxSum20to30
Cells(q + 1, 22).Value = gySum20to30
Cells(q + 1, 23).Value = gzSum20to30

Cells(q + 1, 25).Value = axSum30to40
Cells(q + 1, 26).Value = aySum30to40
Cells(q + 1, 27).Value = azSum30to40
Cells(q + 1, 28).Value = gxSum30to40
Cells(q + 1, 29).Value = gySum30to40
Cells(q + 1, 30).Value = gzSum30to40

Cells(q + 1, 32).Value = axSum40to50
Cells(q + 1, 33).Value = aySum40to50
Cells(q + 1, 34).Value = azSum40to50
Cells(q + 1, 35).Value = gxSum40to50
Cells(q + 1, 36).Value = gySum40to50
Cells(q + 1, 37).Value = gzSum40to50

Cells(q + 1, 39).Value = axSum5to15
Cells(q + 1, 40).Value = aySum5to15
Cells(q + 1, 41).Value = azSum5to15
Cells(q + 1, 42).Value = gxSum5to15
Cells(q + 1, 43).Value = gySum5to15
Cells(q + 1, 44).Value = gzSum5to15

Cells(q + 1, 46).Value = axSum15to25
Cells(q + 1, 47).Value = aySum15to25
Cells(q + 1, 48).Value = azSum15to25
Cells(q + 1, 49).Value = gxSum15to25
Cells(q + 1, 50).Value = gySum15to25
Cells(q + 1, 51).Value = gzSum15to25

Cells(q + 1, 53).Value = axSum25to35
Cells(q + 1, 54).Value = aySum25to35
Cells(q + 1, 55).Value = azSum25to35
Cells(q + 1, 56).Value = gxSum25to35
Cells(q + 1, 57).Value = gySum25to35
Cells(q + 1, 58).Value = gzSum25to35

Cells(q + 1, 60).Value = axSum35to45
Cells(q + 1, 61).Value = aySum35to45
Cells(q + 1, 62).Value = azSum35to45
Cells(q + 1, 63).Value = gxSum35to45
Cells(q + 1, 64).Value = gySum35to45
Cells(q + 1, 65).Value = gzSum35to45
```

```
Cells(q + 1, 70).Value = xyzSum0to10
Cells(q + 1, 71).Value = xyzSum10to20
Cells(q + 1, 72).Value = xyzSum20to30
Cells(q + 1, 73).Value = xyzSum30to40
Cells(q + 1, 74).Value = xyzSum40to50
Cells(q + 1, 75).Value = xyzSum5to15
Cells(q + 1, 76).Value = xyzSum15to25
Cells(q + 1, 77).Value = xyzSum25to35
Cells(q + 1, 78).Value = xyzSum35to45

Cells(q + 1, 66).Value = Sheets("b" & q).Cells(2, 34)
Cells(q + 1, 67).Value = AvgSpd
Cells(q + 1, 68) = Sheets("b" & q).Cells(2, 29)
Next q

Cells(1, 1).Value = "File ID"
Cells(1, 2).Value = "#"
Cells(1, 3).Value = "AvgIRI"
Cells(1, 4).Value = "axSum0to10"
Cells(1, 5).Value = "aySum0to10"
Cells(1, 6).Value = "azSum0to10"
Cells(1, 7).Value = "gxSum0to10"
Cells(1, 8).Value = "gySum0to10"
Cells(1, 9).Value = "gzSum0to10"

Cells(1, 11).Value = "axSum10to20"
Cells(1, 12).Value = "aySum10to20"
Cells(1, 13).Value = "azSum10to20"
Cells(1, 14).Value = "gxSum10to20"
Cells(1, 15).Value = "gySum10to20"
Cells(1, 16).Value = "gzSum10to20"

Cells(1, 18).Value = "axSum20to30"
Cells(1, 19).Value = "aySum20to30"
Cells(1, 20).Value = "azSum20to30"
Cells(1, 21).Value = "gxSum20to30"
Cells(1, 22).Value = "gySum20to30"
Cells(1, 23).Value = "gzSum20to30"

Cells(1, 25).Value = "axSum30to40"
Cells(1, 26).Value = "aySum30to40"
Cells(1, 27).Value = "azSum30to40"
Cells(1, 28).Value = "gxSum30to40"
Cells(1, 29).Value = "gySum30to40"
Cells(1, 30).Value = "gzSum30to40"

Cells(1, 32).Value = "axSum40to50"
Cells(1, 33).Value = "aySum40to50"
Cells(1, 34).Value = "azSum40to50"
Cells(1, 35).Value = "gxSum40to50"
Cells(1, 36).Value = "gySum40to50"
```

```
    Cells(1, 37).Value = "gzSum40to50"

    Cells(1, 39).Value = "axSum5to15"
    Cells(1, 40).Value = "aySum5to15"
    Cells(1, 41).Value = "azSum5to15"
    Cells(1, 42).Value = "gxSum5to15"
    Cells(1, 43).Value = "gySum5to15"
    Cells(1, 44).Value = "gzSum5to15"

    Cells(1, 46).Value = "axSum15to25"
    Cells(1, 47).Value = "aySum15to25"
    Cells(1, 48).Value = "azSum15to25"
    Cells(1, 49).Value = "gxSum15to25"
    Cells(1, 50).Value = "gySum15to25"
    Cells(1, 51).Value = "gzSum15to25"

    Cells(1, 53).Value = "axSum25to35"
    Cells(1, 54).Value = "aySum25to35"
    Cells(1, 55).Value = "azSum25to35"
    Cells(1, 56).Value = "gxSum25to35"
    Cells(1, 57).Value = "gySum25to35"
    Cells(1, 58).Value = "gzSum25to35"

    Cells(1, 60).Value = "axSum35to45"
    Cells(1, 61).Value = "aySum35to45"
    Cells(1, 62).Value = "azSum35to45"
    Cells(1, 63).Value = "gxSum35to45"
    Cells(1, 64).Value = "gySum35to45"
    Cells(1, 65).Value = "gzSum35to45"

    Cells(1, 66).Value = "SectDist"
    Cells(1, 67).Value = "AvgSpeed"
    Cells(1, 68).Value = "VIMSSect#"

    Cells(1, 70).Value = "xyzSum0to10"
    Cells(1, 71).Value = "xysSum10to20"
    Cells(1, 72).Value = "xyzSum20to30"
    Cells(1, 73).Value = "xyzSum30to40"
    Cells(1, 74).Value = "xyzSum40to50"
    Cells(1, 75).Value = "xyzSum5to15"
    Cells(1, 76).Value = "xysSum15to25"
    Cells(1, 77).Value = "xyzSum25to35"
    Cells(1, 78).Value = "xyzSum35to45"

End Sub
Function WBName() As String

    WBName = ActiveWorkbook.Name

End Function

Sub GoToManual()
```

```
Dim xlCalc As XlCalculation

    xlCalc = Application.Calculation
    Application.Calculation = xlCalculationManual

    On Error GoTo CalcBack
    Call FillEmptyCells
    Call FFTCal

    Application.Calculation = xlCalc
    Exit Sub

CalcBack:
Application.Calculation = xlCalc
End Sub

Sub Consolidate()

Dim Fname As String, fPath As String
Dim LR As Long, NR As Long
Dim wbData As Workbook, wsMaster As Worksheet

Application.ScreenUpdating = False
Application.EnableEvents = False
Application.DisplayAlerts = False

Set wsMaster = ThisWorkbook.Sheets("Sub")

With wsMaster
    If MsgBox("Fresh Consolidation? [Yes] for Fresh or [No] for Add Up", vbYesNo) = vbYes Then
        .UsedRange.Offset(1).EntireRow.Clear
        NR = 2
    Else
        NR = .Range("A" & .Rows.Count).End(xlUp).Row + 1
    End If

    MsgBox "Please select a folder containing files to consolidate"
    Do
        With Application.FileDialog(msoFileDialogFolderPicker)
            .InitialFileName = ActiveWorkbook.Path & "¥"
            .AllowMultiSelect = False
            .Show
            If .SelectedItems.Count > 0 Then
                fPath = .SelectedItems(1) & "¥"
                Exit Do
            Else
                If MsgBox("No folder chosen, do you wish to abort?", _
                    vbYesNo) = vbYes Then Exit Sub
            End If
        End With
    Loop
    Fname = Dir(fPath & "*.xls*")
```

```
    Do While Len(Fname) > 0
        If Fname <> ThisWorkbook.Name Then
            Set wbData = Workbooks.Open(fPath & Fname)
            Dim ws As Worksheet
            For Each ws In wbData.Sheets(Array("Summary"))
                LR = ws.Range("A" & ws.Rows.Count).End(xlUp).Row
                If NR = 1 Then 'copy the data AND titles
                    ws.Range("A1:A" & LR).EntireRow.Copy .Range("A" & NR)
                Else 'copy the data only
                ws.Range("A2:A" & LR).EntireRow.Copy .Range("A" & NR)
                End If
                NR = .Range("A" & .Rows.Count).End(xlUp).Row + 1 'Next row
            Next ws
            wbData.Close False
        End If
        Fname = Dir
    Loop
End With

Dim SaveAsFname As String
With Sheets("Sub")
.Visible = True
.Copy
.Visible = False
End With

SaveAsFname = Application.GetSaveAsFilename("Summary", "Excel files (*.xlsx), *.xlsx")
If SaveAsFname = "False" Then
    If MsgBox("Data will not be saved", vbOKCancel) = vbOK Then
        Exit Sub
    Else
       SaveAsFname = Application.GetSaveAsFilename("Summary", "Excel files (*.xlsx),
       *.xlsx")
        If MsgBox("Data will not be saved", vbOK) = vbOK Then
            Exit Sub
        Else
        ActiveWorkbook.SaveAs Filename:=SaveAsFname
        End If
    End If
Else
ActiveSheet.Name = "Main"
ActiveWorkbook.SaveAs Filename:=SaveAsFname
ActiveWorkbook.Close Savechanges:=False
End If


ErrorExit:
ActiveSheet.Columns.AutoFit
Application.DisplayAlerts = True
Application.EnableEvents = True
Application.ScreenUpdating = True
```

```
End Sub
Sub CSVToXls()
Dim mypath, workfile, myFolder, myfPathDone As String

Application.ScreenUpdating = False
Application.EnableEvents = False
Application.DisplayAlerts = False

MsgBox "Please select a folder with files to execute"
Do
    With Application.FileDialog(msoFileDialogFolderPicker)
        .InitialFileName = ActiveWorkbook.Path & "¥"
        .AllowMultiSelect = False
        .Show
        If .SelectedItems.Count > 0 Then
            mypath = .SelectedItems(1) & "¥"
            Exit Do
        Else
            If MsgBox("No folder chose, do you wish to abort?", vbYesNo) = vbYes Then Exit Sub
        End If
    End With
Loop

On Error GoTo Err_Clk
myFolder = Format(Now(), "yyyymmdd_hhmmss")
myfPathDone = mypath & "XLS conversion " & myFolder & "¥"
On Error Resume Next
MkDir myfPathDone
On Error GoTo 0

workfile = Dir(mypath & "*.CSV")

Do While workfile <> ""
   Application.StatusBar = "Now working on " & workfile
   Workbooks.Open Filename:=mypath & workfile

   Columns("A:A").Select
   Selection.TextToColumns Destination:=Range("A1"), DataType:=xlDelimited, _
   TextQualifier:=xlDoubleQuote, ConsecutiveDelimiter:=False, Tab:=True, _
   Semicolon:=True, Comma:=False, Space:=False, Other:=False, FieldInfo _
   :=Array(Array(1, 1), Array(2, 1), Array(3, 1), Array(4, 1), Array(5, 1), Array(6, 1), _
   Array(7, 1), Array(8, 1), Array(9, 1), Array(10, 1), Array(11, 1), Array(12, 1), Array(13, 1 _
   ), Array(14, 1), Array(15, 1), Array(16, 1), Array(17, 1), Array(18, 1)), _
   TrailingMinusNumbers:=True
   Range("A1").Select

   Call InsertID

   ActiveWorkbook.SaveAs Filename:=myfPathDone & _
   Left(ActiveWorkbook.Name, Len(ActiveWorkbook.Name) - 4),
FileFormat:=xlOpenXMLWorkbook
   ActiveWorkbook.Close
```

```
    workfile = Dir()
Loop

Err_Clk:
If Err <> 0 Then
    Err.Clear
    Resume Next
End If
Application.DisplayAlerts = True
Application.EnableEvents = True
Application.ScreenUpdating = True
End Sub
Sub InsertID()
Dim LR As Long
Dim Sht As Worksheet

    LR = Range("B" & Rows.Count).End(xlUp).Row
    Columns("A:A").Select
    Selection.Insert Shift:=xlToRight, CopyOrigin:=xlFormatFromLeftOrAbove
    Range("A1").Select
    ActiveCell.FormulaR1C1 = "#"
    Range("A2").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("A3").Select
    ActiveCell.FormulaR1C1 = "2"
    Range("A4").Select
    ActiveCell.FormulaR1C1 = "3"
    Range("A2:A4").Select
    Selection.AutoFill Destination:=Range("A2", "A" & LR)

For Each Sht In ActiveWorkbook.Worksheets
    If Sht.Visible = xlSheetVeryHidden Then
        Sht.Visible = xlSheetVisible
        If Sht.Name <> ActiveSheet.Name Then
            Application.DisplayAlerts = False
            Sht.Delete
        Else
            Sht.Visible = xlSheetVeryHidden
        End If
    Else
        If Sht.Name <> ActiveSheet.Name Then
            Application.DisplayAlerts = False
            Sht.Delete
        End If
    End If
Next Sht
ActiveSheet.Name = "Sheet2"
End Sub
Sub MatchingRefFiles()
Dim RefFile, DataFile As Variant
Dim RefFolder, RefPathDone, RefPath, RefPathDoneX As String
Dim DataWBName, Fname As String
```

```
Dim DataFileID As Long
Dim DataWB, RefWB As Workbook
Dim RefSheet As Worksheet

MsgBox "Select the reference file"
ChDir ActiveWorkbook.Path
RefFile = Application.GetOpenFilename("Excel Files (*.xls*), *.xls*", Title:="Select File",
MultiSelect:=False)

If RefFile = False Then GoTo Cancel

RefPath = ActiveWorkbook.Path & "¥"
ChDir ActiveWorkbook.Path
MsgBox "Select data file(s) to be matched with the reference file"
DataFile = Application.GetOpenFilename("Excel Files (*.xls*), *.xls*", Title:="Select File(s)",
MultiSelect:=True)

If IsArray(DataFile) Then
    MsgBox "Enter name of folder to save final file(s)"
    Do
        RefPathDoneX = InputBox(Prompt:="Enter folder name", Title:="Folder name",
Default:="Device ")
        If RefPathDoneX <> "Device " Or RefPathDoneX <> vbNullString Then
            Exit Do
        Else
            If MsgBox("No folder name selected, Exit?", vbYesNo) = vbYes Then
                Exit Sub
            Else
            End If
        End If
    Loop

    On Error GoTo Err_Clk
    RefFolder = Format(Now(), "yyyymmdd_hhmmss")
    RefPathDone = RefPath & RefPathDoneX & "XLS with ref data" & RefFolder & "¥"
    On Error Resume Next
    MkDir RefPathDone
    On Error GoTo 0

    Set RefWB = Workbooks.Open(RefFile)
    Set RefSheet = RefWB.Worksheets("Sheet1")
    For DataFileID = LBound(DataFile) To UBound(DataFile)
        Set DataWB = Workbooks.Open(Filename:=DataFile(DataFileID))
        DataWBName = Left(DataWB.Name, InStr(DataWB.Name, ".") - 1)

         RefSheet.Copy DataWB.Sheets(1)


        Fname = Right(DataWBName, Len(DataWBName) - 14)
        Fname = Left(Fname, 15)
        ActiveWorkbook.CheckCompatibility = False
        DataWB.SaveAs RefPathDone & Fname & " Main"
```

```
            ActiveWorkbook.CheckCompatibility = True
            DataWB.Close
      Next DataFileID
      RefWB.Close
Else
            If DataFile = False Then GoTo Cancel
End If

Err_Clk:
If Err <> 0 Then
      Err.Clear
      Resume Next
End If

Cancel:
End Sub
Sub Filter()

Dim fPathResult, fPathSum As String
Dim sPath, fPathDone, RFolder As String
Dim sFile As String
Dim sDir As String
Dim oWB As Workbook
Dim Fname, WBName, WBName1 As String
Dim Alfa, Interval As Variant
Dim ExecFile As Variant
Dim ExecFileNumber As Long

Application.ScreenUpdating = False
Application.EnableEvents = False
Application.DisplayAlerts = False

Alfa = Application.InputBox(Prompt:="Input Alpha for High Pass Filter (0.1~0.9; Or 1 for no
filter)", Type:=1) 'Input Alfa for High Pass Filter
If Alfa <> 1 Then
      If Alfa = False Then
          If MsgBox("No value, Abort? Yes to abort; No to use default value", vbYesNo) = vbYes
          Then
                Exit Sub
            Else
                MsgBox "Default value of 0.1 will be selected"
                Alfa = 0.1
            End If
      Else
            If Alfa < 0.1 Or Alfa > 0.9 Then
                Do
                    Alfa = Application.InputBox(Prompt:="Invalid value (0.1~0.9 or 1 for no filter)",
                   Type:=1)
                Loop Until Alfa >= 0.1 And Alfa <= 0.9 Or Alfa = 1 Or Alfa = False
            End If
            If Alfa = False Then
               If MsgBox("No value, Abort? Yes to abort; No to use default value", vbYesNo) = vbYes
```

```
            Then
                Exit Sub
            Else
                MsgBox "Default value of 0.1 will be selected"
                Alfa = 0.1
            End If
        End If
    End If
End If

If MsgBox("Execute all files in a folder? [Yes]All files, [No]Only selected file", vbYesNo) = vbYes
Then

    MsgBox "Please select a folder with files to execute" 'Promt to select path by user
    Do
        With Application.FileDialog(msoFileDialogFolderPicker)
            .InitialFileName = ActiveWorkbook.Path & "¥"
            .AllowMultiSelect = False
            .Show
            If .SelectedItems.Count > 0 Then
                sPath = .SelectedItems(1) & "¥"
                Exit Do
            Else
              If MsgBox("No folder chose, do you wish to abort?", vbYesNo) = vbYes Then Exit
              Sub
            End If
        End With
    Loop

    On Error GoTo Err_Clk

    RFolder = Format(Now(), "yyyymmdd_hhmmss")
    fPathDone = sPath & "Filter" & RFolder & "¥"
    On Error Resume Next
    MkDir fPathDone
    On Error GoTo 0

    sDir = Dir$(sPath & "*.xls", vbNormal)
    Do Until Len(sDir) = 0
        If sDir <> ThisWorkbook.Name Then
            Set oWB = Workbooks.Open(sPath & sDir)
            WBName = Left(oWB.Name, InStr(oWB.Name, ".") - 1)
            WBName1 = Right(WBName, 1)
            If WBName1 <> "Filtered" Then

                Call HighPassFilter(Alfa)     'Carry Alfa to HighPassFilter Sub

                Fname = Left(WBName, Len(WBName) - 5)
                ActiveWorkbook.CheckCompatibility = False
                oWB.SaveAs fPathDone & Fname & " Filtered"
                ActiveWorkbook.CheckCompatibility = True
                oWB.Close False
```

```
                Else
                    oWB.Close False
                End If
        End If
        sDir = Dir$
    Loop

Else
    sPath = ActiveWorkbook.Path & "¥"
    MsgBox "Please select file(s) to execute" 'Promt to select file name by user
    ExecFile = Application.GetOpenFilename("Excel Files (*.xls*), *.xls*", Title:="Select File(s)",
    MultiSelect:=True)

    If IsArray(ExecFile) Then
        On Error GoTo Err_Clk
        RFolder = Format(Now(), "yyyymmdd_hhmmss")
        fPathDone = sPath & "Filter" & RFolder & "¥"
        On Error Resume Next
        MkDir fPathDone
        On Error GoTo 0

            For ExecFileNumber = LBound(ExecFile) To UBound(ExecFile)
            Set oWB = Workbooks.Open(Filename:=ExecFile(ExecFileNumber))
            WBName = Left(oWB.Name, InStr(oWB.Name, ".") - 1)
            WBName1 = Right(WBName, 1)
            If WBName1 <> "Filtered" Then

                Call HighPassFilter(Alfa)     'Carry Alfa to HighPassFilter Sub

                Fname = Left(WBName, Len(WBName) - 5)
                ActiveWorkbook.CheckCompatibility = False
                oWB.SaveAs fPathDone & Fname & " Filtered"
                ActiveWorkbook.CheckCompatibility = True
                oWB.Close False
            Else
                oWB.Close False
            End If
        Next ExecFileNumber
    Else
        If ExecFile = False Then GoTo Cancel
    End If
End If

Err_Clk:
If Err <> 0 Then
    Err.Clear
    Resume Next
End If

ErrorExit:
Cancel:
```

```
ActiveSheet.Columns.AutoFit
Application.DisplayAlerts = True
Application.EnableEvents = True
Application.ScreenUpdating = True
End Sub
Sub AzimuthX()
Dim x1, y1, x2, y2 As Double
Dim lrr, Azi, Xz As Single
Dim xtemp3, ytemp3, dupli As Single
Dim temp1x, temp1y, col As Single

Sheets("Sheet1").Select
lrr = Range("A" & Rows.Count).End(xlUp).Row
Xz = 1
For Azi = 2 To lrr
    x1 = Cells(Azi, 4).Value
    x2 = Cells(Azi + 1, 4).Value
    y1 = Cells(Azi, 5).Value
    y2 = Cells(Azi + 1, 5).Value

    Cells(Azi, 7) = calcula_acimut(x1, y1, x2, y2)
    If Azi > 2 Then
        If Abs(Cells(Azi, 7) - Cells(Azi - 1, 7)) > 40 Then
            Xz = Xz + 1
            Cells(Azi, 8) = Xz
        End If
    End If
    Cells(Azi, 8) = Xz
Next Azi

col = 8
xtemp3 = Cells(lrr, col).Value
For ytemp3 = 1 To xtemp3
    dupli = Application.WorksheetFunction.CountIf(Range("H1:H" & lrr), ytemp3)
    If dupli <= 10 Then

        Call DelSomeRows(ytemp3, col)

    End If
Next ytemp3

temp1y = 1
For temp1x = 2 To lrr
    If temp1x > 2 Then
        If Cells(temp1x, 8).Value <> Cells(temp1x - 1, 8).Value Then
            temp1y = temp1y + 1
            Cells(temp1x, 2).Value = temp1y
        End If
    End If
    Cells(temp1x, 2).Value = temp1y
Next temp1x
```

```
Cells(1, 7) = "Azimuth"
Cells(1, 2) = "Sect #"
End Sub
Sub AzimuthY()
Dim x1, y1, x2, y2 As Double
Dim lrr, Azi, Xz As Single

Sheets("Temp3").Select
lrr = Range("B" & Rows.Count).End(xlUp).Row
Xz = 1
For Azi = 2 To lrr
    x1 = Cells(Azi, 2).Value
    x2 = Cells(Azi + 1, 2).Value
    y1 = Cells(Azi, 3).Value
    y2 = Cells(Azi + 1, 3).Value

    Cells(Azi, 4) = calcula_acimut(x1, y1, x2, y2)
    If Azi > 2 Then
        If Abs(Cells(Azi, 4) - Cells(Azi - 1, 4)) > 40 Then
            Xz = Xz + 1
            Cells(Azi, 5) = Xz
        End If
    End If
    Cells(Azi, 5) = Xz
Next Azi

End Sub
Public Function calcula_acimut(x1, y1, x2, y2) As Double
Dim Ax, Ay, Pi As Double
Pi = Application.WorksheetFunction.Pi

Ax = x2 - x1
Ay = y2 - y1
If (Ax = 0 And Ay = 0) Then
    calcula_acimut = 0
    Exit Function
End If
If (Ax = 0) Then
    If (Ay < 0) Then
        calcula_acimut = 180
        Exit Function
    Else
        calcula_acimut = 0
        Exit Function
    End If
End If
If (Ay = 0) Then
    If (Ax > 0) Then
calcula_acimut = 90
        Exit Function
    Else
        calcula_acimut = 270
```

```
            Exit Function
      End If
End If
calcula_acimut = Atn(Ax / Ay) * 180 / Pi
If (Ax < 0 And Ay > 0) Then calcula_acimut = calcula_acimut + 360
If (Ax < 0 And Ay < 0) Then calcula_acimut = calcula_acimut + 180
If (Ax > 0 And Ay < 0) Then calcula_acimut = calcula_acimut + 180
End Function
```

Appendix D: Summaries of multiple regression analysis

Device A

	Vehicle 1		Vehicle 2		Vehicle 3		Vehicle 4	
Observations	703		497		314		408	
Multiple R	0.797		0.759		0.855		0.852	
R Square	0.635		0.577		0.731		0.726	
Adjusted R Square	0.634		0.575		0.729		0.725	
F Stat	609.790		336.571		421.594		537.113	
	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat
Intercept	-2.467	-5.868	-6.476	-8.756	-3.484	-5.893	-5.651	-9.096
Magnitude	0.305	28.820	0.498	20.757	0.311	23.603	0.409	24.678
Avg. Speed	-0.013	-2.733	-0.010	-1.578	-0.007	-1.048	0.008	1.391

Device B

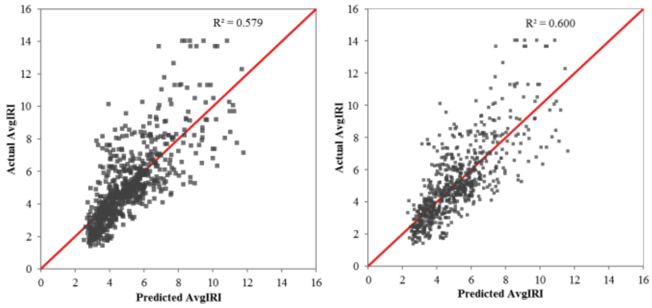
	Vehicle 1		Vehicle 2		Vehicle 3		Vehicle 4	
Observations	674		489		319		411	
Multiple R	0.774		0.798		0.805		0.779	
R Square	0.599		0.638		0.647		0.607	
Adjusted R Square	0.598		0.636		0.645		0.605	
F Stat	501.448		427.417		290.138		314.653	
	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat
Intercept	-2.423	-4.929	-4.317	-7.604	-5.348	-6.918	-3.482	-4.835
Magnitude	0.341	24.595	0.403	23.684	0.383	19.531	0.352	17.879
Avg. Speed	-0.027	-5.415	-0.016	-2.905	0.001	0.106	-0.003	-0.528

Device C (Pocket)

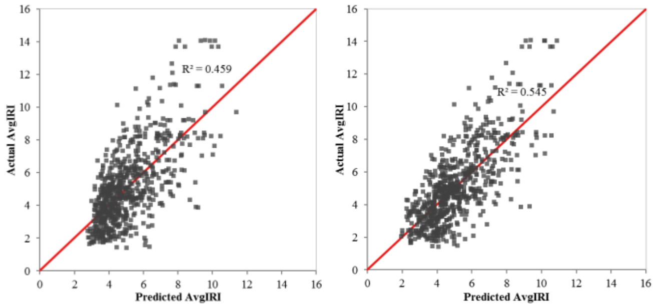
	Vehicle 1		Vehicle 2		Vehicle 3		Vehicle 4	
Observations	311		467		309		382	
Multiple R	0.776		0.741		0.835		0.857	
R Square	0.602		0.550		0.696		0.735	
Adjusted R Square	0.598		0.548		0.694		0.734	
F Stat	183.442		283.184		350.973		525.460	
	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat	Coefficients	t Stat
Intercept	1.877	4.693	1.825	4.491	1.780	4.165	0.373	0.903
Magnitude	0.750	18.688	1.342	19.212	0.661	21.456	1.170	24.621
Avg. Speed	-0.003	-0.318	-0.029	-4.710	-0.023	-3.629	0.003	0.582

Appendix E: Effect of speed

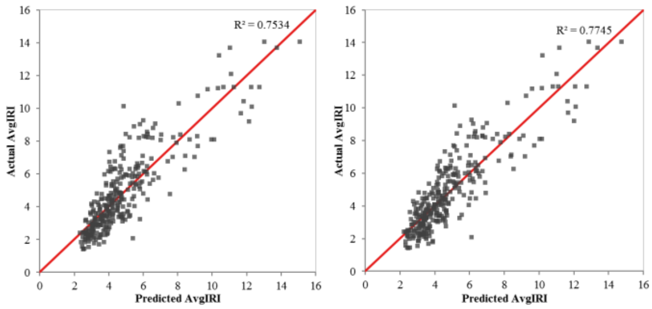
Vehicle 1



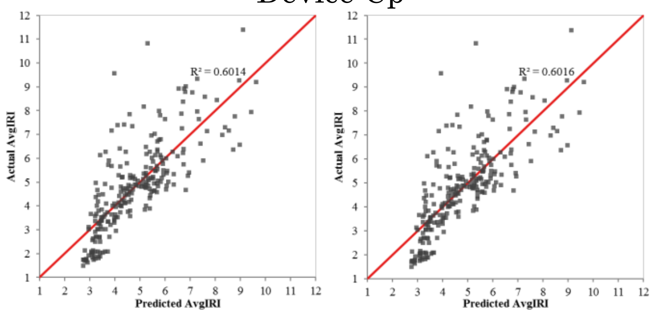
Device A



Device B

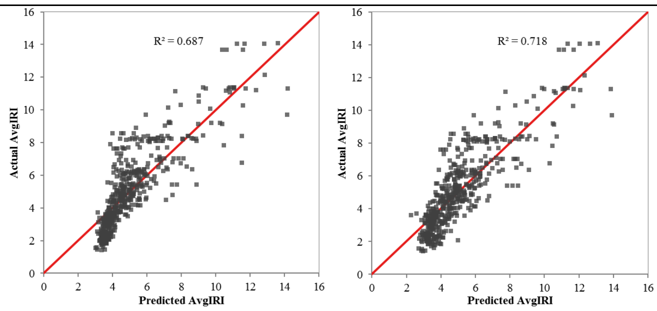


Device Cp

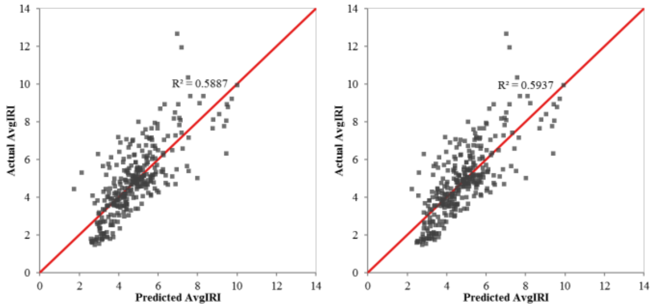


Device Cb

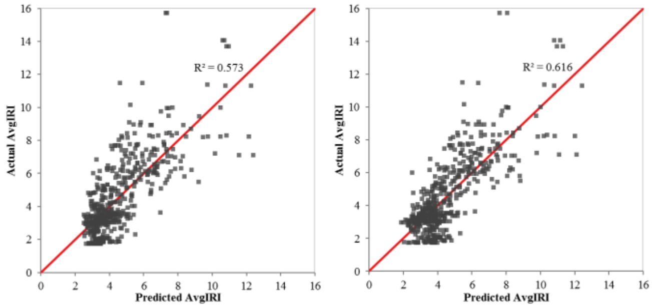
Vehicle 2



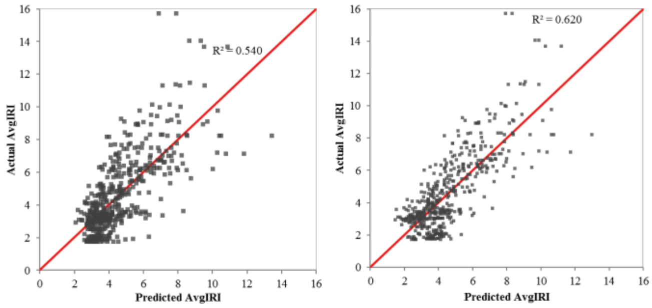
Device Db



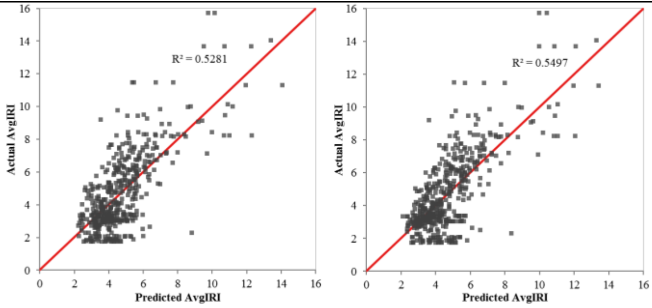
Device Dp



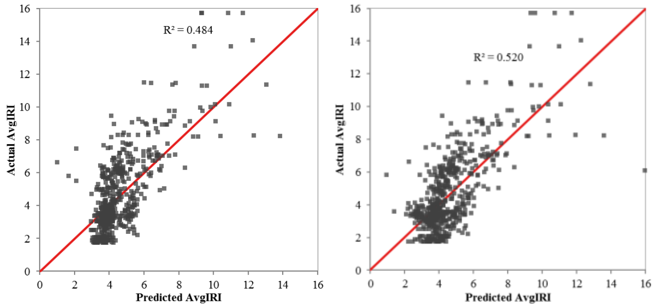
Device A



Device B

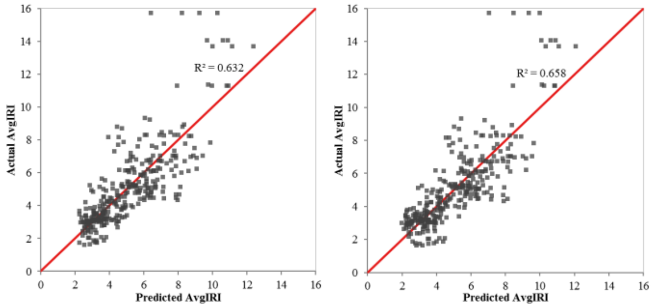


Device C

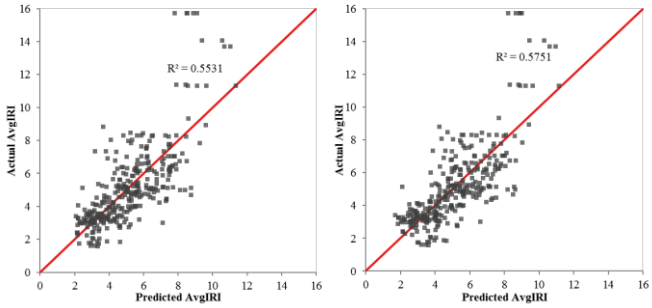


Device D

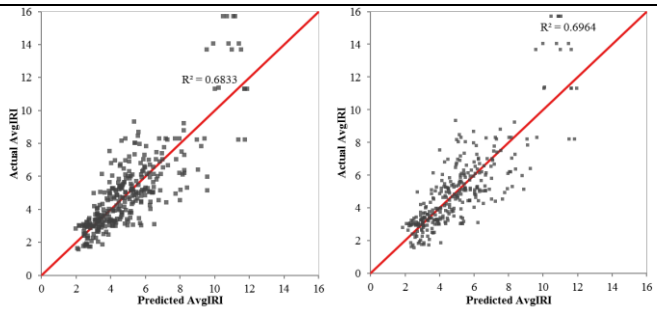
Vehicle 3



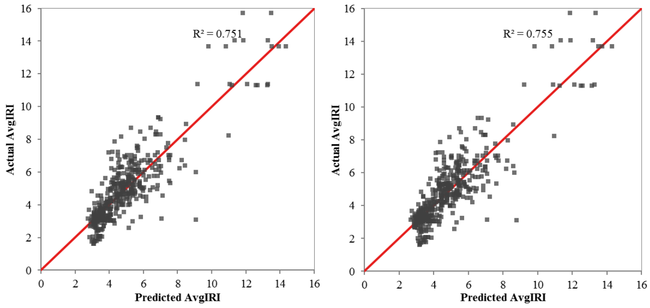
Device A



Device B

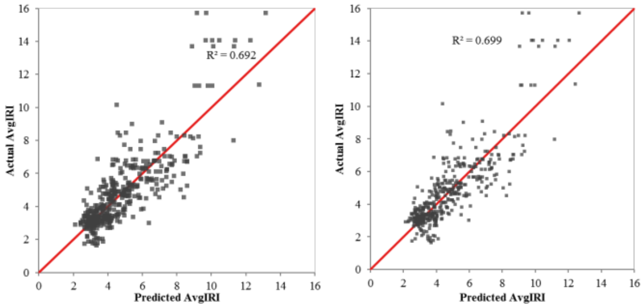


Device C

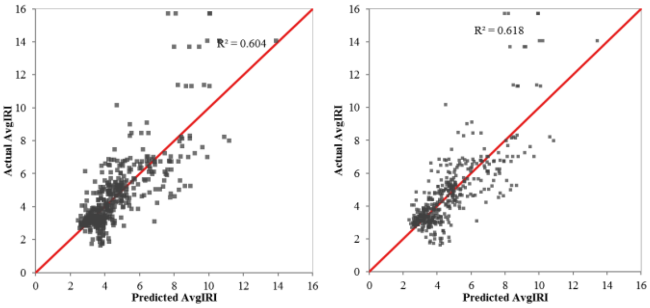


Device D

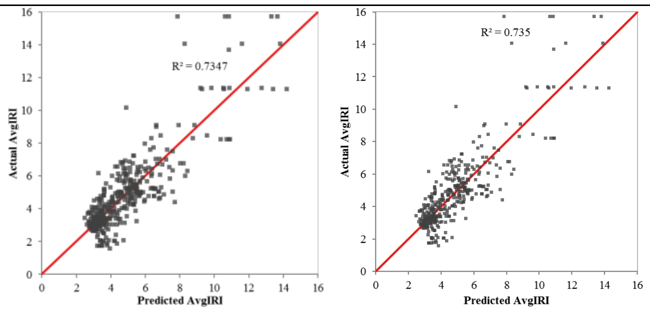
Vehicle 4



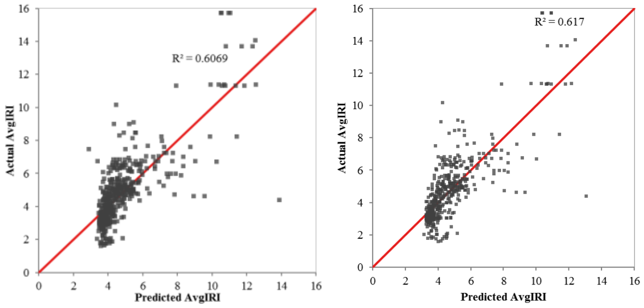
Device A



Device B



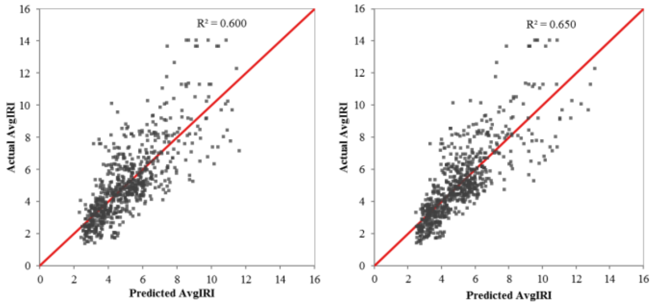
Device C



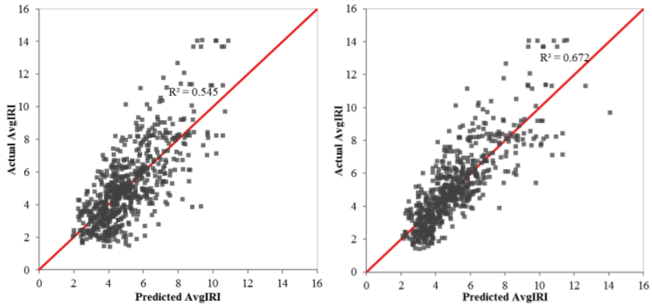
Device D

APPENDIX F: MAGNITUDES OPTION (1) AND (2)

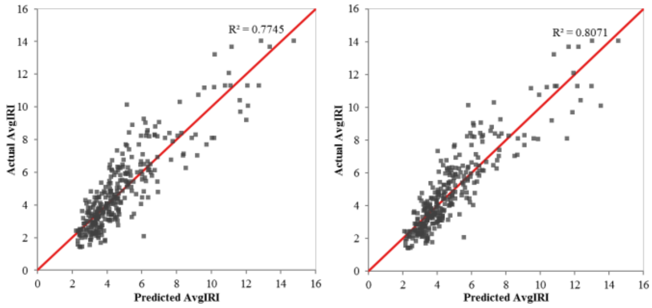
Vehicle 1



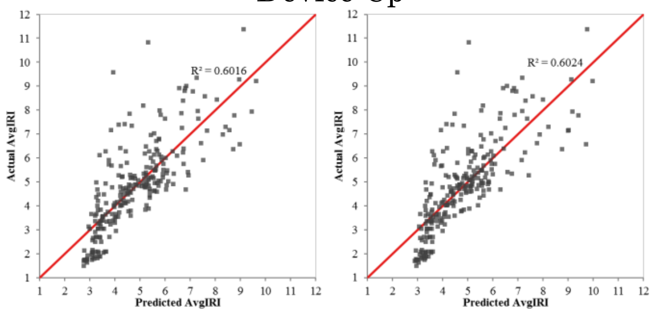
Device A



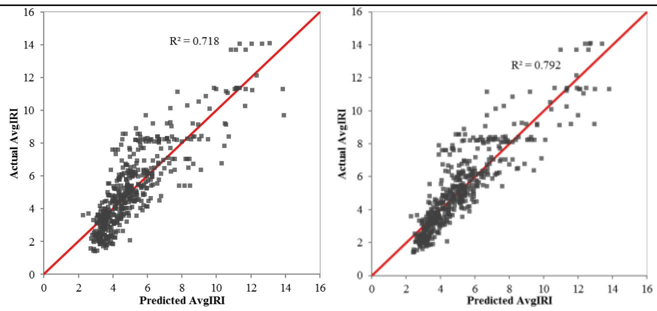
Device B



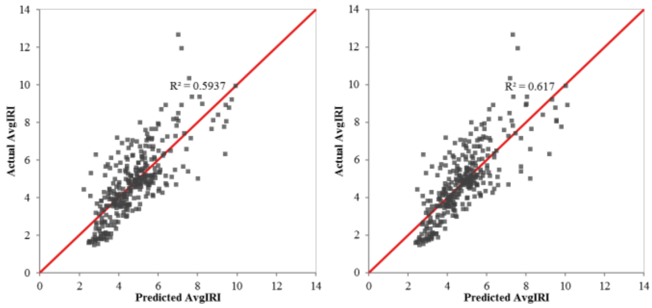
Device Cp



Device Cb

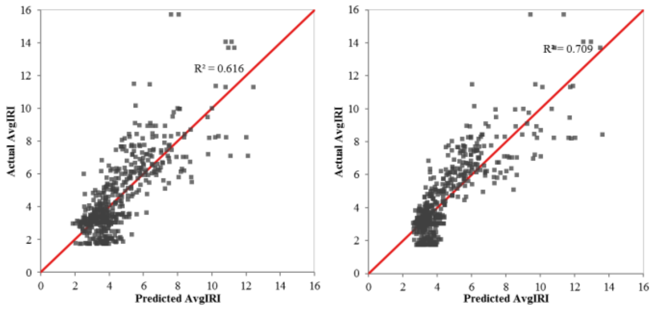


Device Db

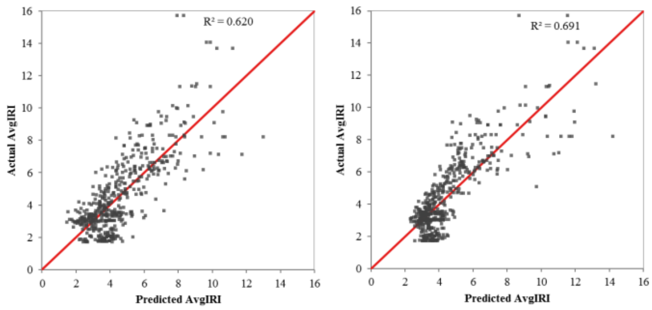


Device Dp

Vehicle 2

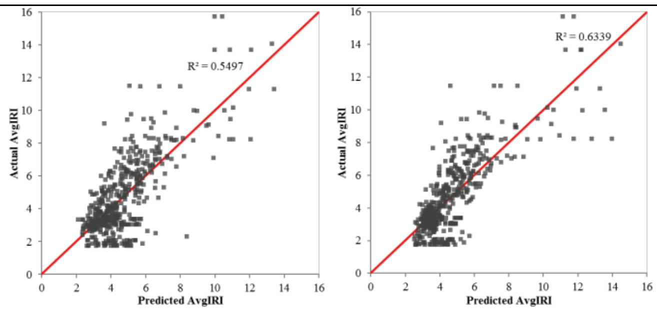


Device A

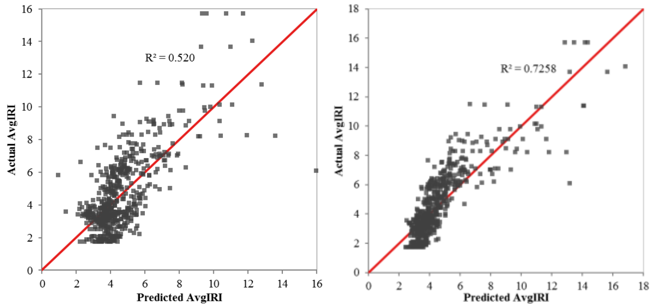


Device B

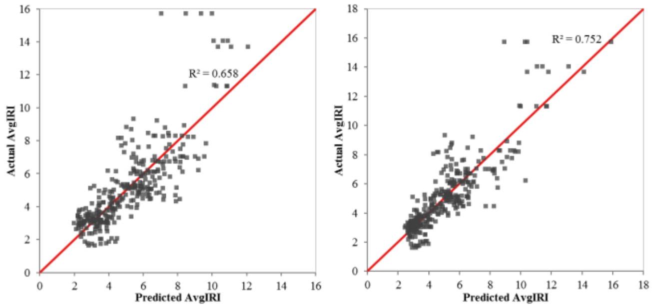
Vehicle 3



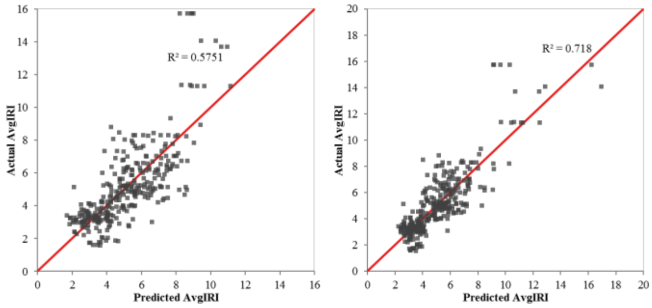
Device C



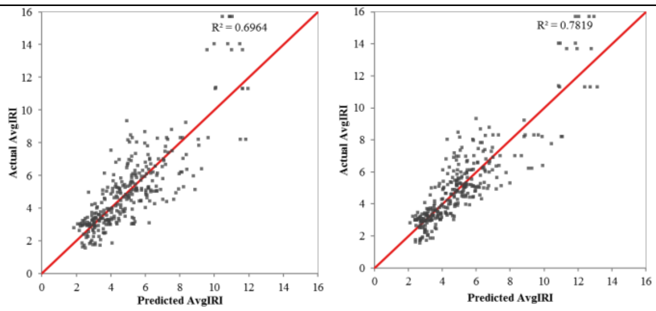
Device D



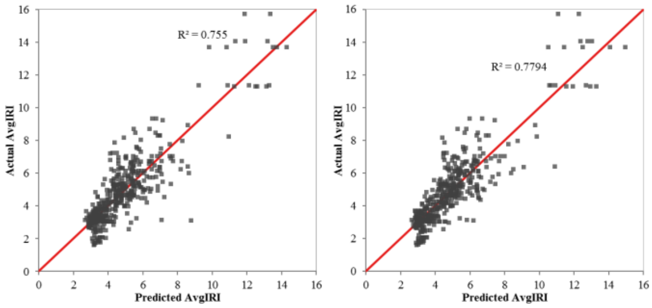
Device A



Device B

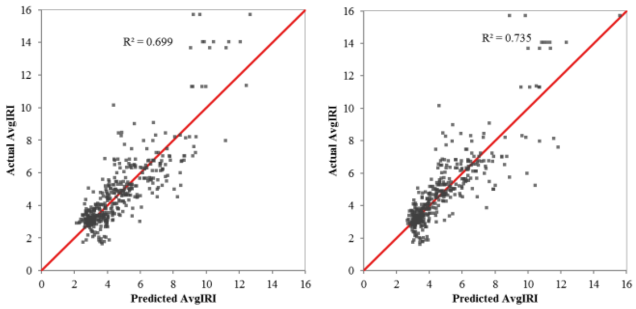


Device C

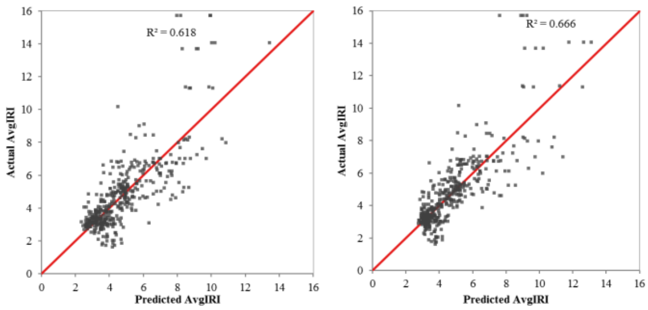


Device D

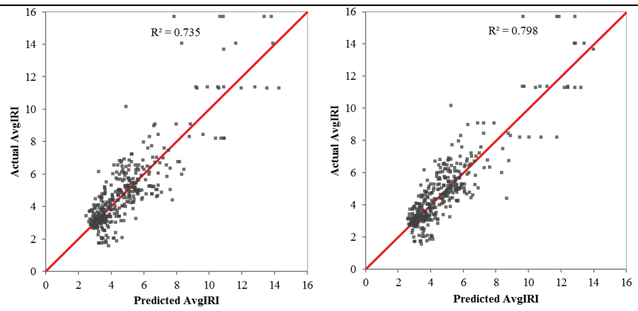
Vehicle 4



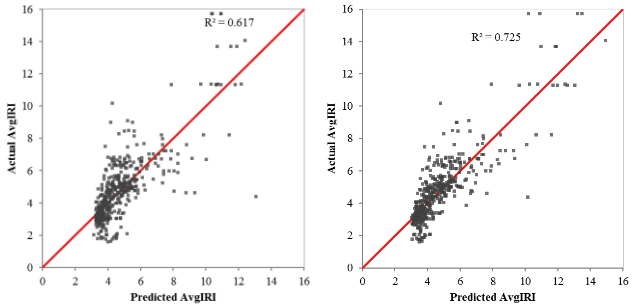
Device A



Device B



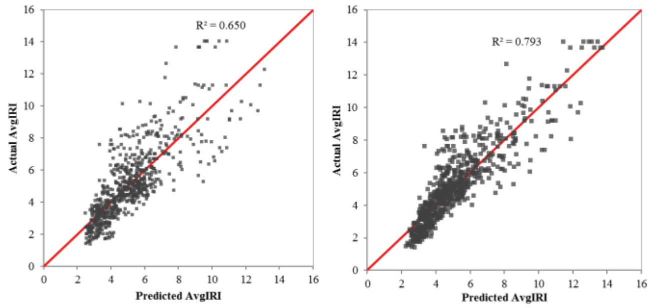
Device C



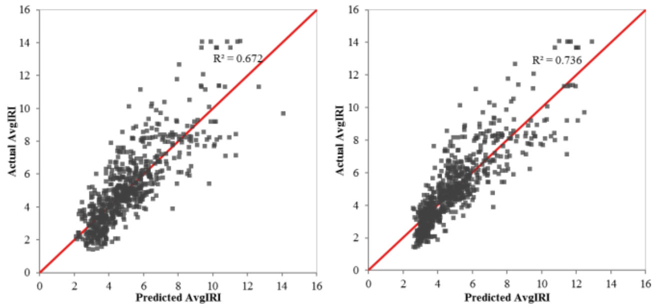
Device D

Appendix G: Consideration of gyroscope sensor

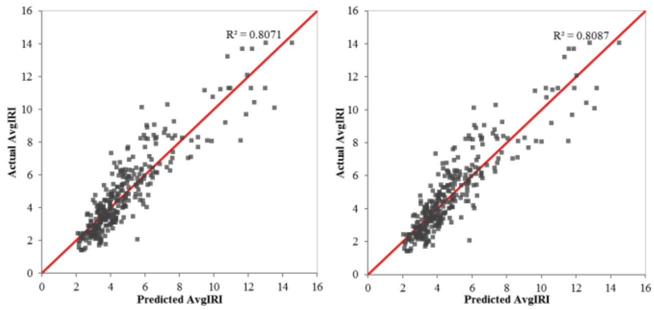
Vehicle 1



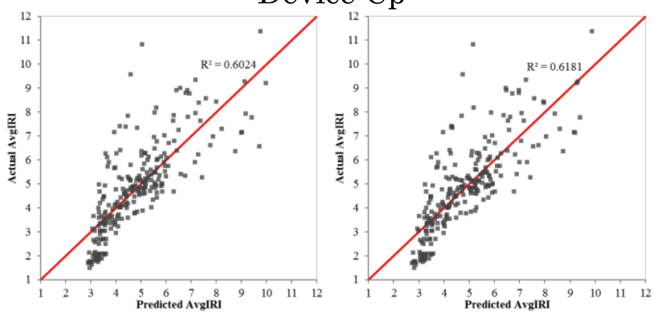
Device A



Device B

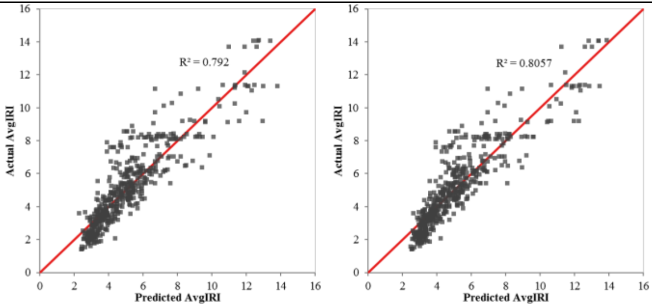


Device Cp

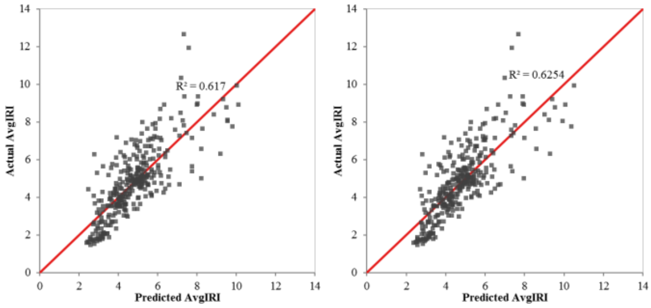


Device Cb

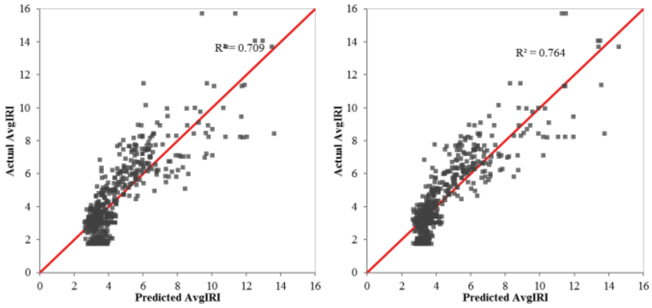
Vehicle 2



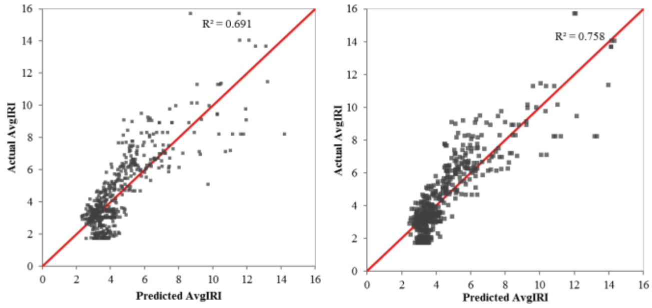
Device Db



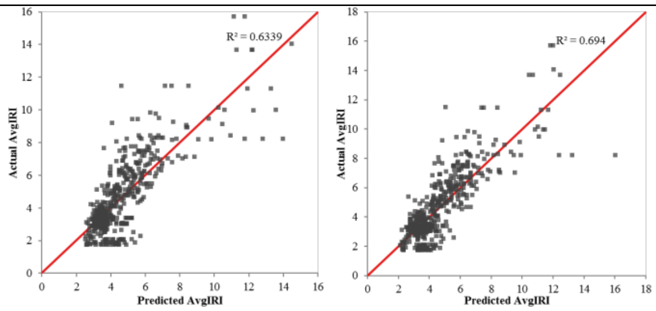
Device Dp



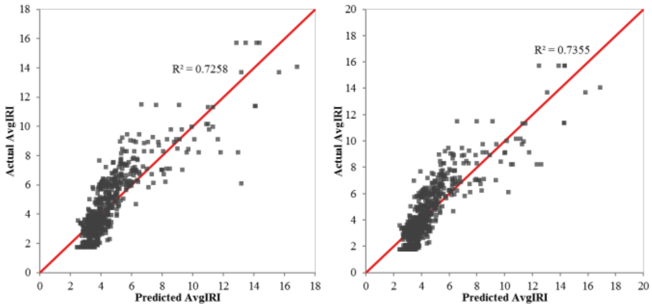
Device A



Device B

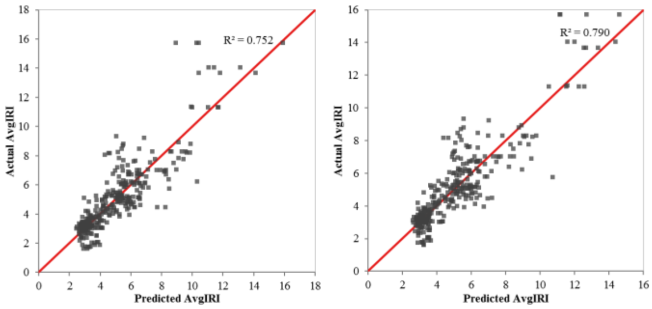


Device C

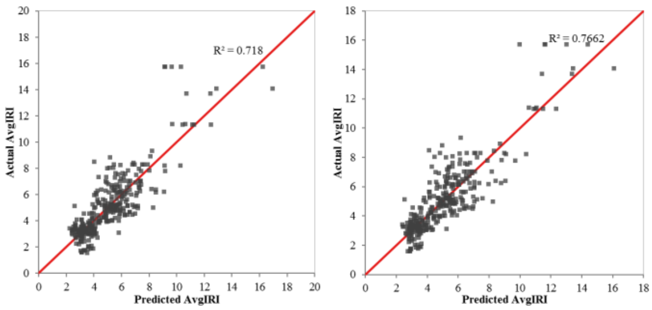


Device D

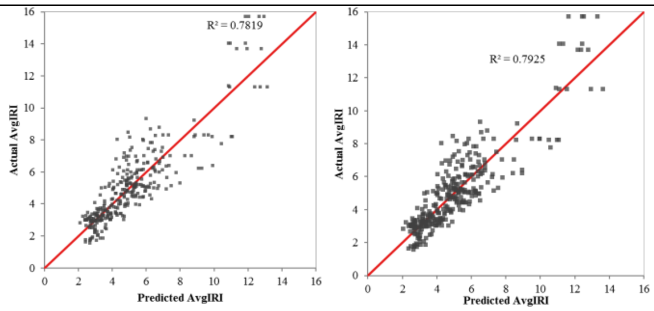
Vehicle 3



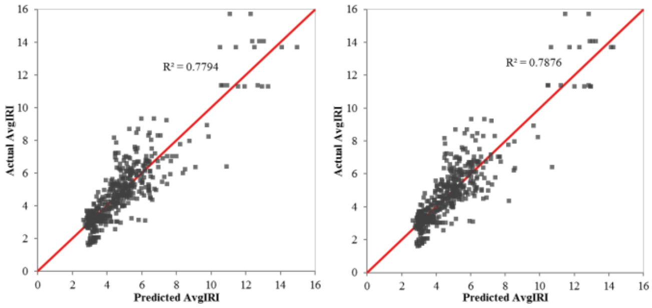
Device A



Device B

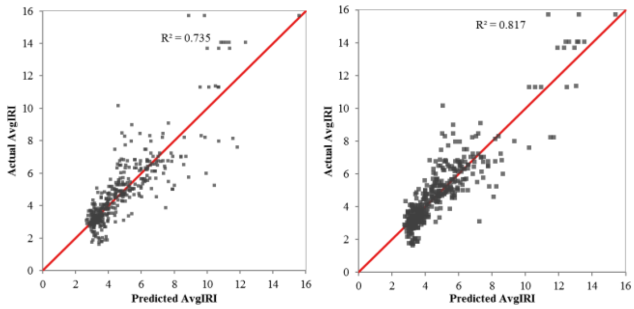


Device C

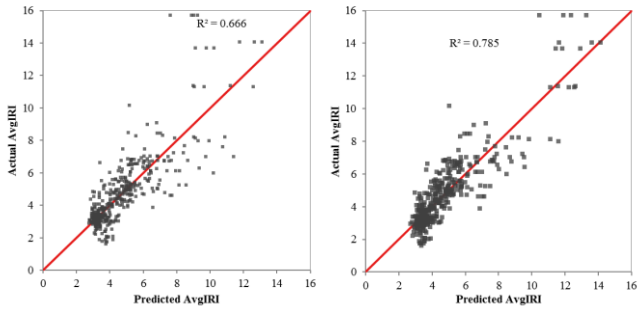


Device D

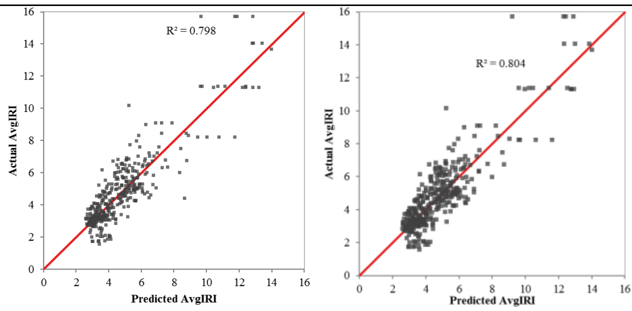
Vehicle 4



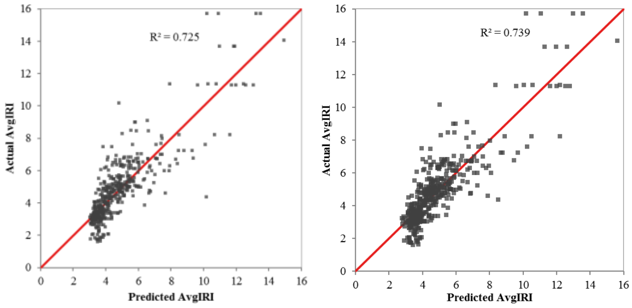
Device A



Device B



Device C



Device D

APPENDIX H: R SCRIPT FOR NUMERICAL EXAMPLES

```
## INITIALIZATION
#setting of number of road sections and vehicles
#klength <- 360   #number of road sections: defined later
ilength <- 10  #number of vehicles(or trips)
jlength <- 12000   #number of observed data
#speed parameter
vmean <- c(54,54,37,30,26,24)
vsd <- c(13,13,10,10,9,7)
vmax <- 80
vmin <- 10

#real IRI value (test network)
ckreal <- c(runif(20, min=7, max=10)
            ,runif(20, min=7, max=10)
            ,runif(20, min=4, max=7)
            ,runif(20, min=4, max=7)
            ,runif(20, min=4, max=7)
            ,runif(20, min=4, max=7)
            ,runif(20, min=7, max=10)
            ,runif(20, min=1, max=4)
            ,runif(20, min=10, max=16)
            ,runif(20, min=7, max=10)
            ,runif(20, min=1, max=4)
            ,runif(20, min=10, max=16)
            ,runif(20, min=4, max=7)
            ,runif(20, min=4, max=7)
            ,runif(20, min=4, max=7)
            ,runif(20, min=4, max=7)
            ,runif(20, min=7, max=10)
            ,runif(20, min=7, max=10))
klength=length(ckreal)

ckrank <- ckreal
for(i in 1:klength){
    if(ckreal[i] < 3){
        ckrank[i] = 1
    } else if(ckreal[i] < 5){
        ckrank[i] = 2
    } else if(ckreal[i] < 7){
        ckrank[i] = 3
    } else if(ckreal[i] < 9){
        ckrank[i] = 4
    } else if(ckreal[i] < 11){
        ckrank[i] = 5
    } else {
        ckrank[i]=6
    }
}

a0real <- runif(ilength, min=-2, max=-1)
```

```
a1real <- runif(ilength, min=0.5, max=5)
a2real <- runif(ilength, min=-0.02, max=-0.01)

ii <- c(seq(1, 1, length = 20*6*20)
        ,seq(2, 2, length = 20*6*20)
        ,seq(3, 3, length = 10*6*20)
        ,seq(4, 4, length = 10*6*20)
        ,seq(5, 5, length = 10*6*20)
        ,seq(6, 6, length = 10*6*20)
        ,seq(7, 7, length = 5*6*20)
        ,seq(8, 8, length = 5*6*20)
        ,seq(9, 9, length = 5*6*20)
        ,seq(10, 10, length = 5*6*20))

ik <- c(rep(1:20, times = 5),rep(41:60, times = 5),rep(121:140, times = 5),rep(181:200, times =
5),rep(241:260, times = 5),rep(321:340, times = 5) #route1,veh1
        ,rep(1:20, times = 15),rep(61:80, times = 15),rep(141:160, times = 15),rep(201:220, times =
15),rep(261:280, times = 15),rep(321:340, times = 15) #route2,veh1
        ,rep(21:40, times = 5),rep(101:120, times = 5),rep(161:180, times = 5),rep(221:240, times =
5),rep(301:320, times = 5),rep(341:360, times = 5) #route1,veh2
        ,rep(21:40, times = 15),rep(81:100, times = 15),rep(141:160, times = 15),rep(201:220, times
= 15),rep(281:300, times = 15),rep(341:360, times = 15) #route2,veh2
        ,rep(1:20, times = 3),rep(41:60, times = 3),rep(121:140, times = 3),rep(181:200, times =
3),rep(241:260, times = 3),rep(321:340, times = 3) #route1,veh3
        ,rep(1:20, times = 7),rep(61:80, times = 7),rep(141:160, times = 7),rep(201:220, times =
7),rep(261:280, times = 7),rep(321:340, times = 7) #route2,veh3
        ,rep(21:40, times = 3),rep(101:120, times = 3),rep(161:180, times = 3),rep(221:240, times =
3),rep(301:320, times = 3),rep(341:360, times = 3) #route1,veh4
        ,rep(21:40, times = 7),rep(81:100, times = 7),rep(141:160, times = 7),rep(201:220, times =
7),rep(281:300, times = 7),rep(341:360, times = 7) #route2,veh4
        ,rep(1:20, times = 5),rep(61:80, times = 5),rep(141:160, times = 5),rep(201:220, times =
5),rep(261:280, times = 5),rep(321:340, times = 5) #route1,veh5
        ,rep(1:20, times = 5),rep(61:80, times = 5),rep(141:160, times = 5),rep(201:220, times =
5),rep(281:300, times = 5),rep(341:360, times = 5) #route2,veh5
        ,rep(21:40, times = 5),rep(81:100, times = 5),rep(141:160, times = 5),rep(201:220, times =
5),rep(281:300, times = 5),rep(341:360, times = 5) #route1,veh6
        ,rep(21:40, times = 5),rep(81:100, times = 5),rep(141:160, times = 5),rep(201:220, times =
5),rep(261:280, times = 5),rep(321:340, times = 5) #route2,veh6
        ,rep(1:20, times = 5),rep(41:60, times = 5),rep(121:140, times = 5),rep(181:200, times =
5),rep(241:260, times = 5),rep(321:340, times = 5) #route1,veh7
        ,rep(1:20, times = 5),rep(61:80, times = 5),rep(141:160, times = 5),rep(201:220, times =
5),rep(261:280, times = 5),rep(321:340, times = 5) #route1,veh8
        ,rep(21:40, times = 5),rep(101:120, times = 5),rep(161:180, times = 5),rep(221:240, times =
5),rep(301:320, times = 5),rep(341:360, times = 5) #route1,veh9
        ,rep(21:40, times = 5),rep(81:100, times = 5),rep(141:160, times = 5),rep(201:220, times =
5),rep(281:300, times = 5),rep(341:360, times = 5) #route1,veh10
)

vobs <- rnorm(jlength,mean=0,sd=1)
vobs <- vobs*vsd[ckrank[ik]]+vmean[ckrank[ik]]
mobs <- (ckreal[ik]-a0real[ii]-a2real[ii]*vobs+rnorm(jlength,mean=0,sd=1))/a1real[ii]
```

```
mobs <- (ckreal[ik]-a0real[ii]-a2real[ii]*vobs)/a1real[ii]*(1+rnorm(jlength,mean=0,sd=0.2))

#flag of prior parameters -> 1:given, 0:not
# observed link:8 and 11
ckobsf <- c(seq(0, 0, length = 140)
            ,seq(1, 1, length = 20)
            ,seq(0, 0, length = 40)
            ,seq(1, 1, length = 20)
            ,seq(0, 0, length = 140))

# observed link:8 and 9
ckobsf <- c(seq(0, 0, length = 140)
            ,seq(1, 1, length = 40)
            ,seq(0, 0, length = 180))

ckobs <- ckreal*(1+rnorm(klength,mean=0,sd=0.1))*ckobsf#prior(or observed) IRI

#gamma <- seq(100, 100, length = klength)    #weight vector for observed IRI
gamma <- 0

#Unit Matrix
uk <- diag(klength)   #unit matrix for road sections
ui <- diag(ilength)    #unit matrix for vehicles(or trips)

axf <- seq(1, 1, length = ilength)     #flag of prior parameters -> 1:given, 2:not given
a0pri <- seq(1, 1, length = ilength)  #prior parameter a0
a1pri <- seq(1, 1, length = ilength)  #prior parameter a1
a2pri <- seq(-0.01, -0.01, length = ilength)#prior parameter a2
#a0pri <- a0real   #prior parameter a0
#a1pri <- a1real   #prior parameter a1
#a2pri <- a2real   #prior parameter a2
eta <- seq(1000000, 1000000, length = ilength)    #weight vector prior parameters IRI

#initial value for unknown variables
ck0 <- seq(0, 0, length = klength)   #initial value for parameter IRI
a00 <- seq(0, 0, length = ilength)          #initial value for parameter a0
a10 <- seq(0, 0, length = ilength)          #initial value for parameter a1
a20 <- seq(0, 0, length = ilength)          #initial value for parameter a2
xx0 <- c(ck0,a00,a10,a20)   #integrated vector (for "optim"-function purpose)

##Objective function (Generalized Least Squared Errors)
fr <- function(xx) {
ck <- xx[1:klength]
a0 <- xx[(klength+1):(klength+ilength)]
a1 <- xx[(klength+ilength+1):(klength+ilength*2)]
a2 <- xx[(klength+ilength*2+1):(klength+ilength*3)]

sum((ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)^2)+gamma*(sum((ck-ckobs)*ckobsf))^2+eta[1]*(su
m(a1)-ilength)^2
}

##Gradient function of objective function
```

```
grr <- function(xx) { #
ck <- xx[1:klength]
a0 <- xx[(klength+1):(klength+ilength)]
a1 <- xx[(klength+ilength+1):(klength+ilength*2)]
a2 <- xx[(klength+ilength*2+1):(klength+ilength*3)]

c(apply((uk[ik,]*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum) +gamma*((ck-ckobs)*ckobsf),
apply(-(ui[ii,]*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum),
apply(-(ui[ii,]*mobs*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum)+eta*(sum(a1)-ilength),
apply(-(ui[ii,]*vobs*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum)
)
}

##Optimization
ll <- optim(xx0,   fr,   grr,   method = "BFGS")   # "BFGS" –@

#ll$par
#ll$value

ck <- ll$par[1:klength]
a0est1 <- ll$par[(klength+1):(klength+ilength)]
a1est1 <- ll$par[(klength+ilength+1):(klength+ilength*2)]
a2est1 <- ll$par[(klength+ilength*2+1):(klength+ilength*3)]
ckobs2 <- subset(ckobs,ckobsf==1)
ckck2 <- subset(ck,ckobsf==1)
result <- lm(ckobs2 ~ ckck2, data = trees)
ckest1 <- result$coefficients[1]+result$coefficients[2]*ck
gamma2 <- 100

##Objective function2 (Generalized Least Squared Errors)
fr2 <- function(xx) {
ck <- xx[1:klength]
a0 <- xx[(klength+1):(klength+ilength)]
a1 <- xx[(klength+ilength+1):(klength+ilength*2)]
a2 <- xx[(klength+ilength*2+1):(klength+ilength*3)]

   sum((ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)^2)+sum(gamma2*((ck-ckest1))^2)
}

##Gradient function2 of objective function
grr2 <- function(xx) { #
ck <- xx[1:klength]
a0 <- xx[(klength+1):(klength+ilength)]
a1 <- xx[(klength+ilength+1):(klength+ilength*2)]
a2 <- xx[(klength+ilength*2+1):(klength+ilength*3)]

c(apply((uk[ik,]*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum) +gamma2*((ck-ckest1)),
apply(-(ui[ii,]*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum),
apply(-(ui[ii,]*mobs*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum),
apply(-(ui[ii,]*vobs*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum)
)
}
```

```
ll <- optim(xx0,   fr2,   grr2,   method = "BFGS")   # "BFGS" –@

#ll$par
#ll$value

ckest2 <- ll$par[1:klength]
a0est2 <- ll$par[(klength+1):(klength+ilength)]
a1est2 <- ll$par[(klength+ilength+1):(klength+ilength*2)]
a2est2 <- ll$par[(klength+ilength*2+1):(klength+ilength*3)]

plot(ckreal,ckest2,xlim=c(0,16),ylim=c(0,16))
abline(0,1)

rmse <- sqrt(mean((ckest2-ckreal)**2))
prmse <- rmse/mean(ckreal)
```

APPENDIX I: R SCRIPT FOR REAL DATA SIMULATION

```
## INITIALIZATION
#setting of number of road sections and vehicles

klength <- 1865   #number of road sections
ilength <- 14   #number of unique vehicles/device-location combinations
jlength <- 5685   #number of observed data

Data1 <- read.csv("C:/Users/Viengnam/SkyDrive/Simulation Feb 2014/Data1 for R Cleaned 
22022014.csv") #Import data
Data2 <- read.csv("C:/Users/Viengnam/SkyDrive/Simulation Feb 2014/Data2 for R Cleaned 
22022014.csv")   #Import data

vobs <- Data1$vobs  #Average vehicle speed
ckreal <- Data2$ckreal   #1865 Entries #real IRI value

ckobsf <- Data2$ckobsf2     #Observed IRI by cases #flag of prior parameters -> 1:given, 0:not
#Cases include ckobsf1, ckobsf2, ckobsf3....


mobs <- Data1$mobs     #Magnitudes at 40-50Hz
ii <- Data1$ii #Veh/Dev ID coresponding to the section
ik <- Data1$ik     #Sect ID corresponding to the Veh/Dev

ckrank <- ckreal
for(i in 1:klength){
  if(ckreal[i] < 3){
    ckrank[i] = 1
  } else if(ckreal[i] < 5){
    ckrank[i] = 2
  } else if(ckreal[i] < 7){
    ckrank[i] = 3
  } else if(ckreal[i] < 9){
    ckrank[i] = 4
  } else if(ckreal[i] < 11){
    ckrank[i] = 5
  } else {
    ckrank[i]=6
  }
}


#gamma
gamma <- 0

#Unit Matrix
uk <- diag(klength)  #unit matrix for road sections
ui <- diag(ilength)    #unit matrix for vehicles(or trips)

axf <- seq(1, 1, length = ilength)    #flag of prior parameters -> 1:given, 2:not given
a0pri <- seq(0, 0, length = ilength)  #prior parameter a0
```

```
a1pri <- seq(1, 1, length = ilength)  #prior parameter a1
a2pri <- seq(-0.01, -0.01, length = ilength)#prior parameter a2

ckobs <- ckreal*ckobsf  #prior(or observed) IRI

eta <- seq(100, 100, length = ilength)   #weight vector prior parameters IRI

#initial value for unknown variables
ck0 <- seq(0, 0, length = klength)   #initial value for parameter IRI
a00 <- seq(0, 0, length = ilength)         #initial value for parameter a0
a10 <- seq(0.4, 0.4, length = ilength)         #initial value for parameter a1
a20 <- seq(-0.06, -0.06, length = ilength)        #initial value for parameter a2
xx0 <- c(ck0,a00,a10,a20)   #integrated vector (for "optim"-function purpose)

##Objective function (Generalized Least Squared Errors)
fr <- function(xx) {
  ck <- xx[1:klength]
  a0 <- xx[(klength+1):(klength+ilength)]
  a1 <- xx[(klength+ilength+1):(klength+ilength*2)]
  a2 <- xx[(klength+ilength*2+1):(klength+ilength*3)]

### model 5###

sum((ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)^2)+gamma*(sum((ck-ckobs)*ckobsf))^2+eta[1]*(su
m(a1)-ilength)^2
}

##Gradient function of objective function
grr <- function(xx) { #
  ck <- xx[1:klength]
  a0 <- xx[(klength+1):(klength+ilength)]
  a1 <- xx[(klength+ilength+1):(klength+ilength*2)]
  a2 <- xx[(klength+ilength*2+1):(klength+ilength*3)]

### model 5 ###
  c(apply((uk[ik,]*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum) +gamma*((ck-ckobs)*ckobsf),
    apply(-(ui[ii,]*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum),
    apply(-(ui[ii,]*mobs*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum)+eta*(sum(a1)-ilength),
    apply(-(ui[ii,]*vobs*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum)
  )
}

##Optimization
ll <- optim(xx0,   fr,   grr,   method = "BFGS")   # "BFGS" -@

ck <- ll$par[1:klength]
a0est1 <- ll$par[(klength+1):(klength+ilength)]
a1est1 <- ll$par[(klength+ilength+1):(klength+ilength*2)]
a2est1 <- ll$par[(klength+ilength*2+1):(klength+ilength*3)]
ckobs2 <- subset(ckobs,ckobsf==1)
ckck2 <- subset(ck,ckobsf==1)
result <- lm(ckobs2 ~ ckck2, data = trees)
```

```
ckest1 <- result$coefficients[1]+result$coefficients[2]*ck
gamma2 <- 100

#ckest1 <- ckobs

##Objective function2 (Generalized Least Squared Errors)
fr2 <- function(xx) {
  ck <- xx[1:klength]
  a0 <- xx[(klength+1):(klength+ilength)]
  a1 <- xx[(klength+ilength+1):(klength+ilength*2)]
  a2 <- xx[(klength+ilength*2+1):(klength+ilength*3)]

  sum((ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)^2)+sum(gamma2*((ck-ckest1))^2)
}

##Gradient function2 of objective function
grr2 <- function(xx) { #
  ck <- xx[1:klength]
  a0 <- xx[(klength+1):(klength+ilength)]
  a1 <- xx[(klength+ilength+1):(klength+ilength*2)]
  a2 <- xx[(klength+ilength*2+1):(klength+ilength*3)]

  c(apply((uk[ik,]*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum) +gamma2*((ck-ckest1)),
    apply(-(ui[ii,]*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum),
    apply(-(ui[ii,]*mobs*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum),
    apply(-(ui[ii,]*vobs*(ck[ik]-a0[ii]-a1[ii]*mobs-a2[ii]*vobs)), 2, sum)
  )
}

ll <- optim(xx0,   fr2,   grr2,   method = "BFGS")   # "BFGS" -@

ckest2 <- ll$par[1:klength]
a0est2 <- ll$par[(klength+1):(klength+ilength)]
a1est2 <- ll$par[(klength+ilength+1):(klength+ilength*2)]
a2est2 <- ll$par[(klength+ilength*2+1):(klength+ilength*3)]

plot(ckreal,ckest2,xlim=c(0,16),ylim=c(0,16))
abline(0,1)
```