A Low Cost Method to Develop an Initial Pavement Management System

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

A Low Cost Method to Develop an Initial Pavement Management System

Mohammed Al-Dabbagh

Implementation of a pavement management system requires data collection to estimate system needs, performance modeling to forecast time sensitive changes and decision making to allocate interventions. Many agencies have embarked into the implementation of a pavement management system which eventually after some years render its fruits, however, implementation typically involves expensive equipment, years of data collection and hundreds of hours of workmanship. This all result in a barrier that impedes implementation at small municipalities and governments in developing countries. A low cost solution to estimate road surface roughness condition and to implement an initial pavement management system is proposed in this research. Pavement roughness can be estimated with an accelerometer built-in tablets and smart phones. Vertical accelerations normalized by speed can be used to produce a proxy for International Roughness Index. Testing of the method was done by comparing different tablets, applications, vehicles, speeds and location of the instrument inside the vehicle. Performance models were developed using World Bank's equation of IRI, road repair strategies were correlated to testing sections in need of maintenance or rehabilitation repairs. This research shows a case study of the town of Saint-Michelle in Quebec. Data was collected for all municipal roads in Saint Michelle and a pavement management system was developed. It was found that $254,418 dollars is required in order to sustain current levels of condition. It is recommended that in the future performance models are based on several years of observations in order to replace the synthetic deterministic curves herein adopted.

DEDICATION

To my wife: Hind, my daughter: Reema and my son: Ibrahim

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I would like to express my sincere gratitude to my supervisor Dr. Luis Amador for his advice, guidance and continuous support during all the time of research and writing of this thesis. I was so honored to work under his supervision.

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society of Testing and Materials
COST	European Cooperation in the Field of Scientific and Technical Research
DOT	Department of Transportation
ESAL	Equivalent Single Axle Load
FHWA	Federal Highway Administration
GPS	Global Positioning System
HDM	The Highway Design and Maintenance Standards Model
HMA	Hot Mix Asphalt
IRI	International Roughness Index
RI	Roughness Indicator
TAC	Transportation Association of Canada
UDOT	Utah Department of Transportation

CHAPTER 1

INTRODUCTION

1.1 Background

An effective road network is a fundamental component of the economic and social development of any country; therefore, pavements are one of the major investments administered by governments around the world (Watanatada, et al., 1987). Maintenance and rehabilitation has been identified as a key task to preserve pavements and ensure they remain productive throughout their lifespan. They are also expensive (Posavljak, et al., 2013).

First implementations of pavement management dates from the 1980's with silo-type systems for pavements (Tarpay, et al., 1996) (Chen, et al., 1996). Pavement management was the precursor of bridges, water systems, and other assets management systems, which are referred in general under the umbrella of asset management (Falls, et al., 2001).

Today Pavement Management Systems (PMS) are widely used by the governments of many countries, provinces and states of developed countries (Chen, et al., 1996) (Falls, et al., 2001). However they are no so common in poor countries or small municipalities that lack the resources to implement them.

The implementation of a PMS is typically challenging task because it requires an intensive data collection campaign (Khan, et al., 2003) which in turn necessitates utilization of expensive equipment such as profilometers or deflectometers (Noureldin, et al., 2003).

Without such equipment, estimation of road condition is difficult if not impossible. Some have used visual inspections in this circumstances (Amador & Magnuson, 2011), but visual inspections suffer from two drawbacks: first are incapable of estimate the condition of the structure and secondly are entirely related to human subjectivity which is an issue when visiting thousands of kilometers of roads.

Another problem comes from the fact that treatment allocation should be based upon a consistent repeatable criteria (Ksaibati, et al., 1999) which must relate to some measurable indicator of damage (Mactutis, et al., 2000). The two most widely suggested criteria are as rutting (also known as rut depth) and cracking (Hall & Muñoz, 1999).

Another difficulty to implement is the need to count with at least two condition data points (Amador & Mrawira, 2011) traditionally recommending data collection for at least 5 years to observe trends. This because it requires the development of performance curves (Falls, et al., 2001).

The final restriction comes from the fact that an optimization software is required in order to support decision making for the allocation of resources and development of strategic, tactical and operational plans (Posavljak, et al., 2013).

1.2 Problem Statement

There is a need to evaluate road condition with a low cost accessible method for small municipalities and poor governments lacking the financial capability to develop and implement a pavement management system.

1.3 Research Objective

1.3.1 Overall Goal

Propose a low cost method to capture pavement surface condition and develop a low-cost initial pavement management system.

1.3.2 Specific Objectives

1. Establish a low cost procedure to collect data for surface condition; and
2. Develop an initial pavement management systems based on a low-cost data-acquisition method.

1.4 Scope and Limitations

This research proposes a low cost method to collect pavement surface condition data and evaluate the pavement condition for the purpose of developing initial pavement management system. Specifically, the research is limited to pavement surface roughness assessment, although it is indirectly capable of incorporating structural decay when observing time trends of longitudinal data collected across time. There is no characterization of specific damage; however this is not required because operational ranges for treatment allocation can be learnt from visiting deficient sections already categorized to be in need of a specific type of intervention. No assessment of pavement layers structural capacity or state of degradation is done, but this is not needed as surface roughness is sufficient to be used in the decision criteria. Further testing will be required to investigate the effect of horizontal and vertical curves in rebalancing of vertical accelerations into horizontal accelerations.

1.5 Research Significance

This research makes the following contributions:

1. It proposes a method to evaluate surface condition of a pavement with a low cost technology;
2. It proposes a procedure to establish an initial pavement management system in about a year on the basis of low cost data acquisition; and
3. It demonstrates the method through a case study for municipal road network.

1.6 Organization of the Thesis

This thesis is presented in five chapters as follows; Chapter 1 defines the problem and presents the objectives of the research and structure of the thesis. Chapter 2 displays a review of concepts related to pavement management, specifically road surface condition, performance curves and optimization to support decision making. Chapter 3 presents the methodology employed for data collection. Chapter 4 presents a short case study demonstrates the implementation of the proposed method for the purpose of dissemination to potential users. Chapter 5 presents conclusions and recommendations, as well as suggestions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Pavement Condition

New pavements start out smooth and increase in roughness over the time (UDOT, 2009). They deteriorate due to a combination of detrimental effects including frequent traffic loading, climate and weather conditions and repeated civil infrastructure maintenance (Mannering, et al., 2009). Pavement roughness is an important indicator of pavement condition. It reflects the distress of the pavement surface as well as the underneath layers (UDOT, 2009) (Figure 1); therefore, it is used in measuring road performance which is useful for producing feasibility studies (Bennett, 1996). The International Roughness Index (IRI) is widely used to reflect the amount of roughness and it is reported in inches per mile (in/mi) or meters per kilometer (m/km).

The American Society of Testing and Materials (ASTM-E867) defines road roughness as the vertical variation on the pavement surface from a base level considered to be perfectly flat. Such variations affect the smoothness of the ride and may lead to damage on the vehicle (Sayers & Karamihas, 1998). The World Bank (HDM-III, 1987) has a more applied perspective for road roughness stressing the fact that it is the effect of traffic loading which results in *"damage in the form of rut depth variations, surface defects from spalled cracking, potholes, and patching, and a combination of aging and environmental effects"* (Watanatada, et al., 1987). Several other definitions had been given to roughness for the past four decades (Guignard, 1971) such as: irregularities in the pavement surface affect the ride quality of a vehicle and user. They cause vehicle delay costs, fuel consumption, greenhouse gas emissions and vehicle operating costs; therefore, road roughness was identified as a primary factor in the analyses and trade-offs involving road quality vs. user cost (Sayers, 1995).

Road profile consists of large number of wavelengths ranging from several centimetres to tens of meters, with different amplitudes. The excitation of different traversing vehicles in response to these wavelengths depend on several factors including vehicle speed, suspension system type, wheel and frame inertial properties, and etc. (Papagiannakis & Masad, 2008).

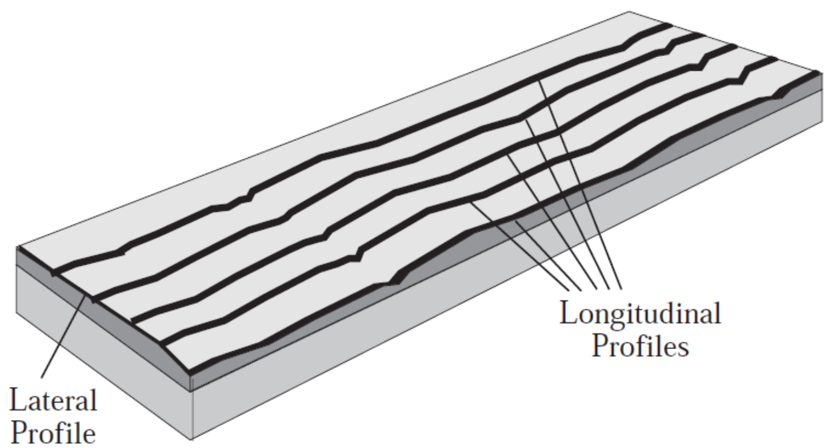

Figure 1: Sketch of pavement roughness in wheel-paths (Sayers & Karamihas, 1998)

2.1.1 Pavement Distress

Pavement distress such as rutting, cracking spalling, ravelling, bleeding and etcetera are the sign of inappropriate mix design, poor workmanship or aging over time or all of the aforementioned. There are several types of road pavement distress with variety of severity levels; however, these types can be classified into three main groups: cracking, surface deformation, and surface defects (Papagiannakis & Masad, 2008). Cracking and rutting are main contributors to road pavement roughness; therefore, a brief description of each is given hereinafter along with common examples, possible reasons and rectification methods.

Cracking

There are several types of flexible pavement cracking: Block Cracking, Fatigue Cracking, Microcracking, Top-Down Cracking, Longitudinal Cracking, Transverse Cracking, Slippage Cracking and Reflection Cracking. As shown in Figure 2, block cracking appears in the form of separated pavement blocks. They range in size from approximately 0.1 m^2 (1 ft^2) to 9 m^2 (100 ft^2) due to net of surface cracks spread in different directions. This type of cracks is mainly caused by either aging and/or low quality of binder of the asphalt mix which both make the binder unable to expand and contract with temperature cycles. The result is moisture infiltration and pavement roughness. Repair approach depends on the severity of the cracks. For low severity cracks of less than ½ inch thickness, crack seal is the best solution while for the high severity ones of greater than ½ inches thickness and raveled edges, replacing the cracked pavement with an overlay is optimum repair solution (Roberts, et al., 1996).

Figure 2: Block cracking (Pavemanpro.com, 2013)

As shown in Figure 3, fatigue cracks are similar to the crocodile shape. They are caused by fatigue failure of the hot mix asphalt surface because of the repeated traffic loading (Dore & Zubeck, 2009). This type of cracks is mainly caused by actual traffic loads greater than what was considered during the design stage or inadequate structural design of pavement layers or poor construction performance. The result is moisture infiltration, pavement surface roughness and possibility of further deteriorate to a pothole. An investigation is commonly required to stand on the right reason behind fatigue cracking. For limited crack area, which is considered as an indication of subgrade support failure, it is required to remove the cracked area, replace the poor subgrade layer and patch over the rectified subgrade. For wide crack area, which is considered as an indication of general structural failure, it is required to place a strong hot mix asphalt (HMA) coat over the entire pavement surface (Roberts, et al., 1996).

Figure 3: Fatigue cracks (Butler, 2013)

Pavement transverse cracks are seen in the direction perpendicular to the pavement's main direction (Figure 4). The suggested causes for this type of cracks are of ambient temperature changes, cracks beneath the surface hot mix asphalt (HMA) layer (Thom, 2008). Transverse cracks result in moisture infiltration into the underneath pavement layers and roughness. If cracks are not repaired at the right time, more crack deterioration will occur which means poorer riding quality which requires more extensive repairs and resurfacing or rehabilitation. Repair method depends on the size and severity level of existing cracks. For less than ½ inch wide infrequent crack, crack seal is the best strategy to be followed in order to prevent moisture infiltration to underneath layers and avoid further raveling of the crack edges. While for greater than ½ inch wide and numerous cracks, replacement of cracked layer and overlying strategy is the optimum solution (Roberts, et al., 1996).

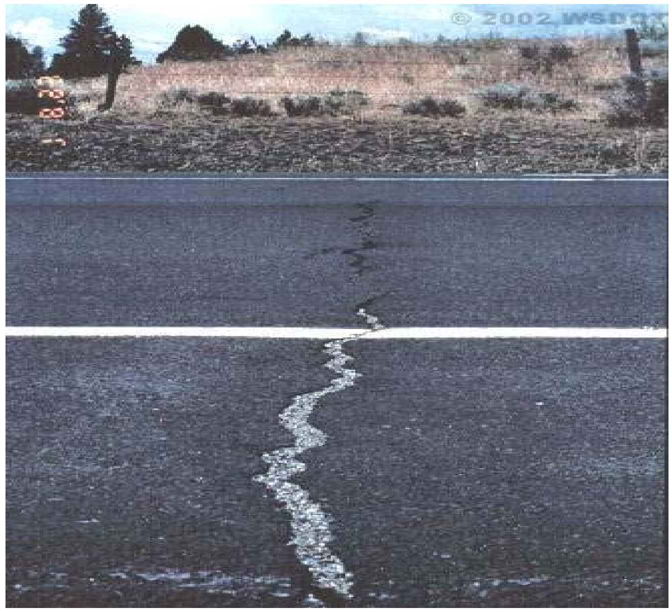

Figure 4: Transverse cracks (WAPA, 2013)

Rutting

Rutting is longitudinal surface depressions in the wheel-paths as a result of repeated traffic loads (Dore & Zubeck, 2009) (Figure 5). Ruts have different shapes depending on the reasons behind them (Thom, 2008) and they can be classified to two kinds: Asphalt rutting and unbound underneath layers rutting. Asphalt rutting happens when only pavement surface deforms due to compaction and/or mix design problems, while unbound underneath layers rutting happens when these layers, and consequently the pavement surface, demonstrate wheel-path depressions as a result of the axle loading (Dore & Zubeck, 2009). Pavement inability to stand for these traffic loads is resulted from improper pavement design and/or poor workmanship. Repair strategy depends on the rutting severity and reason behind it. For low severity ruts (less than 1/3 inch deep), pavement can generally be left untreated, while for high severity ruts pavement needs to be leveled and overlyed (Mallick & El-Korchi, 2013).

Figure 5: Pavement rutting (Pavementinteractive, 2013)

2.1.2 Pavement Condition Indices

There are two types of pavement condition indicators: those that relate to specific types of pavement distress and those that reflect general pavement condition without identification of specific damages (Mactutis, et al., 2000). The second type may impede the appropriate selection of the corresponding treatment; however, it is useful for the development of initial pavement management systems.

As per the European Cooperation in the Field of Scientific and Technical Research (COST), Pavement Condition Indicator is *"A superior term of a technical road pavement characteristic (distress) that indicates the condition of it (e.g. transverse evenness, skid resistance, etc.). It can be expressed in the form of a Technical Parameter (dimensional) and/or in the form of an Index (dimensionless)"* (Litzka, et al., 2008). Pavement performance and condition over time is expressed, in general, using certain indices. These indices are either subjective depending on site inspections or objective that make them mechanically reproducible. Performance indices can be produced through different methods depending on the ultimate desired purpose such as design decision making and road network planning decision making. There are several examples of performance indices used in pavement management field such as; International Roughness Index (IRI), Present Serviceability Index (PSI), Pavement Quality Index (PQI) Pavement Condition Index (PCI), Pavement Rating Index (PCR), Surface Distress Index (SDI), and so on. The choice to consider a certain performance index depends basically on the desirable use of the performance model and the existing data.

2.1.3 Pavement Roughness Evaluation

Evaluation of pavement roughness is essential for modern pavement rehabilitation and design methodologies (Mactutis, et al., 2000). Pavement roughness evaluation process consists of two steps:

- **Pavement Roughness Data Collection** which can be conducted through either of the two systems explained next, and
- **Data Process** which includes filtering the raw data obtained from the previous step to extract the desired profile information and conclude summary index (roughness index) using computer software.

There are two methods to collect the road pavement roughness: Response-Type Method and Profilometer-Type Method. Response-Type devices are utilized to measure the response of the testing vehicle to the surface undulations of the tested road. The meter mounted in the testing vehicle yields a continuous trace of the relative displacement of the middle of the axle with respect to the frame of the vehicle. The captured data is divided by the traveled distance and reported in units of meter per kilometer or inches per mile (Bennett, 1996).

The Response-Type roughness measuring system has a number of limitations. It lacks the stability and the university required. i.e., it is not repeatable for a particular device and not comparable between devices of the same producer and model. This is because the collected roughness data depend on varying factors; mainly on the properties of the mechanical system used such as the spring elasticity, shock absorber damping type and tire inflation pressure (Papagiannakis & Masad, 2008); however, recent study has shown that results can approach those values of IRI from a profilometer (Dawkins, et al., 2011).

The use of Profilometer-Type Pavement Roughness instruments solves the problem posed by vehicle-related variations that as explained before affect the results of the Response-Type Pavement Roughness Method. Hence profilometers measure the actual profile of the pavement in order to gather data about its roughness. Most of the transportation departments in the United States use laser-type road profilers for roughness measurement (Ksaibati, et al., 1999) (Figure 6). The Profilometer-Type system measures the actual pavement profile without contacting the road surface. Instead, it uses laser or sound waves to record the road profile. The gathered data is then analyzed and translated to corresponding pavement roughness analysis software such as RoadRuf (Sayers & Karamihas, 1998).

Figure 6: Laser pavement profilometer (Roadex, 2013)

2.1.4 International Roughness Index (IRI)

The International Roughness Index (IRI) is the first widely used road profile index. It is an effective index to reflect a pavement roughness (Capuruco, et al., 2005). It is also defined as a specific mathematical transform of road profile. In other words, it is a summary number calculated from many numbers that reflect a road profile (Sayers & Karamihas, 1998). IRI evolved out of a study conducted by the World Bank in Brazil in 1982 (Sayers & Karamihas, 1998) to establish uniformity of the physical measurement of pavement roughness regardless of technology used for measurement. The IRI is reported in inches per mile (in/mi) or meters per kilometer (m/km). The lower the value of the IRI, the smoother the pavement surface and vice versa. Under the IRI, the scale of roughness ranges from zero for a true planar surface, about 2 for good condition pavements, 6 for a fair rough paved roads, 12 for an extremely rough paved roads, and escalating to about 20 for extremely rough unpaved roads (Archondo, 1999).

The advantage of IRI is that it is considered as a general indicator of road pavement condition. Furthermore, it is reproducible, portable, stable with time, and can be computed from different types of profiles (Sayers & Karamihas, 1998). Also, it meets the profiling needs with regard to the assessment of road condition, the road serviceability level, and the setting of priorities for planning for road maintenance and repair (Delanne & Pereira, 2001).

Calculation process of IRI begins with transforming the digital signals obtained from the profilometers-type measurement stage to elevation values. The next step is filtering the raw profile by eliminating the wavelengths that do not affect the ride quality of the vehicle traversing the pavement under evaluation (Papagiannakis & Masad, 2008). Such as wavelengths shorter than the pavement macrotexture dimensions and longer than roadway geometric features. Moving average (MA) is a popular technique for pavement profile filtering. Profile filtering falls in two types; Low-pass filtering and High-pass filtering (Papagiannakis & Masad, 2008).

The IRI is calculated through algorithm of a series of differential equations relate the vertical motion of a simulated quarter-car to the road profile (Bennett, 1996). Specifically, IRI can be calculated by accumulating the relative displacement of the tire with respect to the frame of the quarter-car and dividing the result by the profile length, as represented in the following Equation (2-1) (Sayers, 1995).

$$\text{IRI} = \frac{1}{\text{L}} \int_0^{\text{L}/\text{S}} |\text{Z}_\text{S} - \text{Z}_\text{U}| \, d_t \tag{2-1}$$

Where:

IRI: International Roughness Index (m/km)

L: length of the profile in km

S: simulated speed (80 km/h)

Zs: time derivative of the height of the sprung mass and

Zu: time derivative of the height of the unsprung mass

2.2 Civil Infrastructure Asset Management

The U. S. Department of Transportation defines asset management as a "systematic process of maintaining, upgrading, and operating physical assets cost-effectively. In the broadest sense, the assets of a transportation agency include physical infrastructure such as pavements, bridges, and airports, as well as human resources (personal and knowledge), equipment and materials, and other items of value such as financial capacities, right of way, data, computer systems, methods, technologies and partners" (FHWA & AASHTO, 1997).

In line with the abovementioned definition, asset management encompasses pavements and other infrastructure assets; therefore, asset management is wider, in terms of scope, than pavement management although the latter had predated the current interest in asset management by several decades (Falls, et al., 2001). As per the *Pavement Design and Management Guide*, asset management is new or modified terminology, but the basic principles are quite similar to what has been developed and applied as pavement (Falls, et al., 2001) (TAC, 1997).

2.3 Pavement Management Systems

A pavement management system is a process that involves a wide range of elements including the scheduling of investments related to maintenance, rehabilitation, upgrading and expansion of a network or roads, for this it requires several components capable of assessing deficiencies, estimating cost effectiveness of possible alternative courses of action and attempting to foresees the future in order to measure the impact of decisions across time. It has been defined to involve the comparison of alternatives, coordination of interventions, decision making (TAC, 1977).

However, it should not be forgotten that the aim of any infrastructure management system is quality of the service to the final user which in conglomerate implies the community. Another element is that having assets that remain productive throughout their lifespan (RTA, 1996).

A pavement management not only involves people but also technology to collect and interpret information in order to allocate resources across alternative (TAC, 1999). Advantages of pavement management had been elsewhere documented, among them one finds better allocation of resources, faster achievement of performance goals, sustainable levels of condition across time. Also the possibility to incorporate other assets such as bridges, pipes and other systems such as safety.

Falls et al. (2001) had defined the basic purpose of a pavement management systems as that to achieve the best value possible for the available public funds and to provide efficient, safe, comfortable, and economic transportation. This concept involves all modes of transportation and is made by comparing investment alternatives at both levels: network and project; coordinating design, construction, maintenance, and evaluation activities; and using the existing practices and knowledge efficiently.

Borrowing from this, a pavement management system, therefore, encompasses a wide range of activities including tradeoff of investment alternatives, design, construction, maintenance, periodic evaluation of performance and decision making. The processes of the later ranges from policy-related levels that deal with a number of projects to practice-related and detailed levels that deal with particular projects. They are all important to maintain efficient management (Falls, et al., 2001) (TAC, 1997).

There are two levels at which pavement management tasks are performed: network level, and project level (Haas, et al., 1994). At the network level, the planners and decision makers look at the overall strategy of the pavement network and examine the suggested fund and other planning issues; while at the project level, the concentration is on a limited component of the whole network and specific decisions on maintenance strategies and funding allocations are made (Huang & Mahboub, 2004).

The two levels of infrastructure management, network and project, are indicated in the Figure 7 below. This flow chart has been produced by Hudson et al. to show the operational framework of infrastructure management (Hudson, et al., 1997). As seen, it involves data at its core which is then used to assess the overall level of needs and to allocate interventions.

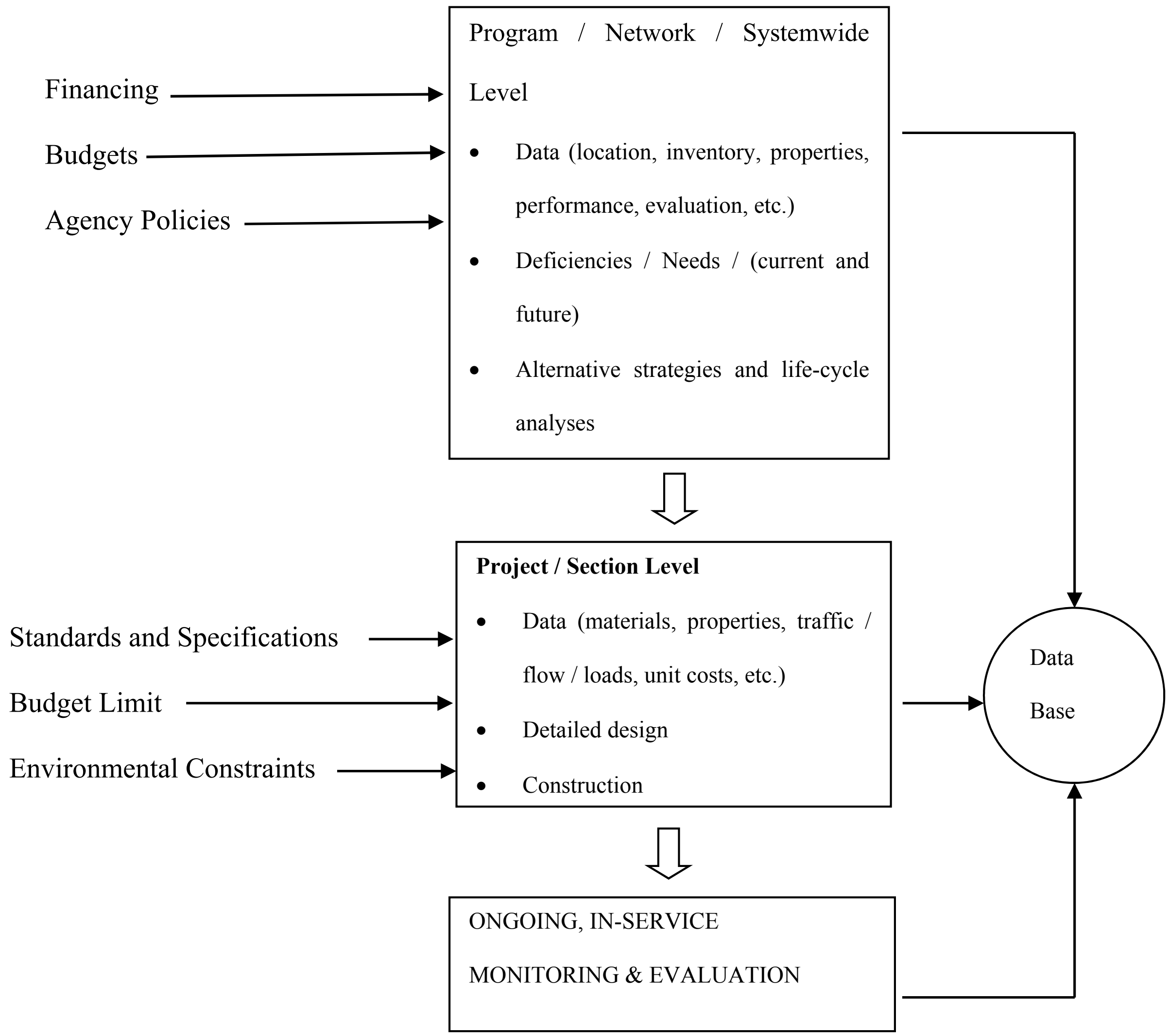

Figure 7: Operational framework for infrastructure management, including pavements (Hudson, et al., 1997)

2.4 Pavement Performance Prediction Modeling

There are two types of performance prediction models; Deterministic and Stochastic (George, et al., 1989) (Prozzi & Madanat, 2003). While deterministic models generate single value of the response variable (such as a performance indicator) for a given set of independent variables (such as time, age, traffic loading, usage rate, environmental exposure, preservation activity level, etc.), stochastic models generate a statistical distribution function of the response variable, performance indicator, of the asset.

For deterministic models, statistical regression is the most popular analysis technique used while stochastic models utilize Markov chain (MC) and survivor curves as widely accepted technique. Given the current road condition (state *i*), the MC technique predicts the future condition of the road (state *j*) as a probability distribution.

2.4.1 Stochastic Model

There are two advantages of stochastic model formulation; the power to incorporate uncertainty (which is actuality in assets design and planning processes) and the capability to adopt expert opinions to supplement historical data, where quality data is unavailable.

In Markov Chain model a base condition vector (BCV) representing the current year pavement condition is multiplied by a square matrix called transition probabilities matrix (TPM) to predict the probability distribution of next year condition. This procedure can be redone for as many as required for future prediction purpose. Figure 8 shows an example of a TPM when deterioration and improvements occur.

$$\text{Stages:}\quad 1 \quad 2 \quad 3 \quad\quad n$$

$$\text{TPM}_1 = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & & & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \qquad \text{TPM}_2 = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1n} \\ 0 & p_{22} & p_{23} & \cdots & p_{2n} \\ 0 & 0 & p_{33} & \cdots & p_{3n} \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix}$$

Figure 8: An example of Markov Chain Performance Model for deterioration prediction (Amador & Mrawira, 2009)

p_{ij} represents the probability that an element in condition situation "*i*" transfer to situation "*j*" if a one transition occurs. The values at the right side of the main diagonal are for deterioration while the values situated at the left side of the same are for improvement. The more far from the main diagonal, the higher deterioration or improvement is forecasted. As time passes, the probabilistic process lose reliability; therefore, periodically updating the program of works, decreases the need for high reliability of the prediction model further into the future.

There are two benefits of the prediction model; the first is identification of the optimum time for preservation interventions to prolong the road's life, the second is representing effectiveness of each preservation treatment and consequently the ability to conduct comparison between the treatment alternative in the optimization and/or trade-off analyses. Figure 9 shows a scholastic performance prediction graph with density functions and related terms and concepts. Two cases are indicated: (a) an improvement TPM composed of zeros above the diagonal with improvement values below it, and (b) a mixed (improvement – deterioration) TPM with values all across its cells. In the mixed TPM the values overhead the main diagonal signify deterioration and the values below it stand for the treatment improvement.

Performing periodical modifications is very important to achieve the desired reliability of investments optimization results for the network over the long term. The dispersion of future condition values can only be constricted by enriching the training population with all new periodic condition surveys and data update.

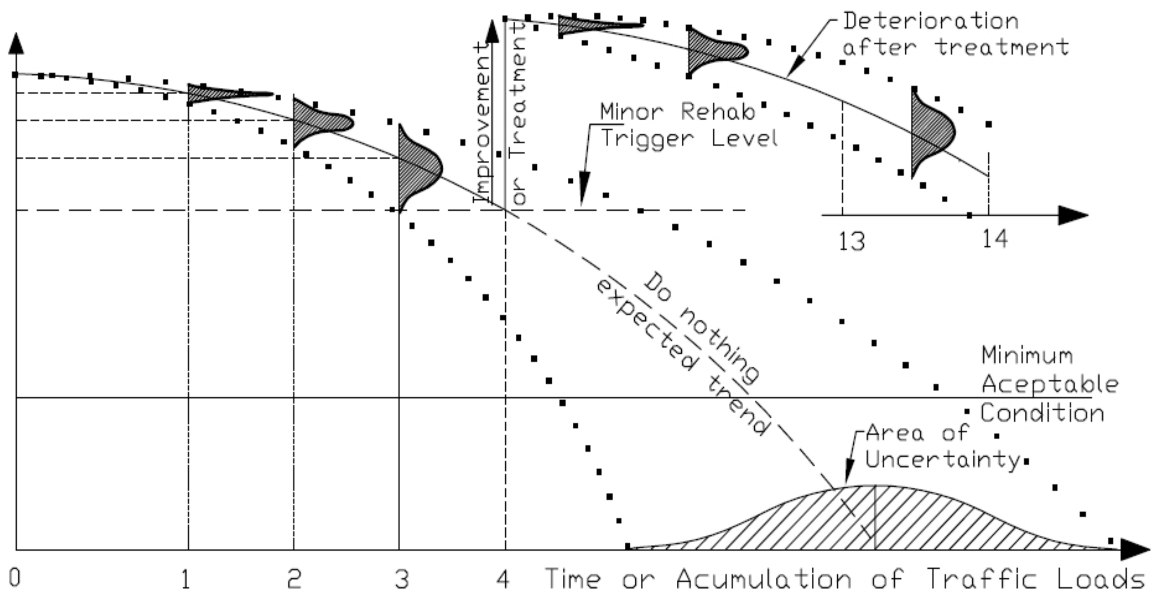

Figure 9: Uncertainty in pavement performance prediction curve (Amador & Mrawira, 2009)

2.4.2 Deterministic Model

The World Bank proposed in the Highway Design and Maintenance Standards Model (HDM) during the late 1980s equations for the development of performance models. In such model, minimization of total transport costs resulted from roads deterioration, within financial, quality and policies constraints, was set as desired by all governments and municipalities. To achieve this goal, alternative rehabilitation and maintenance plans must be compared and the tradeoffs between them carefully assessed. This in sequence requires the ability to quantify and predict performance and cost functions for the desired period of analysis. This was the motivation for the World Bank to commence a study in 1969, which later became a large-scale program, resulted in producing the HDM model. This model is used to conduct comparative cost estimates and economic evaluations of different policy options, including different time staging strategies, either for a given road project or for entire network. In the HDM model, the current pavement condition is updated each consecutive year during the analysis period as shown diagrammatically in Figure 10. The values of the road condition variables after maintenance (i.e., cracking, raveling, potholing and patching areas, rut depth and consequently roughness) are computed and become initial values for the next analysis year. The cycle continues through successive years to the final analysis year (Watanatada, et al., 1987).

Computational logic

The main variables used from one analysis year to the following to define pavement condition, history and strength are classified into groups as indicated below (see variables definitions in Table 1):

[CONDITION] = [ACRA, ACRW, ARAV, APOT, RDM, RDS, QI]

[HISTORY] = [AGE1, AGE2, AGE3]

[TRAFFIC] = [YE4, YAX]

[STRUCTURE] = [SNC, DEF, HS.., PCRA, PCRW, CRT, RRF]

The computational logic adopted by the HDM model (Watanatada, et al., 1987) is illustrated in Figure 10 and briefly explained below:

Pavement condition at the beginning of the analysis year is initialized either from input data if it is the first year of the analysis or the first year after construction, or otherwise from the result of the previous year's condition after maintenance:

The surface conditions before maintenance at the end of the year are predicted as indicated below (2-2):

$$[ACRA, ACRW, ARAV, APOT]b = [ACRA, ACRW, ARAV, APOT]a + \Delta[ACRA, ACRW, ARAV, APOT]d \quad (2\text{-}2)$$

The rut depth and roughness conditions before maintenance at the end of the years are predicted as indicated below (2-3):

$$[RDM, RDS, QI]b = [RDM, RDS, QI]a + \Delta[RDM, RDS, QI]d \quad (2\text{-}3)$$

Maintenance intervention criteria are applied to determine the nature of maintenance to be applied, if any:

Condition responsive:

if [ACRW, ARAV, APOT, QI]b >= [ACRW, ARAV, APOT,QI] intervention (2-4)

Or Scheduled:

if [AGE1, AGE2, AGE3]b >= [AGE1, AGE2, AGE3]intervention (2-5)

Highest-ranking applicable maintenance is applied and the effects on pavement condition computed:

[CONDITION]a(next year) = [CONDITION]b+ Δ[CONDITION]m (2-6)

Where:

[Condition]a: condition at the beginning of analysis year (after maintenance of the previous year);

[Condition]b: condition at the at end of analysis year (before maintenance);

Δ[Condition]d: change of condition due to deterioration;

Δ[Condition]m: change of condition due to maintenance.

Road Roughness Prediction

Roughness progression is predicted as the resultant of three components (Watanatada, et al., 1987):

Structural deformation which is related to roughness, equivalent standard axle load flow, and structural number;

Surface condition which is related to changes in cracking, potholing and rut depth variation; and

Age-environment which is related roughness term.

$$\Delta QI_d = 13\ K_{gp}\ [134\ EMT\ (SNCK + 1)^{-5.0}\ YE4 + 0.114\ (RDS_b - RDS_a)$$

$$+ 0.0066\ \Delta CRX_d + 0.42\ \Delta APOT_d] + K_{ge}\ 0.023\ QI_a \quad (2\text{-}7)$$

Where:

ΔQI_d: the predicted change in road roughness during the analysis year due to road deterioration in QI;

K_{gp}: the user-specified deterioration factor for roughness progression (default value= 1);

K_{ge}: the user-specified deterioration factor for the environment-related annual fractional increase in roughness (default value = 1);

EMT: exp (0.023 K e AGE3)

SNCK: the modified structural number adjusted for the effect of cracking, given by:

SNCK: max (1.5; SNC - ΔSNK)

ΔSNK: the predicted reduction in the structural number due to cracking since the last pavement reseal, overlay or reconstruction (when the surfacing age, AGE2, equals zero), given by:

ΔSNK: 0.0000758 [CRX'_a HSNEW + ECR HSOLD]

CRX'_a: min (63; CRX_a);

ECR: the predicted excess cracking beyond the amount that existed in the old surfacing layers at the time of the last pavement reseal, overlay or reconstruction given by:

ECR: max [min (CRX_a- PCRX; 40); 0]

PCRX: area of previous indexed cracking in the old surfacing and base layers, given by:

PCRX: 0.62 PCRA + 0.39 PCRW

Roughness at the end of the analysis year, before maintenance and imposing an upper limit of 150 QI, is given by:

$QI_b = \min(150; QI_a + \Delta QI_d)$

YAX: flow of all vehicle axles (YAX) – annual millions per lane

YE4: flow of equivalent 80 KN standard axle loads annual millions per lane

Predictions from the model are illustrated in Figure 11 for two Pavements (SNC-values of 3 and 5) under six volumes of traffic loading and minimal maintenance comprising the patching of all potholes (Watanatada, et al., 1987).

Table 1: Definitions of variables used in HDM model (Watanatada, et al., 1987)

Variable	Definition
$ACRA_a$, $ACRA_b$	The total area of all cracking, in percent of the total carriageway area
$ACRW_a$, $ACRW_b$	The total area of wide cracking, in percent of the total carriageway area
$ARAV_a$, $ARAV_b$	The total area ravelled, in percent of the total carriageway area
$APOT_a$, $APOT_b$	The total area of potholing, in percent of the total carriageway area
AGE1	The preventive treatment age, defined as the time since the latest preventive treatment, reseal, overlay, reconstruction standard axle load and 520 kPa tire pressure) of the surfacing
AGE2	The surfacing age defined as the time since the latest reseal, overlay, reconstruction or new construction activity, in years
AGE3	The construction age, defined as the time since the latest overlay, reconstruction or new construction activity, in years
CMOD	The resilient modulus of soil cement, in GPa (required for cemented base pavements only)
COMP	The relative compaction in the base, subbase and selected subgrade layers, in percent (see note in 4.2.6)
CQ	The construction quality indicator for surfacing, where CQ = 1 if the surfacing has construction faults, = 0 otherwise
CRT	The cracking retardation time due to maintenance, in years (as elaborated in 4.3.3)
CRX_a, CRX_b	The total area of index cracking area, in percent of the total carriageway
DEF	The mean Benkelman Beam rebound deflection of the surfacing in both wheelpaths under 80kN standard axle load, 520 kPa tire presure, and 30°C average asphalt temperature), in millimeters
HBASE	The thickness of the base layer in the original pavement (required only for cemented base pavements), in millimeters
HSNEW	The thickness of the most recent surfacing, in millimeters
HSOLD	The total thickness of previous, underlying surfacing layers, in millimeters
MMP	Mean monthly precipitation, in m/month
PCRA	The area of all cracking before the latest reseal or overlay, in percent of the total carriageway area
PCRW	The area of wide cracking before the latest reseal or overlay, in percent of the total carriageway area
QI_a, QI_b	The road roughness, in QI units (see Figure 1.4 for conversion relationships, and note that the model accepts alternate units with linear conversion)
RDM_a, RDM_b	The mean rut depth in both wheel paths,in mm
RDS_a, RDS_b	The standard deviation of rut depth (across both wheel paths), in mm
RRF	The ravelling retardation factor due to maintenance (dimenssionless - as elaborated in 4.3.3)
RH	The rehabilitation indicator, where RH = 1 for surface types asphalt concrete overlay (OVSA) or open-graded cold-mix (OCMS) overlays, = 0 otherwise
SNC	Modified structural number of the pavement, computed as defined in Section 4.1.3.
YAX	The total number of axles of all vehicle classes for the analysis year, in millions/lane
YE4	The number of equivalent standard axle loads for the analysis year based on an axle load equivalency exponent of 4.0, in millions/lane

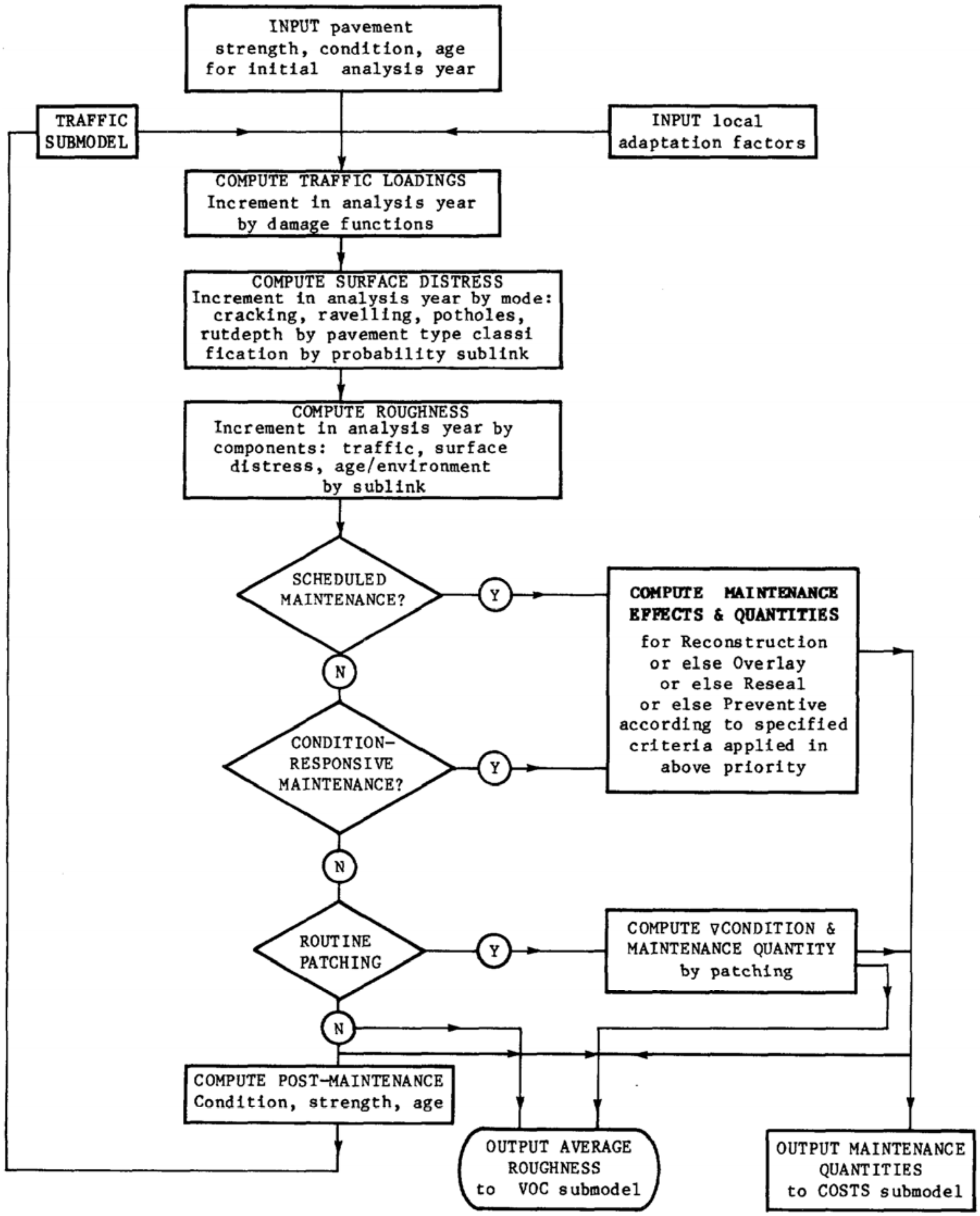

Figure 10: Logic sequence of road deterioration and maintenance submodel – paved roads (Watanatada, et al., 1987)

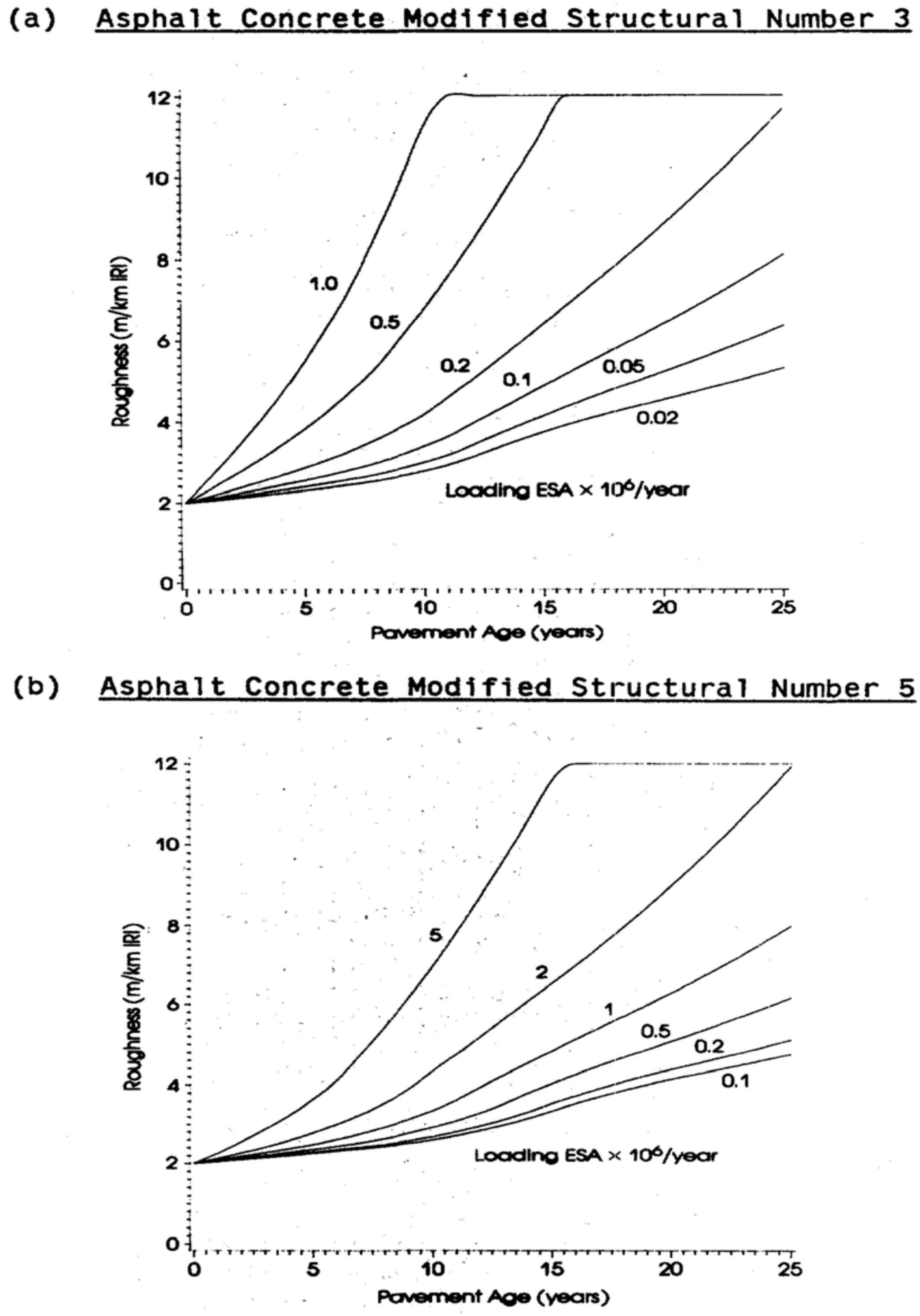

Figure 11: Prediction of roughness progression for flexible and semi – rigid pavements under minimal maintenance of patching all the potholes (Watanatada, et al., 1987)

2.5 Decision making for Pavement Management

The decision making process involved in pavement management system works first with analysing alternatives at the long term, that is, it creates possible courses of action and examines the impact following each of them. In this regard the system is a two-tier in which a total enumeration process creates a decision-tree-like mechanism, the second step consist of the assessment of the consequences of each course of action by measuring its impact on the variables of interest (i.e., condition, cost, etc.). The decision making process is guided by a mathematical algorithm that defines the optimization problem in terms of its objectives and constraints. The sense of the optimization is given by the nature of the objective and is restricted by constraints which typically limit the achievement of the objective; hence, objectives and constrains are exchangeable. In other words, an objective could be turn into a constraint and vice versa.

2.5.1 Typical Mathematical Algorithms

The choice of a certain mathematical algorithm to serve an optimization process depends on the objective of the optimization itself. The algorithm used to achieve a common objective which is determination of the budget required to maintain a non-declining level of service (*Q*), is presented in Equation (2-8):

MINIMIZE: $Z = \sum_{t=1}^{T} \sum_{i=1}^{N} \sum_{j=1}^{m} C_{t,j} X_{t,i,j} L_i$ (2-8)

Subject to: $\sum_{t=1}^{T} \sum_{i=1}^{N} L_i Q_{t,i} \geq \sum_{t=1}^{T} \sum_{i=1}^{N} L_i Q_{t-1,i}$

Where:

$Q_{t,i,j}$: level of service based on condition at year t, of section i, after action j

$x_{t,i,j}$: *{0, 1}*: 1 if treatment (*j*) is applied on asset (*i*) on time (*t*), zero otherwise

L_i: length (size) of the asset

$C_{t,i,j}$: cost of treatment *j* on section *i* at year *t*

B_t: budget for year t

Another algorithm approach is used to achieve another common objective which is determination of the budget required to achieve a target mean Level of Service (LOS_n) as presented in Equation (2-9)

$$\text{MINIMIZE: } Z = \sum_{t=1}^{T} \sum_{i=1}^{N} \sum_{j=1}^{m} C_{t,j}\, X_{t,i,j}\, L_i \qquad (2\text{-}9)$$

Subject to: $\sum_{t=1}^{T} \sum_{i=1}^{N} L_i Q_{t,i} \geq \boldsymbol{(LOS_n)} \sum_{i=1}^{N} L_i$ …..(term is fixed, constant)

Where:

$Q_{t,i,j}$: level of service based on condition at year t, of section i, after action j

LOS_n: target level of service for network *n (when you have more than one network of assets)*

$x_{t,i,j}$: yes = 1 and no = 0;

L_i: length (size) of the asset

$C_{t,i,j}$: cost of treatment *j* on section *i* at year *t*.

B_t: budget for year t.

Also, there is an algorithm to achieve a very common objective that follows the determination of minimum budget and is that when we have a fixed budget per year (Bt) and need to determine the best Level of Service (Q) achievable (Equation 2-10)

MAXIMIZE: $Z = \sum_{t=1}^{T} \sum_{i=1}^{N} L_i Q_{t,i,j}$ (2-10)

Subject to: $\sum_{t=1}^{T} \sum_{i=1}^{N} \sum_{j=1}^{m} C_{t,j} X_{t,i,j} L_i \leq B_t$

Where:

$Q_{t,i,j}$: level of service based on condition at year t, of section i, after action j

$x_{t,i,j}$: yes = 1 and no = 0;

L_i: length (size) of the asset

$C_{t,i,j}$: cost of treatment *j* on section *i* at year *t*.

B_t: budget for year t.

2.5.2 Total Enumeration

The mathematical algorithms is supported by a total enumeration process (Watanatada, et al., 1987) that consist of a decision-like-tree with arcs connecting paths and nodes recording levels of service and cost per treatment option and follows a binary nature in which a treatment may be selected or not. This enumeration process delivers expected consequences of applying each available treatment at each segment of road at every time step during the length of the analysis. It produces chains of alternative decision variables from which the software selects the optimal in terms of the particular objectives and constraints (Figure 12). Integer linear programming (as herein suggested) or a heuristic method such as an evolutionary algorithm may be used to obtain a solution (although approximate) (Imani & Amador, 2013).

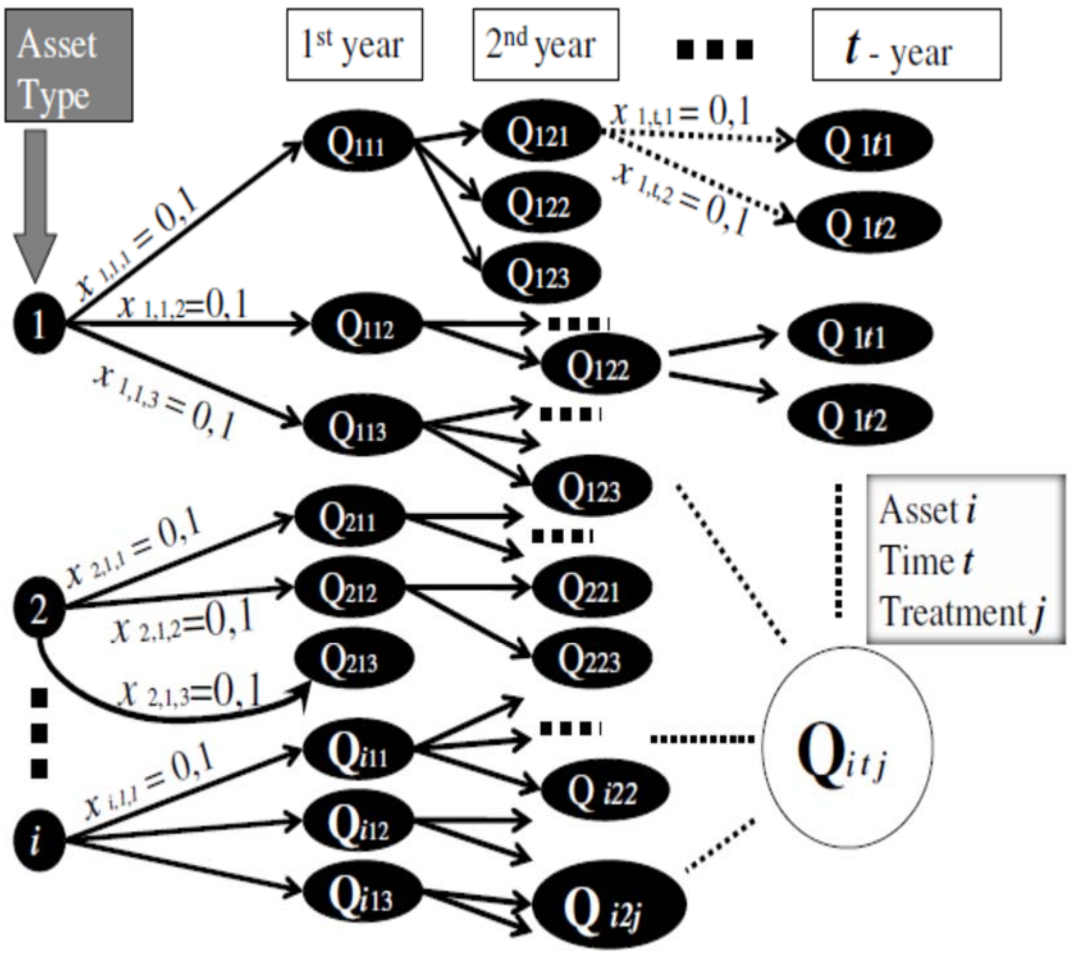

Figure 12: Total enumeration process

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter presents the methodology used for data acquisition and database preparation which are necessary to develop initial pavement management system. The chapter is divided into two main sections; the first section explains the method used to measure road pavement roughness and presents complementary analysis to validate the proposed approach. The second section presents the method used to prepare the database required for the management system. The development of pavement performance curves and treatment characterization are explained in the case study chapter for better explanation. It is important to mention that the method herein presented aims to typify average condition of road pavement and not to identify nor locate damage along the road pavement.

3.2 Road Roughness Measurement

Accelerometers can be used to capture vertical accelerations which are correlated to road surface condition. Accelerometers can be found in most tablets and smart phones, they capture accelerations in three-dimensional fashion. For the purpose of this thesis, only vertical accelerations were of interest although the long range trend of x-accelerations seems to map well horizontal curves and this could be used for road safety.

Standard deviations of accelerometer vertical accelerations captured variability or spread around the mean of the vertical accelerations. The larger the value, the larger the vertical accelerations. Once filtered by speed, standard deviations provided with an estimate of pavement condition (Figure 13).

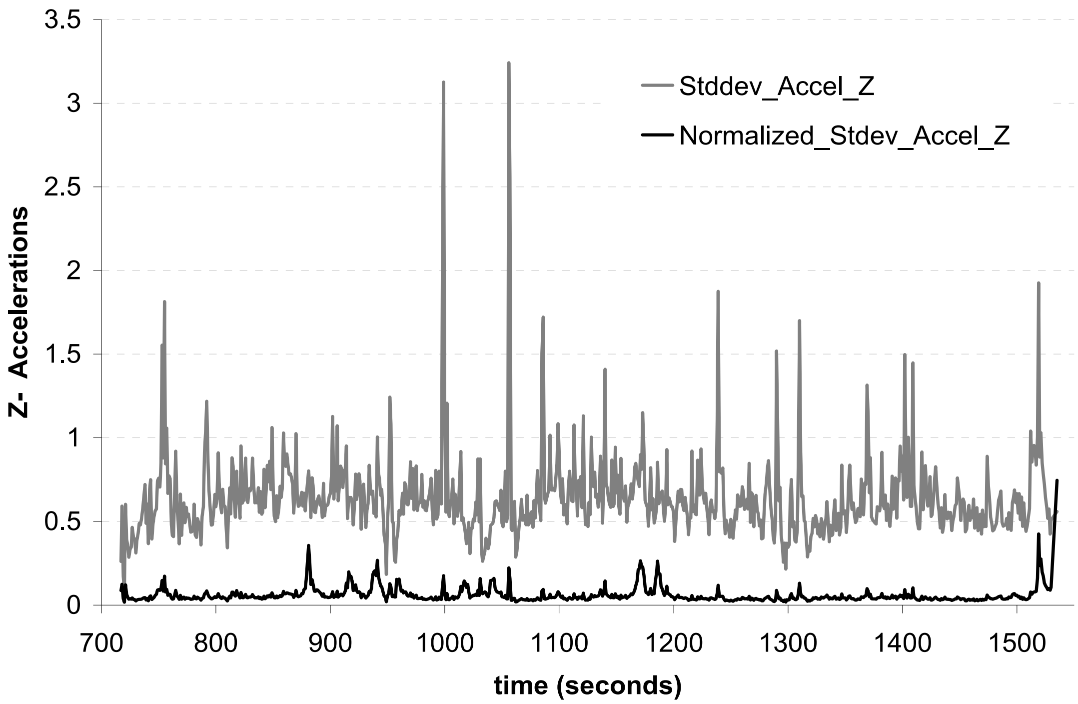

Figure 13: Standard Deviation of vertical acceleration with and without speed-normalization

3.2.1 Data Collection Protocol

There are several mobile device software applications able to log accelerations. These applications utilize the accelerometers originally built in the mobile devices to control their screens orientation. Few applications are able to log spatial coordinates (latitude, longitude), speed and accelerations altogether. It is possible then to use separate applications at one time to collect the desired data; i.e., one application to collect coordinates and speed and other one to collect accelerations.

The data collection procedure herein proposed uses two sets of mobile devices and compatible acceleration applications, as listed below:

1. Android-based device *Lenovo ThinkPad* with two compatible applications *MyTracks* and *Accelogger* (*MyTracks* for collecting coordinates and speeds data and *Accelogger* for collecting accelerations data); and
2. IOS-based devices *IPad* (Sometimes *IPhone* was used) with one compatible application *SensorLog* for collecting the desired data altogether.

Data collection started at rest (zero speed) and finished at rest as well, in order to have a known location given by a Global Positioning System (GPS). *MyTracks* application required somewhere from 2 to 10 seconds to find GPS signals and triangulate the location of the device. *Lenovo ThinkPad* tablet was placed horizontally on the floor of a vehicle near the middle of it. It was a 1998 Mazda pick-up truck. For other test, various vehicles were used to compare the acceleration observations resulting from using different dumping systems (vehicles). This is detailed under item no. 3.2.6.

The data collection steps fall into two stages; Field Work Stage and Desk Work Stage. The following procedure is for data collection using *Lenovo* device with two applications *MyTracks* and *Accelogger*:

Field Work:

1. Start at rest and set both applications to collect data at the same time;
2. Wait for GPS signal;

3. Drive the vehicle non-stopping and maintain constant speed. Do not exceed 40 kph on horizontal curves to avoid major impact of x-accelerations on z-accelerations;
4. Stop the vehicle when the traversed road surface type is changed or when 10 minutes travel time is reached (whichever happens first). Once vehicle at rest, stop the data collection of both applications. Data collection of any segment was stopped with changes in surface type so that each segment contained only one type of surface. Short changes of surface type should not be a reason to stop data collection; and
5. Register, on a field-book, date and time (beginning and end), spatial location coordinates, surface type, qualitative appreciation of overall condition, possible treatment type.
6. Export the collected data from the device to the computer (using email or any other suitable mean) to the purpose of Desk Work.

Desk Work:

The data collected during the field work stage were processed to obtain the standard deviations of the z-accelerations per second. The desk work steps are:

1. Join the collected acceleration, coordinates and speeds data;
2. Estimate the standard deviations of the vertical z-accelerations per second;
3. Estimate speeds in meter per second;
4. Normalize the standard deviations of z-accelerations by dividing them by the corresponding speeds;
5. Multiply each normalized standard deviation by 100 to obtain the Roughness Indicators (RIs) in one column;

6. Generate a column for the accumulative distance;
7. Draw a (RI-Accumulative Distance) graph; and
8. Obtain a spatial database with normalized standard deviations of z-accelerations.

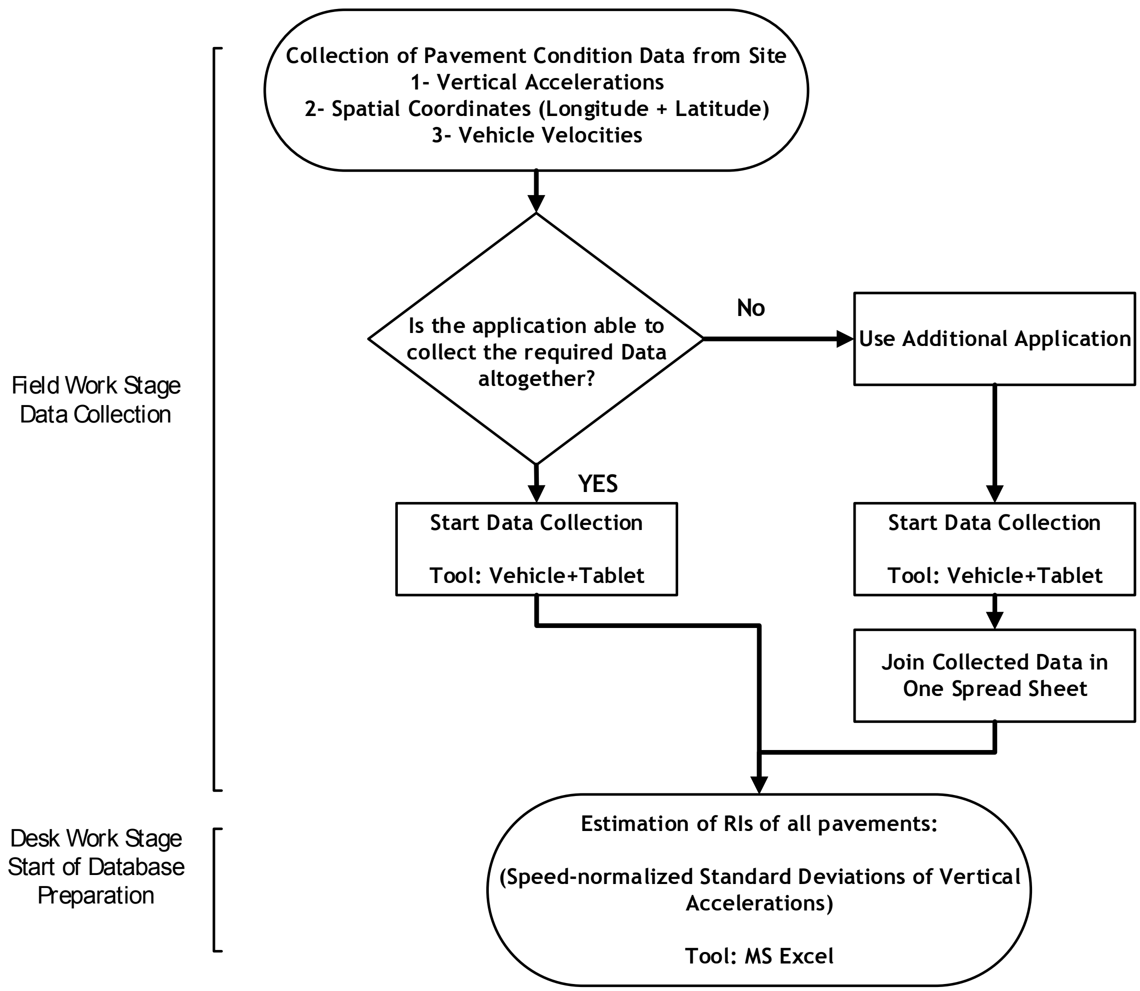

Figure 14: Flow chart of data collection procedure

The abovementioned procedure which was followed to collect data from site using *Lenovo* set is applicable for *IPad* or *IPhone* set; however, since the latter were able to collect spatial location, accelerations and speeds data altogether, there was no need to do data join mentioned under step no. 1 of the desk work stage.

In both tablets *IPad* and *Lenovo,* the loggers took somewhere from 10 to 100 observations per second. Each road segment contained observations for a maximum of 10 minutes. It was observed that the logger took more points on rougher surfaces. For this, one should estimate how many observations were taken in total and how many seconds passed from start to end. Figure 14 shows the main steps of the procedure used for data collection and processing.

3.2.2 A Proxy for International Roughness Index

The Root Mean Square (RMS) is often used to capture variation on cyclical responses of sinusoidal form. Equation (3-1) suggests that if the mean (a) is zero, the RMS equation is equivalent to the standard deviation. Equation (3-2) shows speed-normalized RMS and speed-normalized standard deviations of z-accelerations. As shown, such normalized-measure captures variability on the vertical scale (z), and its units are of frequency (1/s).

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{N} a_{zi}^{2}} = St.Dev. = \sqrt{\frac{1}{n}\sum_{i=1}^{N} \left(a_{zi} - a\right)^{2}} \tag{3-1}$$

$$\frac{RMS}{v_{yi}} = \sqrt{\frac{1}{n}\sum_{i=1}^{N} \left(\frac{a_{zi}}{v_{yi}}\right)^{2}} = \frac{\sigma_{z}}{v_{yi}} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{N} \left(a_{zi} - \overline{a}_{z}\right)^{2}}}{v_{yi}} \tag{3-2}$$

Where σ_z is the standard deviation of the z-accelerations (a_z) if the speed v_{yi} is constant for all observations. For this research, speed was treated as a constant because there is corresponding speed value per observation.

A close correlation between the speed-normalized z-acceleration and the International Roughness Index (IRI) has been suggested elsewhere (Dawkins, et al., 2011). Values of RMS normalized by speed and multiplied by 100 could be used as proxy for IRI (Dawkins, et al., 2011). For this research, values of speed-normalized standard deviation of z-accelerations were equivalent to those of speed-normalized RMS, and then multiplied by 100 to obtain a roughness index in m/km. The observed values of normalized standard deviations are kind of 0.05, 0.04, 0.07, 0.1; so multiplying them by 100 make them similar to the IRI values which are within a scale from 0 to 12. This doesn't have effect on capturing of the pavement condition, it is simply rescaling the digits to look like IRI digits.

The idea of the Roughness Indicator (RI) estimation is similar to that of International Roughness Index (IRI), however, the RI values depend on the wheel path of the vehicle and therefore will vary with the path followed by the driver. Also, the proposed roughness indicator (RI) acts similarly to the International Roughness Index (IRI), lower values of RI are associated with better condition and higher values with poorer condition.

3.2.3 Normalization by speed

Observed standard deviations of vertical (z-axis) accelerations were divided by observed vehicle speed (in meter per second) to take into consideration the variability of vehicle speed during the trip. A vehicle driver normally drives at a speed appropriate to the road surface condition; i.e., if the road is in poor condition, the driver will slow down to avoid violent movements which cause discomfort and vehicle damage. In this context, similar values of accelerations obtained from traversing two identical hypothetical road segments, one driven at high speed and the other one at low speed, resulted in different values of roughness; as the standard deviations of the segment traversed with higher speed were divided by larger speed-range and therefore delivered overall lower levels of the condition indicator. This speed normalization process is kind of filtering the standard deviation of vertical accelerations.

Normalization by speed (1/s) was validated using a comparison of observed values resulted from driving a vehicle at several speeds and on different surfaces. An experiment was set to measure vertical accelerations for three test segments at 3 speed ranges as summarized in Table 2. Speed ranges were measured in meter per second and each value of vertical acceleration was divided by the observed speed in meter per second.

Table 2: Target speeds (kph) for tested surfaces

Asphalt (poor condition)	Gravel (fair to good)	Earth (poor condition)
20	20	10
40	40	20
60	60	30

A comparison of speed-normalized RMS for the materials and speeds listed in Table 2 is shown on Figures 15, 16 and 17.

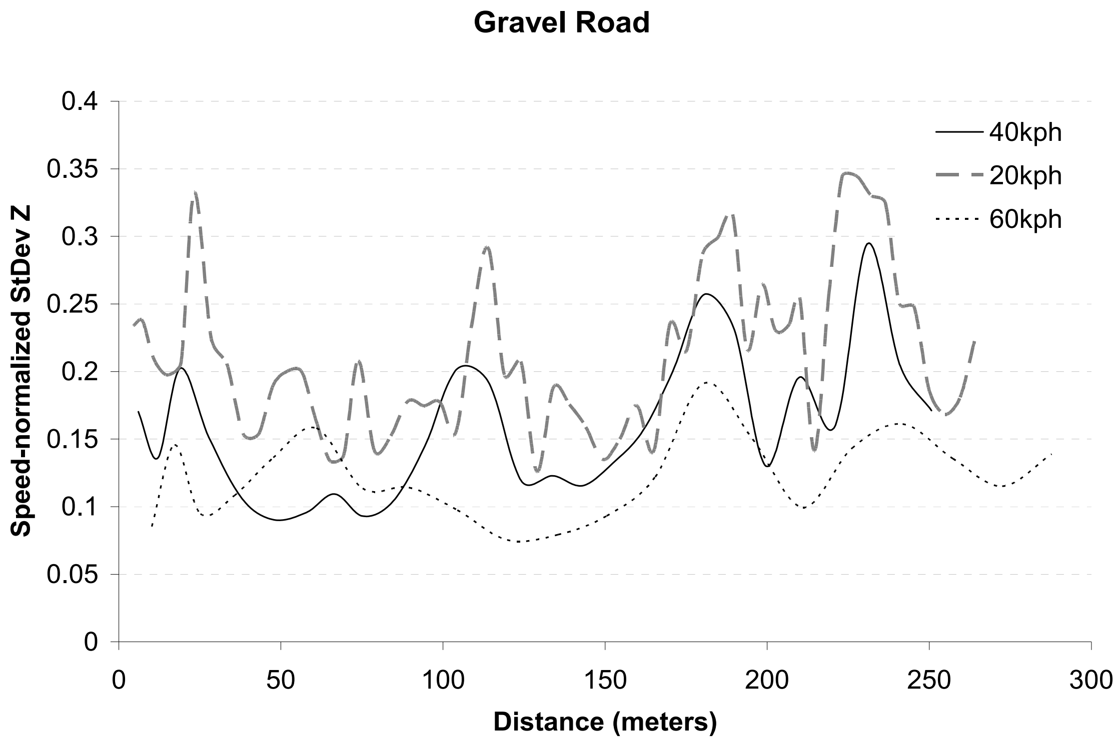

Figure 15: Comparison of speed-normalized standard deviation of z-accelerations – gravel – fair to good condition – same vehicle – various speeds

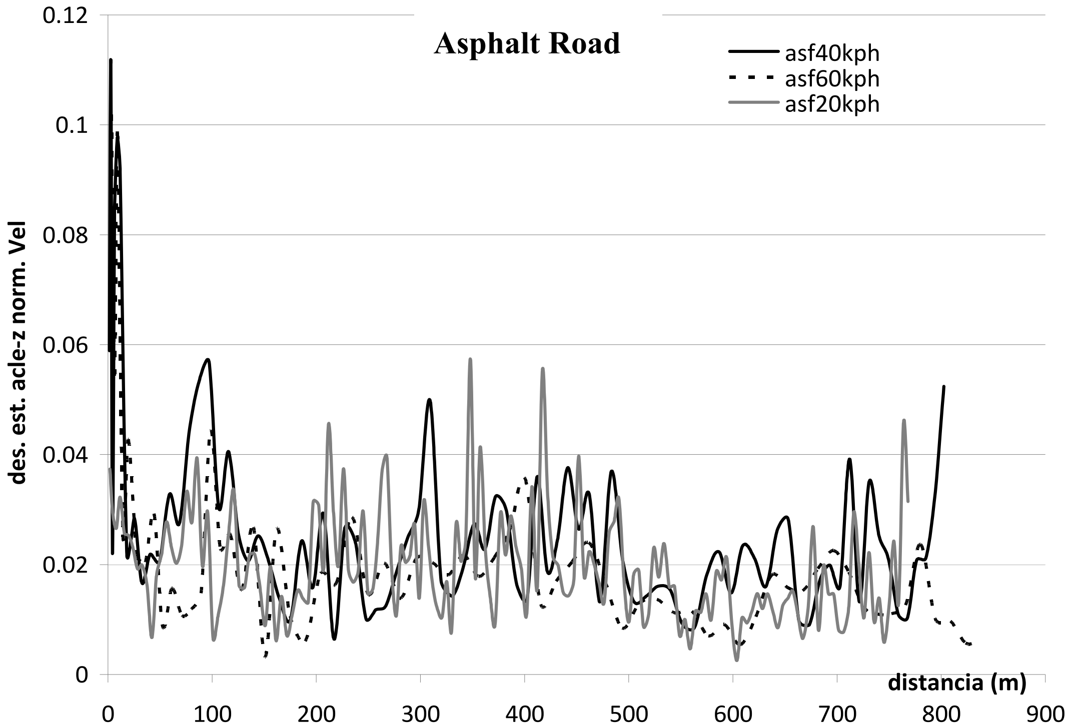

Figure 16: Comparison of speed-normalized standard deviations of z-accelerations – asphalt – poor condition – same vehicle – various speeds

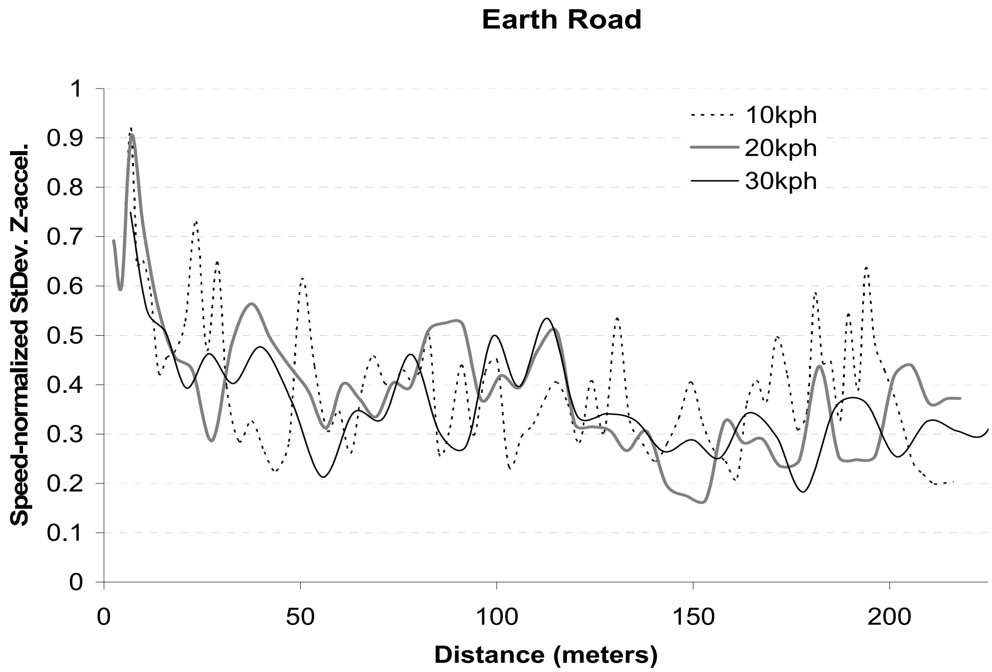

Figure 17: Comparison of speed normalized standard deviations of z-accelerations – Earth – poor condition – same vehicle – various speeds

It should be noticed that no two trials ran over the exact same wheel path, therefore the values of speed-normalized standard deviation of accelerations (or RMS normalized by speed) for the same road segment are close to each other but not exactly the same. Another reason for that is the speed effect and vehicles ability to travel over the complete vertical irregularity. At lower speeds the vehicle is able to go all the way down and back up on a given vertical deformation (for instance a pothole) but at higher speeds the accelerometer is not able to register the complete vertical variation because it will travel between fewer points of such vertical irregularity. This can be seen by comparing the vertical profiles of gravel roads at 20, 40 and 60kph in Figure 15.

3.2.4 Comparison of Various Surface Conditions

Results showed that the use of response normalized by vehicle speed (i.e., standard deviation normalized by speed) is capable of identifying roads at different levels of condition (good, fair, poor) regardless of their surface material, as shown in Figure 18 for two road segments: five and eight, S5 and S8 respectively.

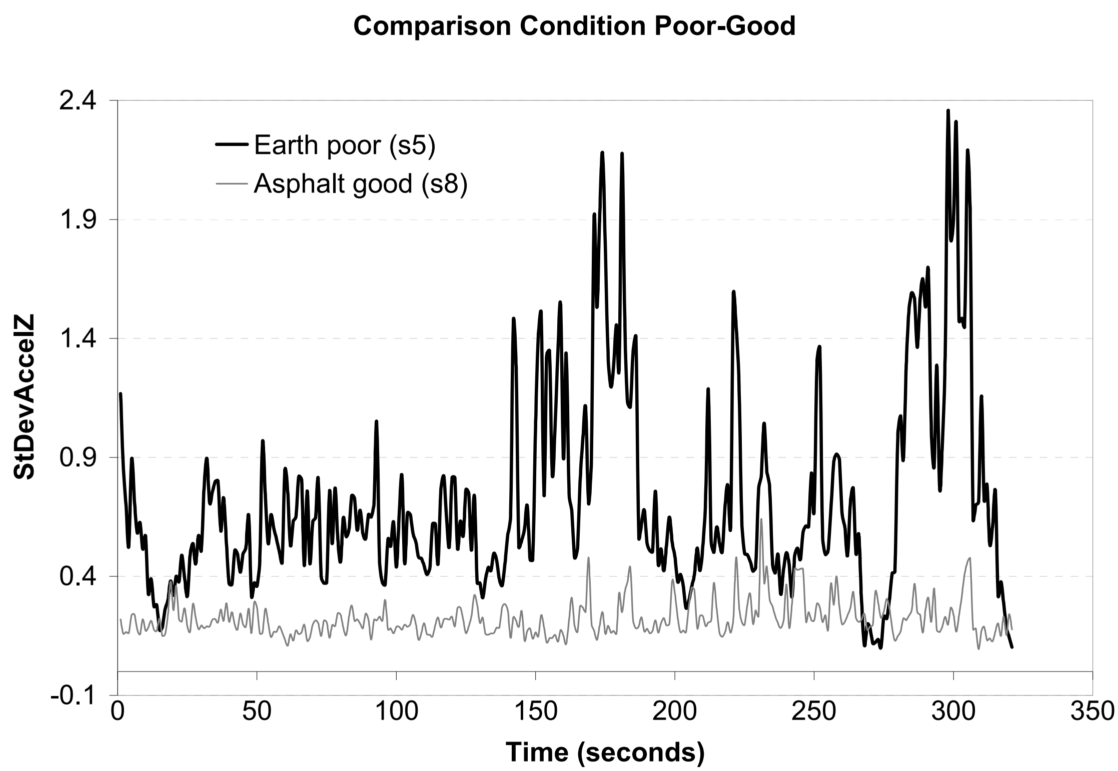

Figure 18: Comparison of earth in fair- poor and asphalt in good condition

Comparison of different material segments at same levels of qualitative condition showed similar values for the normalized response. This empirical result provides an argument in favour of the normalization by speed. It appears that it is capable of returning a response able to represent levels of condition (Figure 19).

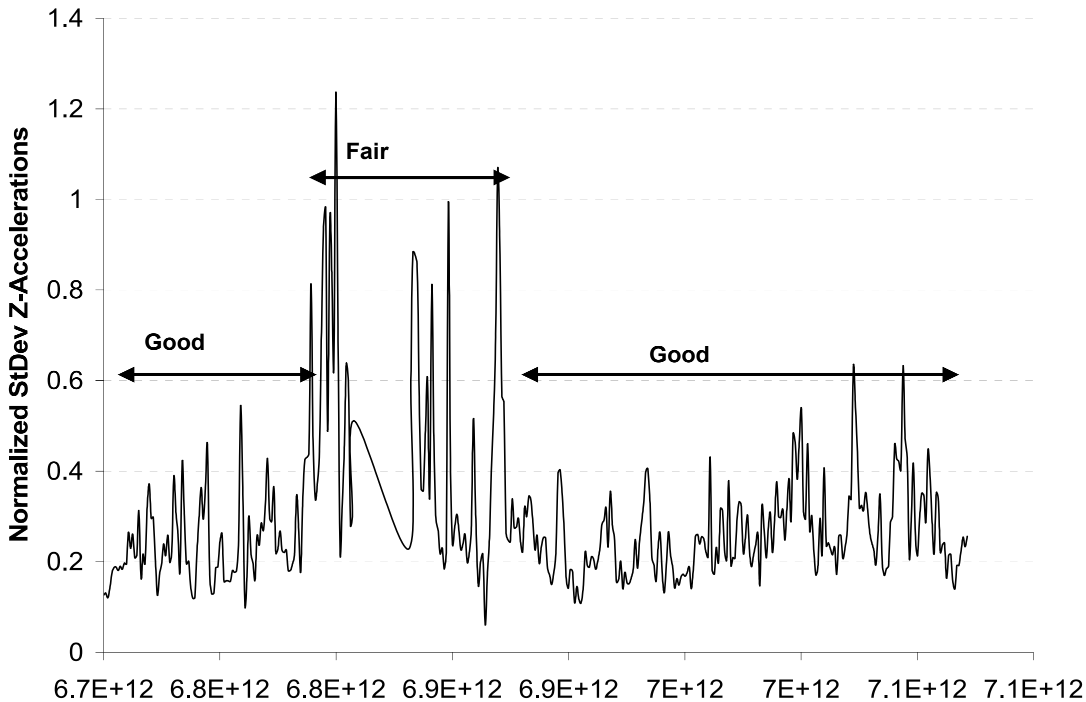

Figure 19: Asphalt Good-Fair condition

3.2.5 Comparison of Applications and Devices Used for Data Collection

A test of equivalency was made between the iOS's platform application *SensorLog* (compatible to *IPhone 4S*) and Android's platform application *Physics Toolbox Accelerometer* (compatible to *Samsung Galaxy S4 mini*). The road segment length was 275 meter and it was traversed two times in the same day. Each time for one device. Each device was placed horizontally on the dashpool of the car which was a *2011 Toyota Corolla*. The profiles of accelerations (speed-normalized standard deviations) are shown in Figure 20.

The *SensorLog* application measures accelerations in terms of gravity acceleration (G) that is as a percentage of $9.81 m/s^2$ (Thomas, 2013); therefore, it was required to multiply the acceleration readings by $9.81\ m/s^2$. The *SensorLog* application collects 10 observations per second while the *Physics Toolbox Accelerometer* collects 15 observations per second. As shown in Figure 20, the observations are close to each other.

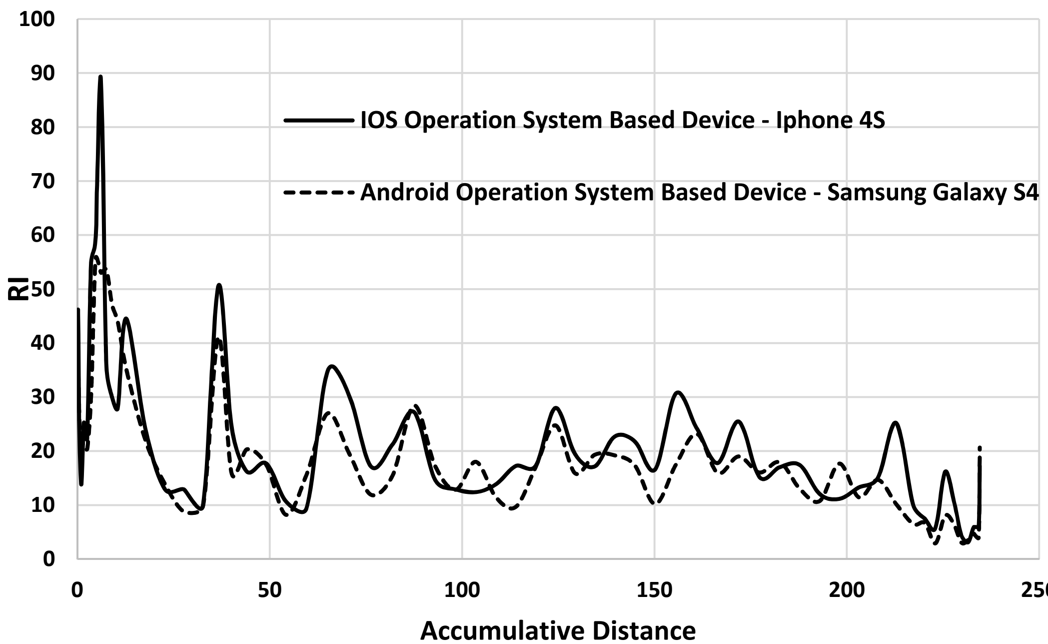

Figure 20: Comparison of observations – Iphone (SensorLog) vs Samsung (Physics Toolbox Accelerometer)

The differences between the applications observations could be explained by the slight difference in the sensitivity of the accelerometers built in the devices, by the difference in number of observations per second collected by each application as well as different wheelpath traversed during the trips, because in reality there are no two trips run over the same wheel path.

3.2.6 Comparison of Vehicles Sizes

Another experiment made to compare the acceleration readings collected by the same device and mounted on different vehicles. The experiment made by visiting the same road section in the same day, utilizing 3 vehicles of various sizes, namely a 45 passenger bus, a 12 passenger bus, two axle truck and a car.

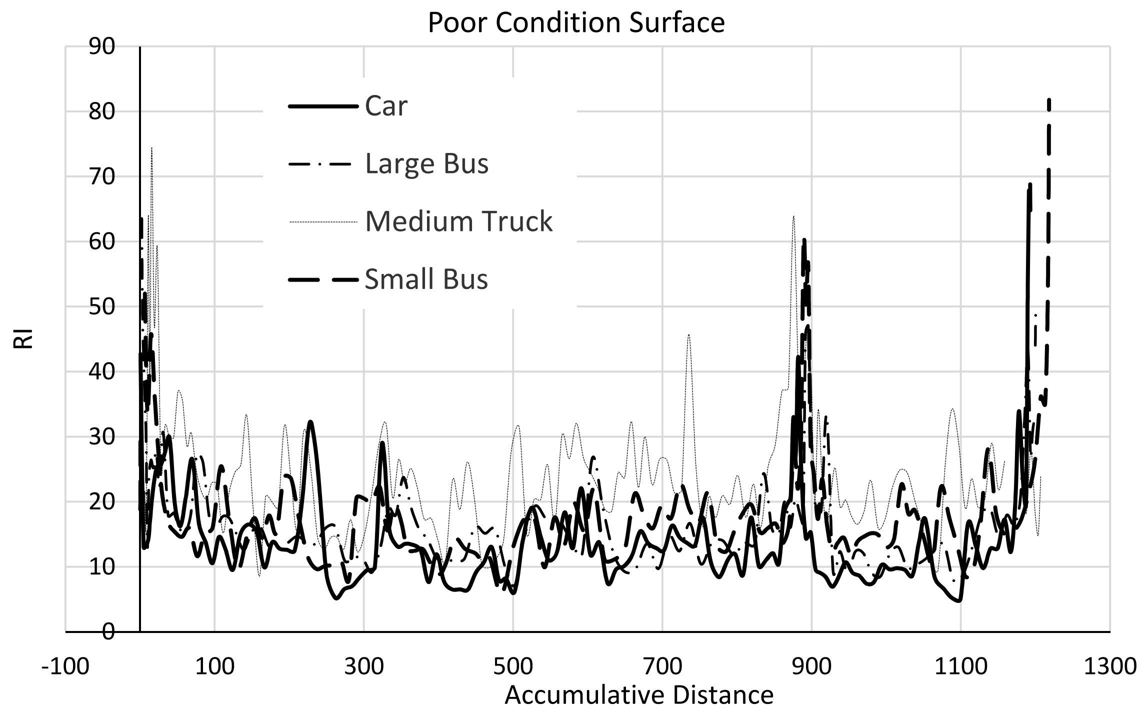

Figure 21: Comparison of RI – segment in poor condition - various vehicles

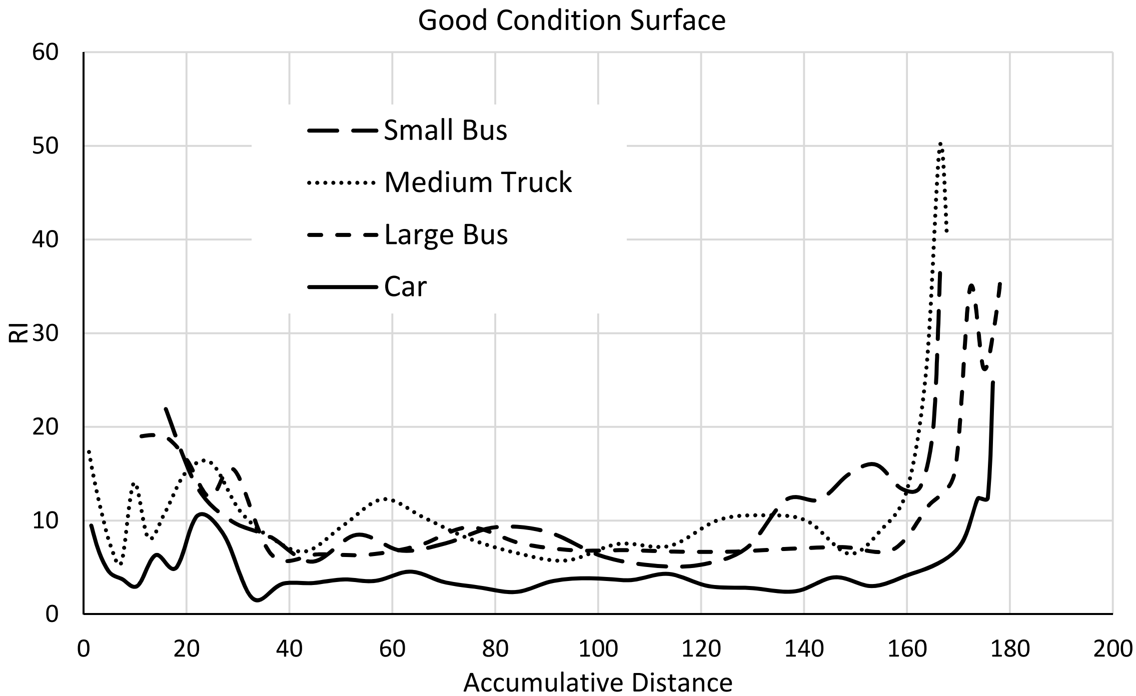

Figure 22: Comparison of RI – segment in good condition – various vehicles

Vehicle size do make a difference (especially for trucks) as seen on Figures 21 and 22. It was also confirmed that initial and final observations are highly affected by the influence of y-acceleration resulting from brake/acceleration from/to rest effects; therefore they must be removed. At station 0+900 in Figure 21 there was a portion of heavily deteriorated unpaved road which induced large vertical movements on the vehicles.

3.2.7 Comparison of Sensor Locations

Finally, a test was made to examine the impact of device location, inside the vehicle, on the roughness indicator. In this test, a road segment was visited three times on the same day using the same vehicle but the *IPhone* was placed at different location every time. As seen in Figure 23, it was found that the location of the instrument within the vehicle has ignorable impact on the observed vertical accelerations.

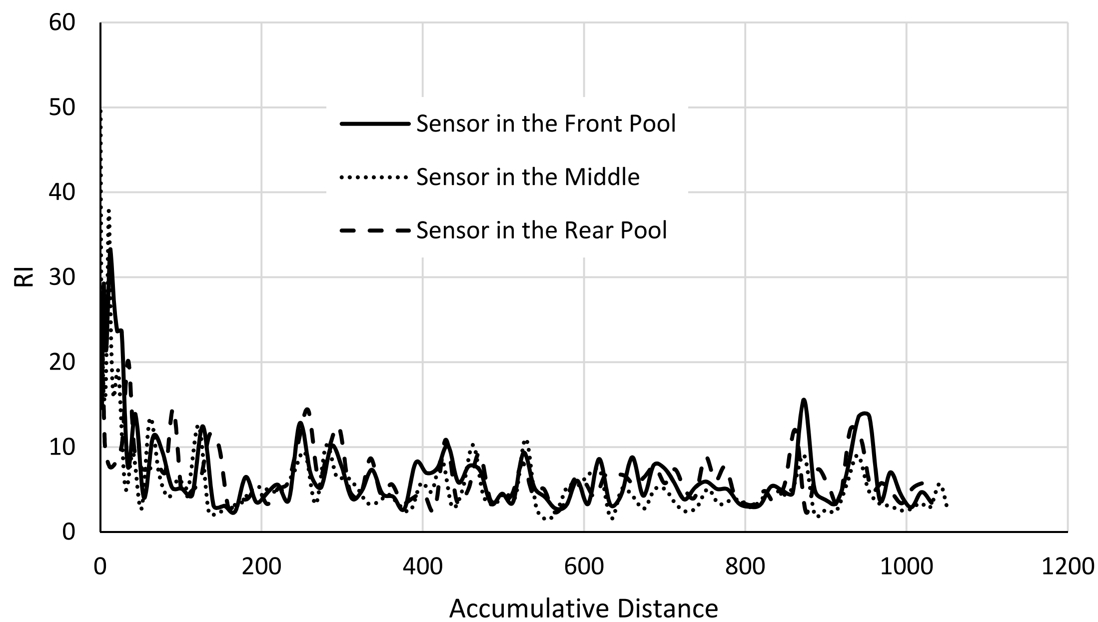

Figure 23: Comparison of RI – same vehicle - same sensor at different locations

3.3 Database Preparation

The condition data collected from site, in the previous step, need to be prepared prior to its use for developing a pavement management system. Preparing the database encompasses several steps including extraction of the required data from the accelerometer records, processing them and joining them (in decimal degrees WGS84) with a blank base map (in NAD1983 CSRS). The idea of preparation phase was to obtain the average condition for road segments of 25meters. The complete steps of database preparation are listed below and they correspond to the case study presented in the next chapter. Also, Figure 25 illustrates the flow chart of these steps:

1. Point condition data in comma separated vector format (csv) collected from site was processed to retain the location, speed and vertical accelerations.
2. The processed condition data was imported into ARCMAP and plotted with same spatial reference. Each road was represented in dot format, (Figure 24).
3. The dots of each road were merged into one line. The result was linearly referenced condition map.
4. Each road of Saint-Michelle road network was divided to segments of 25 meters.
5. Quebec roads network was imported into *ARCGIS*. This file is in GSC North American 1983 CSRS in decimal degrees
6. Only Saint-Michelle road network was emphasized.
7. The linearly referenced map (the 25 meters segmented map) was joined with Quebec roads network by spatial proximity, road by road.

8. The RI (IRI proxy) was calculated for each segment (average value of vertical accelerations normalized by speed and multiplied by 100.
9. Using Paterson performance model and the RI(s), the apparent age of each road segment was calculated.
10. The final map contained database included condition data, segment length, apparent ages and four attributes, namely, type of asset, functional classification, type of surface and last type of intervention applied. The final map was saved as shape file and it was the primary input for the long-term planning and optimization software (*REMSOFT*).

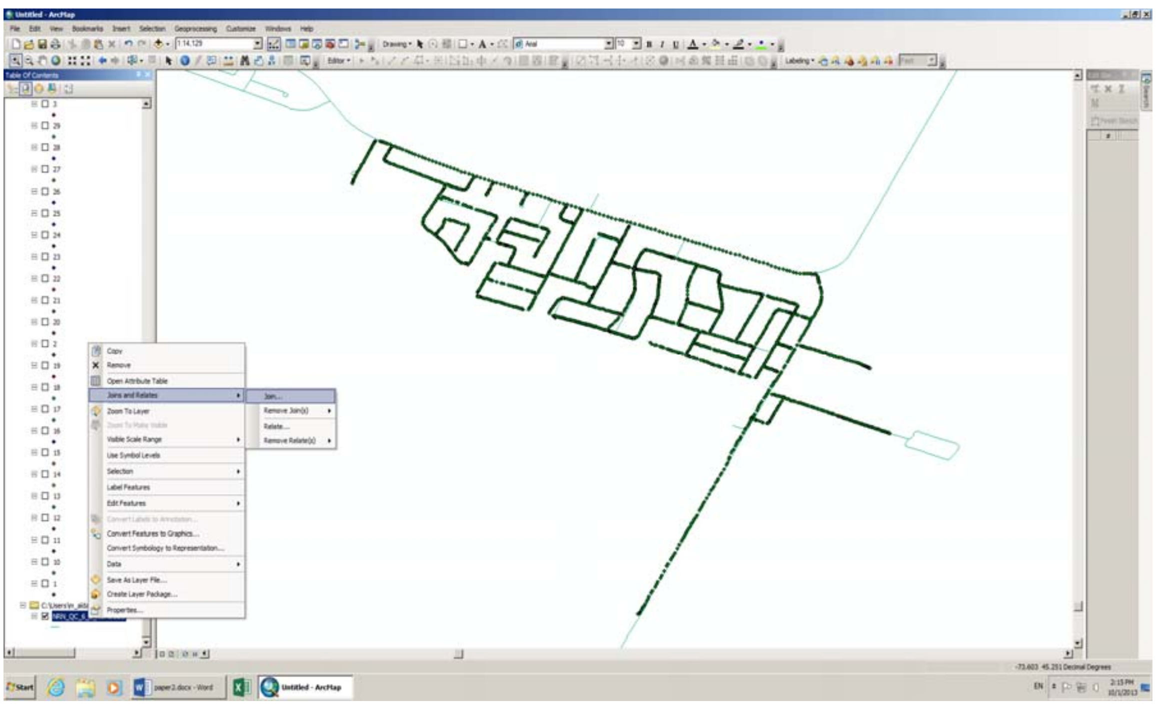

Figure 24: Point condition data-*ARCGIS*

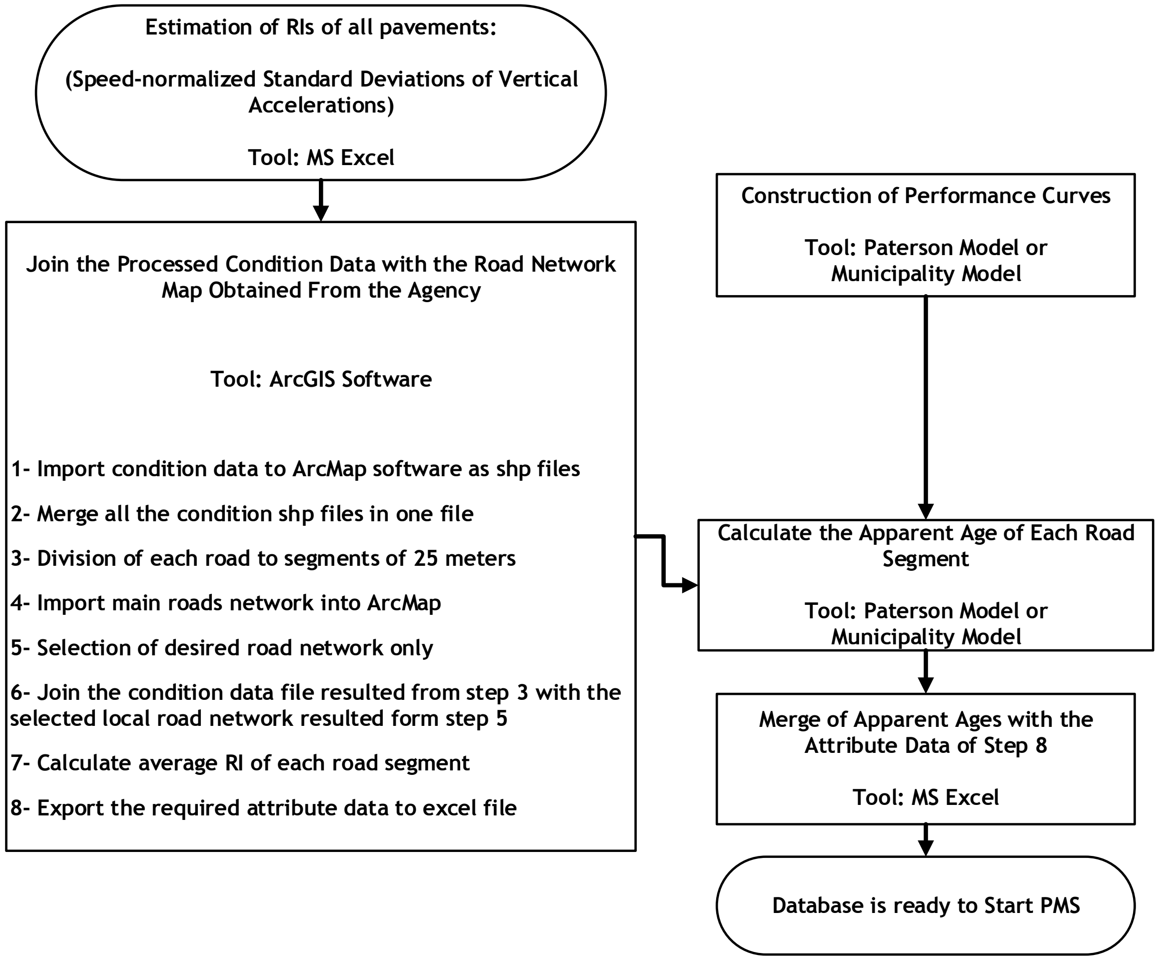

Figure 25: Database preparation flow chart

CHAPTER 4

CASE STUDY: TOWN OF SAINT-MICHELLE

4.1 Introduction

This case study focuses on the development of initial pavement management system (PMS) for the town of Saint Michelle, Quebec, Canada using low cost solution. Figures 26 and 27 shows town location and road network image taken by satellite, respectively. The case study presents a novel methodology to estimate initial road surface condition in a situation where limited budget impedes the purchase of traditional condition measurement equipment such as Falling Weight Deflectometers (FWD) or Profilometers to estimate International Roughness Index, which are over $125,000 in cost each. This initial condition estimation was used to demonstrate the possibility to run a budget exercise capable of determining long term funding needs for the allocation for maintenance and rehabilitation of the municipal road's pavement.

Good quality data for performance modeling is always the biggest challenge in the implementations of initial pavement management systems that are capable of optimization and trade-off analyses; a spatial database containing line shapefiles for the road network of the town of Saint Michelle was assigned with condition data estimated using a vertical accelerometer. Performance model was calibrated to indicate pavement condition across time. Investment decisions such as what budget strategy would sustain the asset value in the long run were performed. This decision making process required, as mentioned, the ability to predict future asset conditions under each such investment strategy. All these matters are explained in detail in this case study. Figure 28 shows flow chart of the main work stages of the case study.

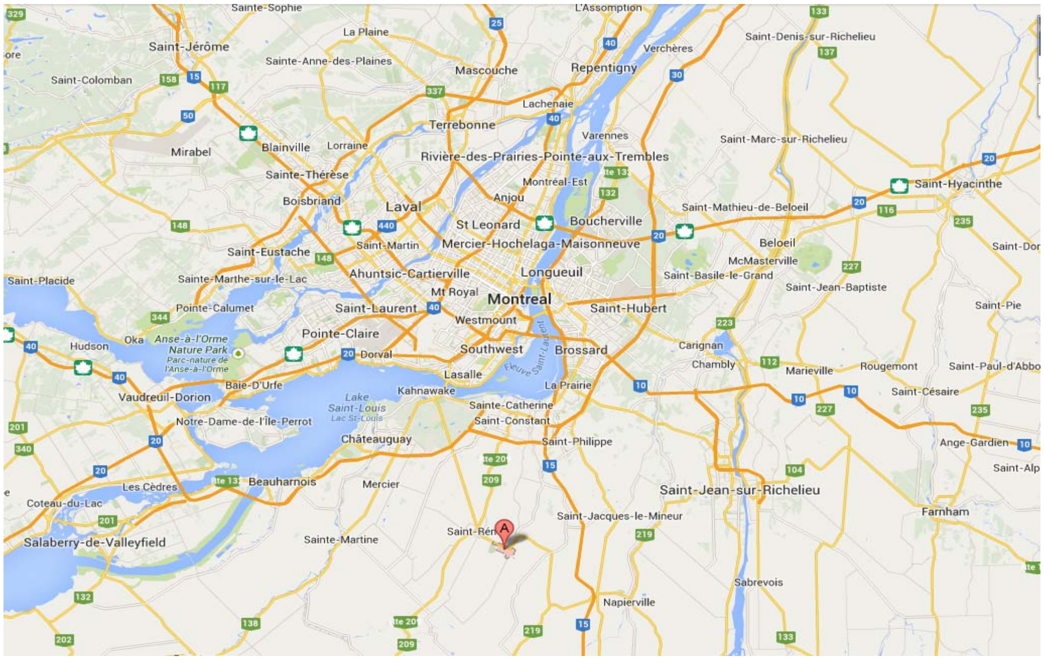

Figure 26: Location of Saint-Michelle city (Google Maps)

Figure 27: Saint-Michelle city (Google Maps)

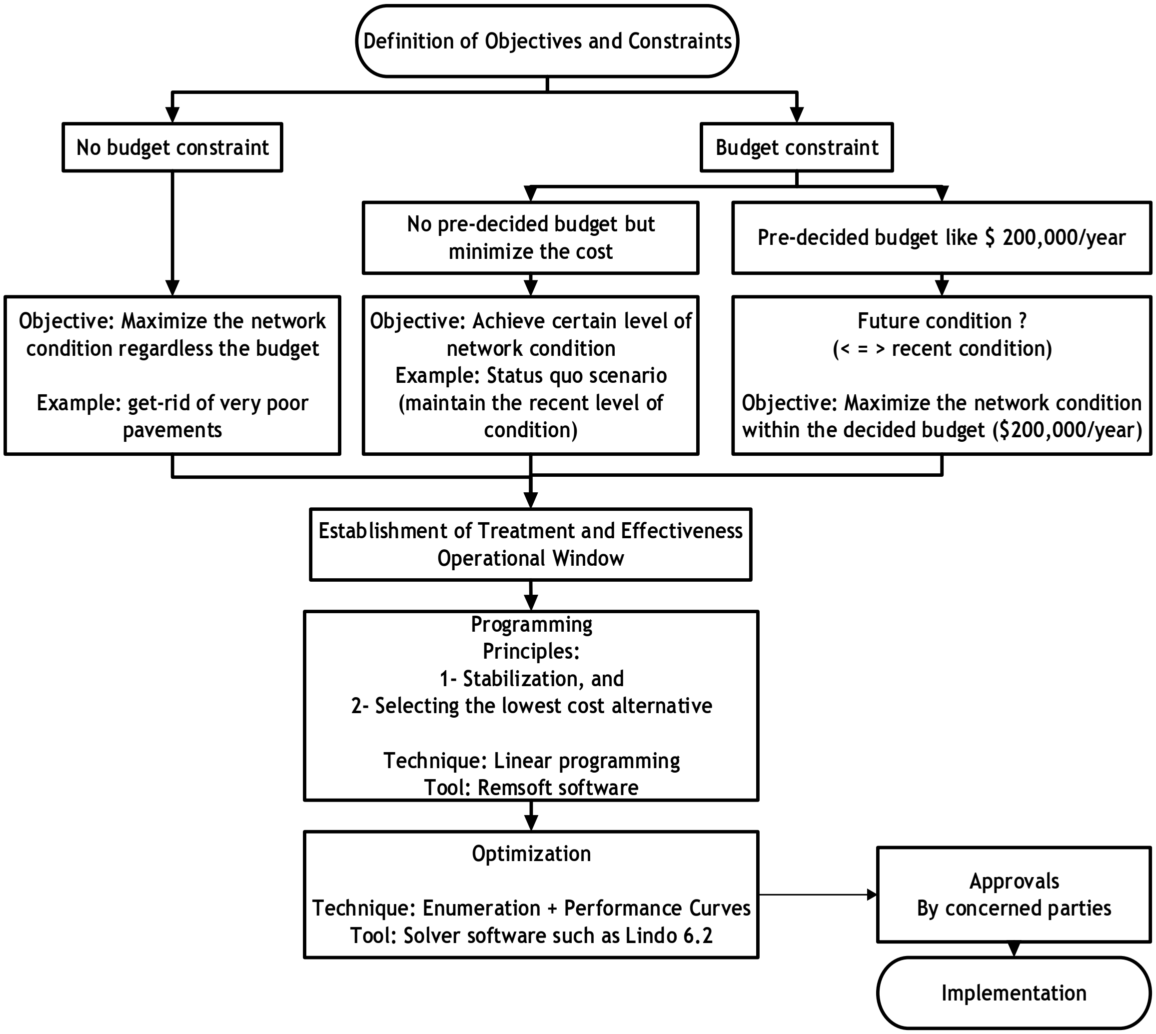

Figure 28: Case study main work stages

4.2 Construction of Saint Michelle Road Spatial Database

The first challenge was to integrate information obtained from two sources, and collected over different spatial location systems. The first set of information were surface condition data of 52 roads forms the road network of Saint-Michelle city. This information were spatially referenced roughness data in point format and were collected by driving the whole road network of the city. This condition data have been integrated with a blank base map in line format of the same city obtained from GeoBase (GeoBase, 2013).

The method used for constructing Saint Michelle road database is indicated in the following steps and the flow chart of Figure 29:

1. Point condition data in comma separated vector format (csv) collected from site was processed to retain the location, speed and vertical accelerations.
2. The processed condition data was imported into ARCMAP and plotted with same spatial reference. Each road was represented in dot format, (Figure 24).
3. The dots of each road were merged into one line. The result was linearly referenced condition map.
4. Each road of Saint-Michelle road network was divided to segments of 25 meters.
5. Quebec roads network was imported into *ARCGIS*. This file is in GSC North American 1983 CSRS in decimal degrees
6. Only Saint-Michelle road network was emphasized.
7. The linearly referenced map (the 25 meters segmented map) was joined with Quebec roads network by spatial proximity, road by road.

8. The RI (IRI proxy) was calculated for each segment (average value of vertical accelerations normalized by speed and multiplied by 100.
9. Using Paterson performance model and the RI(s), the apparent age of each road segment was calculated.
10. The final map contained database included condition data, segment length, apparent ages and four attributes, namely, type of asset, functional classification, type of surface and last type of intervention applied. The final map was saved as shape file and it was the primary input for the long-term planning and optimization software (*REMSOFT*).

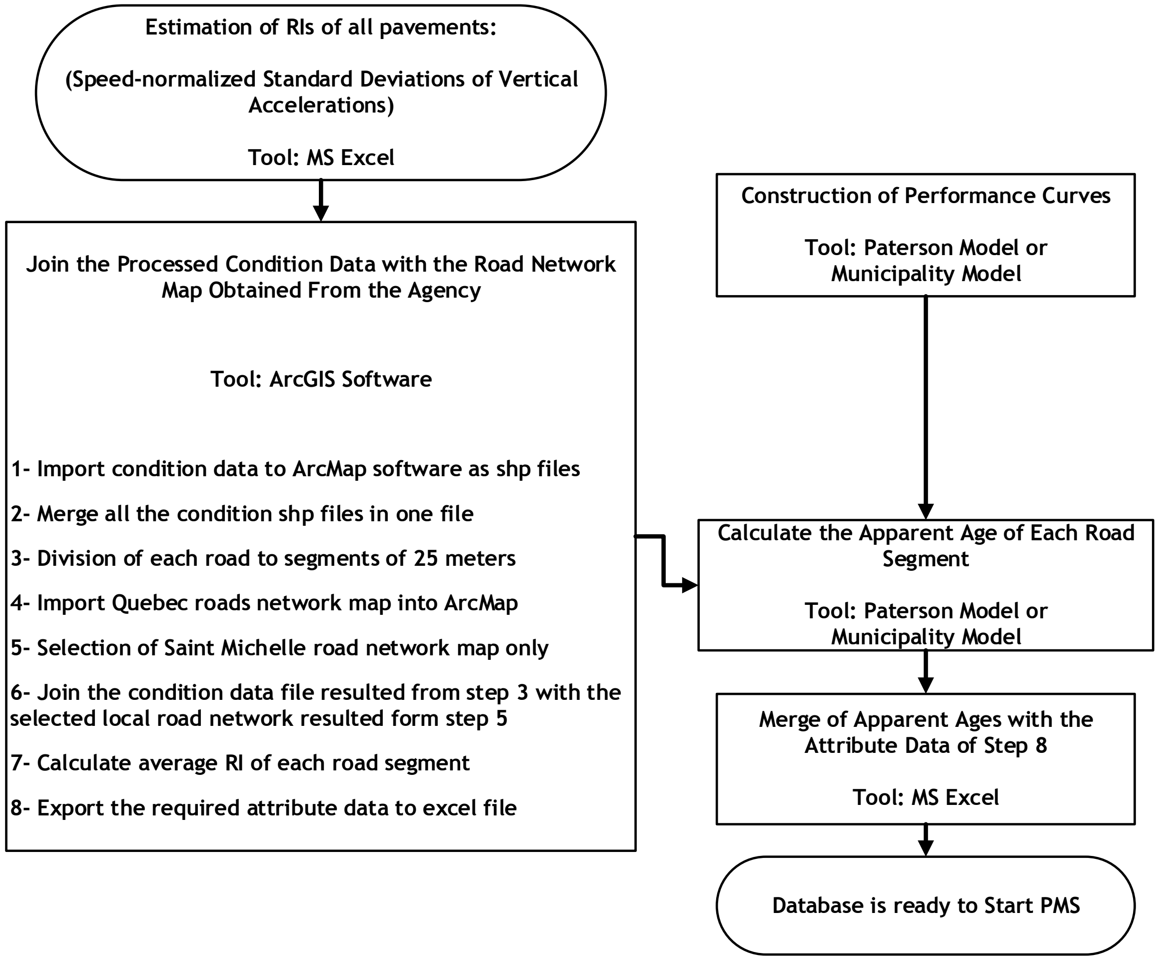

Figure 29: Constructing Saint Michelle road network database – flow chart

4.3 Construction of Performance Curves

Strategic and long-term planning for sustainable civil infrastructure, including pavements and other transportation systems, relies on performance prediction models. Effective prediction of pavement performance requires adoption of the major causal contributors to pavement deterioration which can realistically be included in the performance model. Traffic load intensity has been recognized as the most significant factor affecting pavements deterioration (Pedigo, et al., 1981). Also, the decision of which causal variable to include was driven by the availability of data. Therefore, in this case study, traffic loading was used as the primary causal factor in the performance model.

Obtaining the traffic load (ESALs) across the whole city network was limited. The two main routes; 221 and *rue Principale* were assigned with Annual Average Daily Traffic (AADT) values by Transports Qubec (TransportsQuebec, 2013) Figure 30. The rest of the network, which are local roads, was assumed to be exposed to 35,000 ESALs over its design life. This assumption complies with one of the methods proposed by Patterson and Attoh-Okine back in 1992. A standard truck factor of 2.0 was assumed and percentage of trucks was set to 10% for the sake of this academic exercise. Traffic counts should be conducted in order to obtain a better estimate of AADT and truck percentage.

Transports Québec

Figure 30: Annual Average Daily Traffic (AADT) (TransportsQuebec, 2013)

Other factors related to pavement structure such as layers thicknesses, material types and soil strength were not available. Therefore, they were assumed to match design code requirements.

Saint-Michelle road pavements were separated into three performance groups depending on the traffic volumes they are exposed to. Each group was assigned different performance curve as shown in Figure 31. These performance curves were based on a calibrated version of modified IRI progression model developed by Paterson and Okine in 1992 (Paterson & Attoh-Okine, 1992) to match observed levels of roughness index which varied from almost 0.4 to levels of about 160. The first performance curve was done for *Rue Principale* as data for AADT levels is available (157,000 ESALs per year), m factor for environment was set to 0.07 (Natural Resources Canada, 2013), traffic growth to 1%

(Statistics Canada, 2013) and thickness of pavement layers to 75mm of hot mixed asphalt and 100mm of granular base and 150 of granular sub-base with structural coefficients of 0.22, 0.09 and 0.065 correspondingly. The second performance curve was done for the route 221 with 350,000 ESALs per year, m equals 0.07 (Natural Resources Canada, 2013), traffic growth to 1.5% (Statistics Canada, 2013) and thickness of pavement layers to 75mm of hot mixed asphalt and 150mm of granular base and 150 of granular sub-base with structural coefficients of 0.22, 0.09 and 0.065 correspondingly. The third performance curve was done for the local roads utilizing the same method with different coefficients.

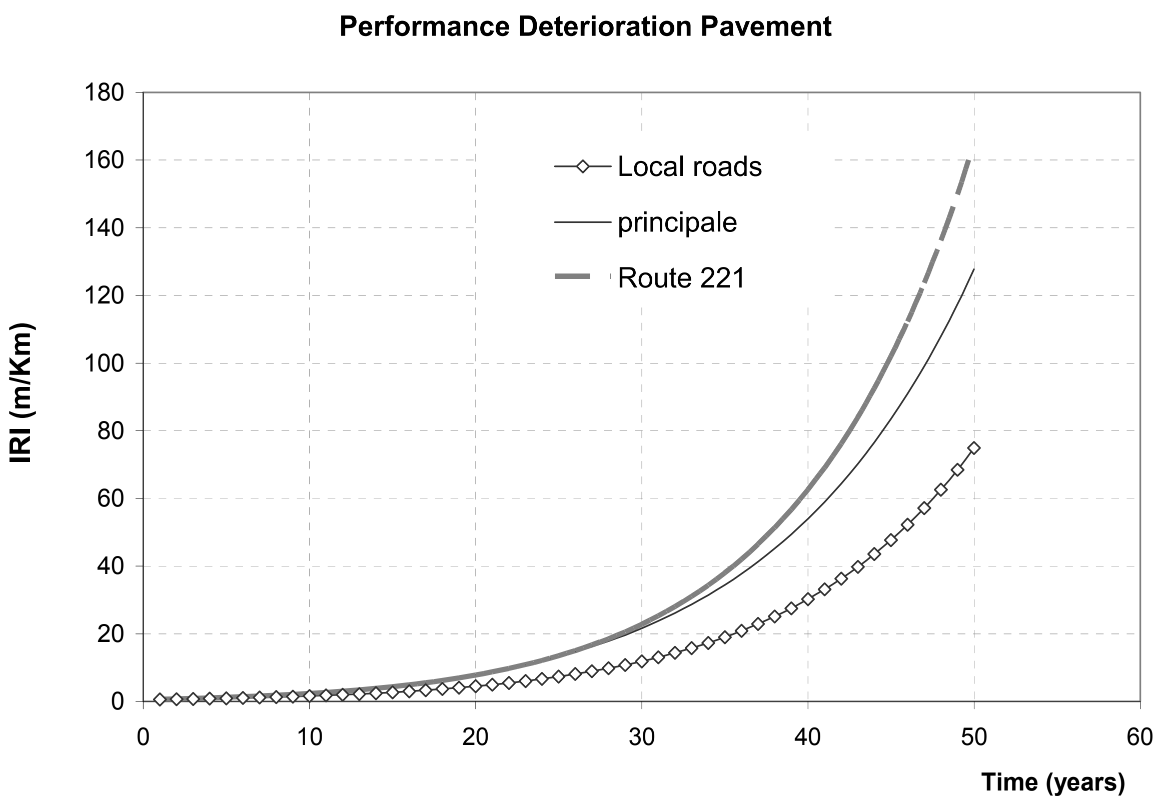

Figure 31: Pavement performance deterioration

4.4 Estimation of Intervention Treatment Type and Effectiveness

Four types of treatments were used in this model: cracksealing, microsurfacing, resurfacing and reconstruction, corresponding to preservation, minor rehabilitation, major rehabilitation and reconstruction for irreparable roads on the basis of one treatment per interval of condition. Table 3 shows the cost, range of application and effectiveness of these treatments.

Table 3: Interventions used in the analysis

Treatment Type	Cost	Operational Window		Treatment Effectiveness
		Lower Boundary	Upper Boundary	
Cracksealing	0.33 $/m2	RI =< 3		3 years
Microsurfacing	6.74 $/m2	RI > 3	RI =< 6	8 years
Resurfacing	25 $/m2	RI > 6	RI =< 12	12 years
Reconstruction	42 $/m2	RI > 12		As new

4.5 Investment Strategies: allocation of funds and scheduling of levels of intervention per year

Linear programming optimization was used to select the optimal combination of interventions across time such that a given objective function is optimized and constraints are met. The optimization procedure is performed iteratively to determine benefits associated with each treatment, on each road element and different time (or condition) states. The optimized schedule of works can be selected to maximize the return on investment, while maintaining roads at an appropriate service level and considering other constraints, such as budgets, limiting available equipment, pre-committed projects, etc. The software used in running the linear programming in this case study was *REMSOFT*, a long-term planning and optimization software. In practice, optimization of practical problems can only be carried out using advanced software – the so-called solvers, e.g., *LPABO, LINDO, MOSEK, CPLEX,* etc.

Tradeoff analysis is a complex process that tries to answer: what asset type, what segment, what treatment should be applied and when should the road be treated over the planning horizon so as to meet a given agency's objective. This is done in order to compare benefits, costs or both and determine the most effective set of strategies. Long term investment planning (LTIP) in asset management requires trade-off of investment strategies across variety of asset types such as bridges versus pavements, etc. The trade-off analysis is applied to the outputs from the optimization process to select the treatment combination (i.e., investment strategy) that will maximize the objective function. Objective functions can include minimizing the cost to maintain a given road condition, maximizing average road condition or road value over the analysis period, etc.

Deterioration curves are used to determine the optimal time to apply treatments to roads as well as their condition after treatment application. The output from the tool is an investment strategy that can be visualized through the map or presented as detailed tabular reports or graphs.

Two investment strategies were analyzed. The first investment strategy evaluated is a scenario called *status quo*. It is used to determine mean levels of budget required to sustain current levels of condition across time. The second scenario looks at an optimization that maximizes condition while restricted by budgets evolved from the budget level obtained from the preceding scenario (*status quo*).

4.6 Optimization and Trade-off Analysis Results

A *status quo* scenario identified the need to allocate about $254,000 per year (ignoring the final 5 years of Table 4 since scheduling of interventions falls to almost none) just to be able to sustain current levels of condition.

It can be seen that allocation of interventions focuses on reconstructions and major rehabilitations, following a somewhat "worst-first" approach. Even after following such worst-first approach, still a group of segments in very poor condition remains with some 3456 (about 12%) linear meters of roads (Table 5).

Table 4: Annual resource allocation per intervention type

Period	Cost of Preservation	Cost of Rehabilitations	Cost of Rehabilitations	Cost of Reconstruction	Total Cost
1	692.48	0	421,534	0	422,226
2	2,489	0	131,819	306,579	440,887
3	0	0	232,674	387,127	619,801
4	0	0	202,921	243,368	446,289
5	0	0	197,379	222,626	420,005
6	0	0	186,902	179,083	365,985
7	0	0	141,884	176,505	318,389
8	0	0	94,053	172,330	266,383
9	0	0	0	171,038	171,038
10	0	0	0	67,011	67,011
11	0	0	0	80,154	80,154
12	1,901	0	0	69,624	71,525
13	2,400	0	0	55,321	57,721
14	1,509	0	0	47,598	49,107
15	1,380	0	0	18,366	19,746
16	1,110	0	0	0	1,110
17	1,094	0	0	0	1,094
18	1,069	0	0	28.86	1,098
19	1,061	0	0	0	1,061
20	415.52	0	0	0	416
				Average	254,418

Table 5: Split of roads by condition group (in linear meters)

Period	Very Poor Condition	Poor Condition	Fair Condition	Good Condition
0	3,581	4,659	6,543	3,300
1	4,117	3,828	5,242	4,897
2	4,839	2,768	3,483	6,993
3	5,571	1,234	2,623	8,655
4	5,692	765.69	1,613	10,013
5	5,318	621.86	990.95	11,153
6	4,988	396.52	526.41	12,173
7	4,662	399.21	0	13,022
8	4,344	52.05	0	13,688
9	4,028	52.05	0	14,003
10	3,905	52.05	0	14,127
11	3,757	52.05	0	14,275
12	3,628	52.05	0	14,403
13	3,578	0	0	14,505
14	3,490	0	0	14,593
15	3,456	0	0	14,627
16	3,456	0	0	14,627
17	3,456	0	0	14,627
18	3,456	0	0	14,627
19	3,456	0	0	14,627
20	3,456	0	0	14,627

The second scenario (maximization scenario) was intended to get-rid of very poor roads and overall increase levels of condition across the network. A first attempt was done with a $200,000 dollar per year just to find that levels of condition dropped as it was below minimum required to sustain them obtained from the *status quo* scenario which is $254,418 dollar per year. A second attempt with $275,000 dollar per year showed sustain improvement across time, however, incapable of fully eliminating very poor roads in twenty years. Therefore, budget was raised to $350,000 per year. This latter level of budget did resulted in full elimination of very poor roads as shown on Figure 32.

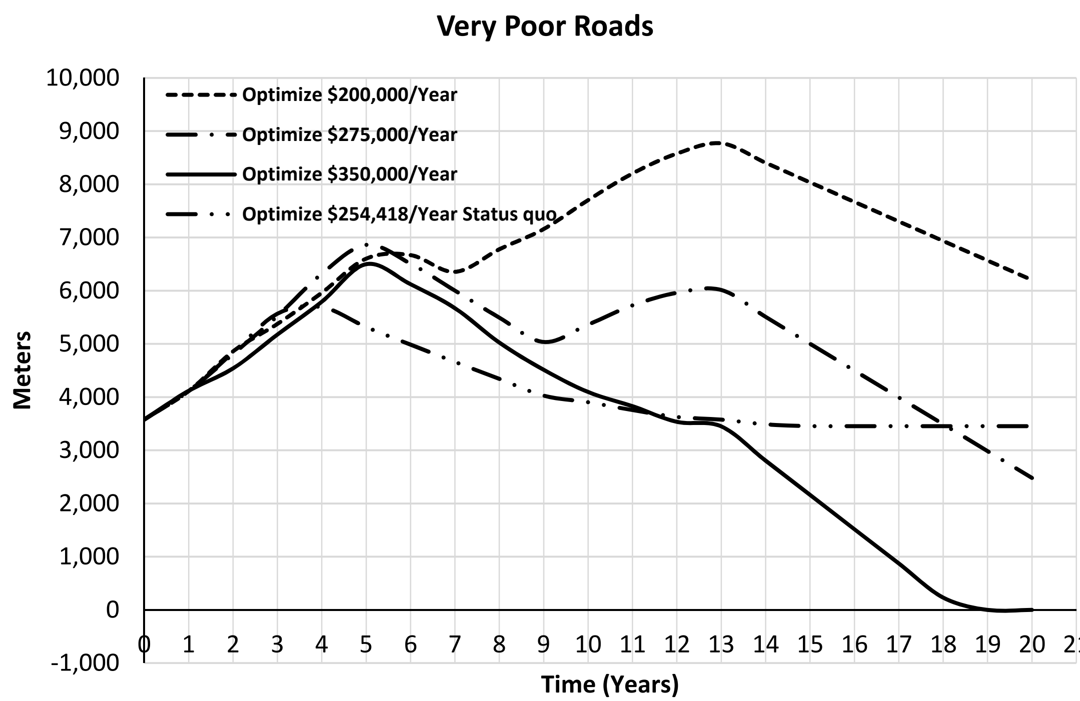

Figure 32: Progression of very poor roads across time

It is also quite interesting to note how at the beginning all segments in fair condition are upgraded to good condition which requires a less onerous expenditure than reconstruction broken roads, once this is achieved some money is spend to make sure good remain good and the vast majority of the budget is used to move poor and very poor into good, this stage is typically called stabilization (Amador & Mrawira, 2009). Figure 33.

This also resulted in faster achievement of a network with overall good levels which resulted in a drastical drop of required budget after year 19. This as much of the interventions required from such a year and on are minor in nature, releasing funds to other activities. This is crucial because it means the ability of the system not only to achieve its goal (to maximize condition) but also to reduce financial requirements as preventive maintenance is cheaper than any other intervention.

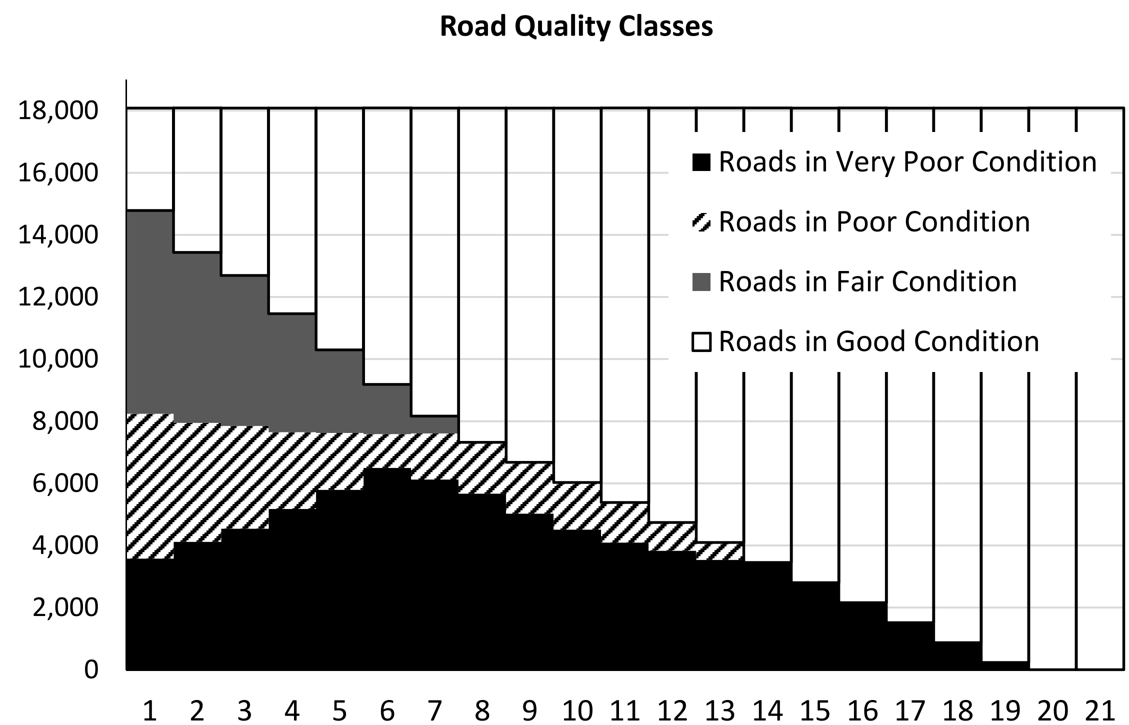

Figure 33: Progression of condition groups across time ($350,000)

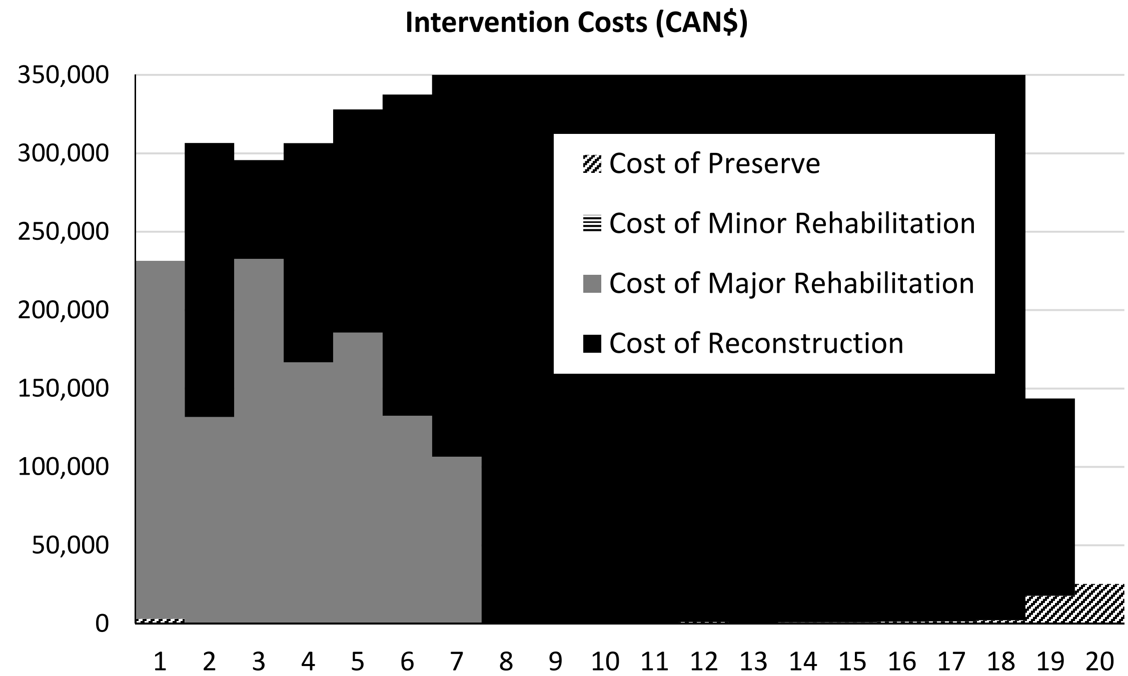

Figure 34: Annual intervention cost ($350,000)

However, Amador and Afghari (2012) also notice a boundary effect that impedes the solver to realize of the impact of the decisions on the long term when there is no long term, this has been also found in economics of overlapping generations. Therefore results from two years before the end of the 20 year period can be seen as a 2 year optimization and those of the final year as isolated annual optimization. A somewhat lazy allocation of treatments can be observed at the beginning, no explanation can be provided on this regard.

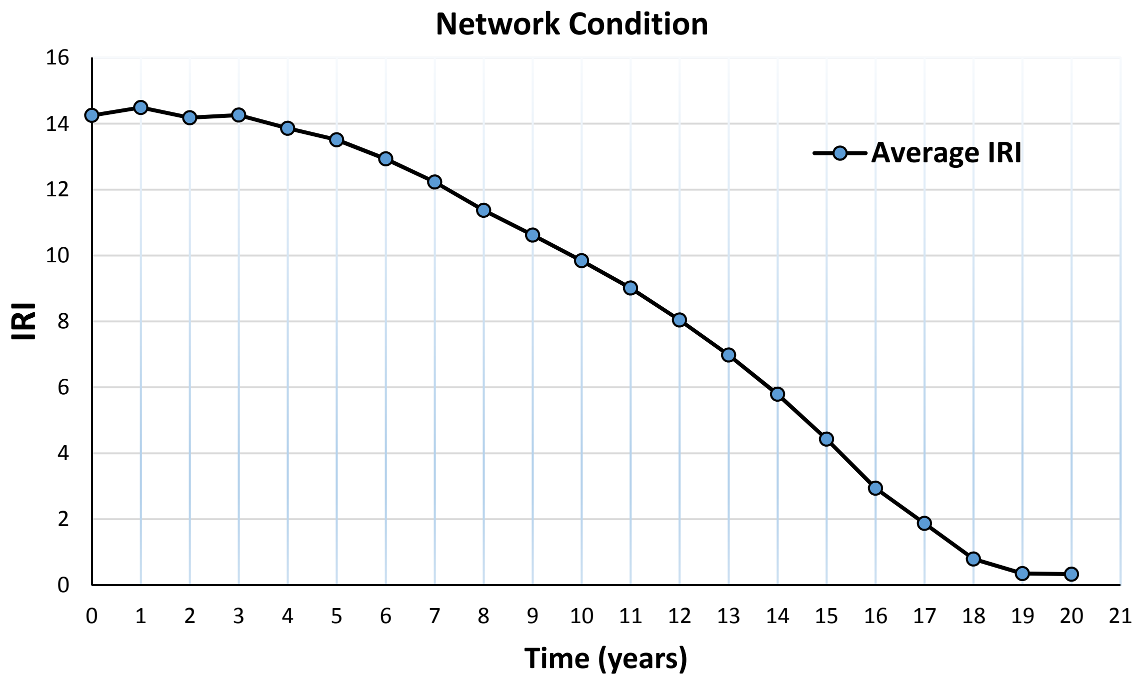

Figure 35: Time progression of mean network condition ($350,000)

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This thesis presents a low cost method to measure pavement surface condition based on roughness and utilize it in developing initial pavement management system. In particular it shows the capability of using the accelerometer built in a tablet or smart phone to capture surface vertical irregularities and condense them into an indicator of condition. This indicator was utilized in the development of initial pavement management system.

This method is expected to help municipalities and governments in developing countries which lack financial resources to purchase expensive equipment to quickly assess the condition of their network and implement a pavement management system. This system is capable of allocating resources in a way that condition across the network is sustained at good levels and public funds are invested in a cost-effective manner. It does so by looking at the impact of long term strategies of sustain funding and their use on preservation, minor and major rehabilitation interventions.

A case study of a small municipality (the city of Saint Michelle in the suburb of Montreal, Quebec) was used to demonstrate how this condition indicator which is resulted from the low-cost road surface condition measurement paved the way for the implementation on an initial pavement management system. Performance curves were produced on the basis of expert criteria and empirical method used by the World Bank (Paterson & Attoh-Okine, 1992)(Watanatada, et al., 1987). A decision making system was used to find out required levels of annual funding to sustain good levels of condition across time.

A fully optimized investment strategy based on network-wide average roughness index was able to restore the whole network in good condition (IRI lesser than 1.8) after 18 years and also eliminate very poor, poor and fair roads. These findings are consistent to many studies (Abaza, et al., 2004) (Abaza, 2006) on pavement preservation best practice – demonstrating that spending money on the good roads first ("keep good roads good") is the most efficient way of managing roads.

In numbers' language, the investment scenarios showed the need to have at least $254,418 per year to sustain current levels of condition. A larger budget of $275,000 per year was required to achieve improvement. An even larger budget of about $350,000 per year was required to recover the entire network and move it into good levels of condition. Moreover, the required levels of funding dropped after year 18, showing that only preservation and minor rehabilitation activities, which are much cheaper than major rehabilitation and reconstruction, were required.

The effect of reducing the budget to $275,000 per year on the optimized program of works is that it will take longer time to achieve a network average roughen index of less than 1.8. In this case, it will take more than 20 years, and yet some roads will remain at very poor condition.

5.2 Recommendations

Future research needs to look into filtering algorithms to clean the collected data in order to remove the effect of undesirable features (per instance speed reducer bumps).

Operational windows for treatment application should be matched with local experience; hence, a group of roads already scheduled to receive dissimilar levels of intervention should be visited in order to learn from local circumstances the range of variation in condition to which specific treatments are allocated.

It is also advisable to measure levels of condition after treatment application in order to estimate treatment effectiveness jump. Intervened roads should be visited annually in order to develop a database of after treatment performance. Non-intervened roads should also be visited in order to estimate deterioration rates and develop deterioration models adjusted to local circumstances. Also, traffic loading should be based on traffic counts and weight estimation for the municipal roads.

All this information should be used in order to update and improve the model such that it is truly calibrated to local circumstances. Finally it should not be forgotten the fact that current interventions as applied for certain circumstances does not rule out other applicable treatments as technology evolves that could be more effective, also the quality of local contractors is not necessarily the best. All this can be estimated by measuring the before and after trends at intervened pavements.

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