TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF ABREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
AM	Asphaltic Mix (per HDM-4)
ADB	Asian Development Bank
AfDB	African Development Bank
DCP	Dynamic Cone Penetrometer
ERR	Economic Rate of Return
ESAL	Equivalent Single Axle Load
CAD	Canadian Dollars
CEBTP	Centre Expérimental de Recherches et d'Études du Bâtiments et des Travaux Publics
CGRA	Canadian Good Roads Association
CPI	Consumer Price Index
EU	European Union
FIDIC	Fédération Internationale des Ingénieurs Conseils
FHWA	US Federal Highway Administration
GAO	Government Accountability Office
GDP	Gross Domestic Product
HDM III	Highway Development Model, 3rd version
HDM-4	Highway Development Model, 4th version
HMA	Hot Mix Asphalt

IID	Inspection in Depth
IMF	International Monetary Fund
IRI	International Roughness Index
LEF	Load Equivalency Factor
LTPP	Long Term Pavement Performance Program
MEPDG	Mechanical-Empirical Design Guide
PCI	Pavement Condition Index
PCSE	Passenger Car Space Equivalent
PDIA	Problem Driven Iterative Adaptation
PIARC	Permanent International Association Road Congresses
PMS	Pavement Management System
PSI	Present Serviceability Index
QA/QC	Quality Assurance/Quality Control
MCA	Millennium Challenge Account
MCC	Millennium Challenge Corporation
MDG	Millennium Development Goals
MEPDG	Mechanistic Empirical Pavement Design Guide
M&R	Maintenance and Rehabilitation
NET	Net Aid Transfers
NPV	Net Present Value
NLPPP	Network Level Project Prioritization Phase
ODA	Overseas Development Assistance
RUE	Road User Effects

RWE	Road Works Effects
SNP	Adjusted Structural Number
SSA	Sub-Saharan Africa
SSATP	Sub-Saharan African Transport Program
ST	Surface Treatment (per HDM-4)
USD	United States Dollars
WB	World Bank
WP	Working Paper
VOC	Vehicle Operating Cost

INTRODUCTION

Road infrastructure is paramount to economic development; the movement of goods and people are a fundamental component of economic growth, with return on investments demonstrating positive returns (Wilson, 2013, Somerville, 2015). Figure 0.1 below shows a recent Canadian economic finding of positive investment returns on GDP and job growth, with varying positive returns to the private sector.

	Discount Rate at:		
	3%	**5%**	**7%**
GDP per $ of Spending			
ROI based on Zero Benefits for Private Sector	1.10	1.10	1.12
ROI based on Half Benefits for Private Sector	2.46	2.28	2.13
ROI based on Full Benefits for Private Sector	3.83	3.46	3.14
Jobs per $ Million of Spending			
ROI based on Zero Benefits for Private Sector	3.0	3.6	4.1
ROI based on Half Benefits for Private Sector	5.0	5.4	5.6
ROI based on Full Benefits for Private Sector	7.1	7.1	7.1

Figure 0.1 Summary of results for public infrastructure spending in Canada in USD$
Taken from Somerville (2015)

The estimated long run effects on GDP by industry are shown in figure 0.2 below, which are positive.

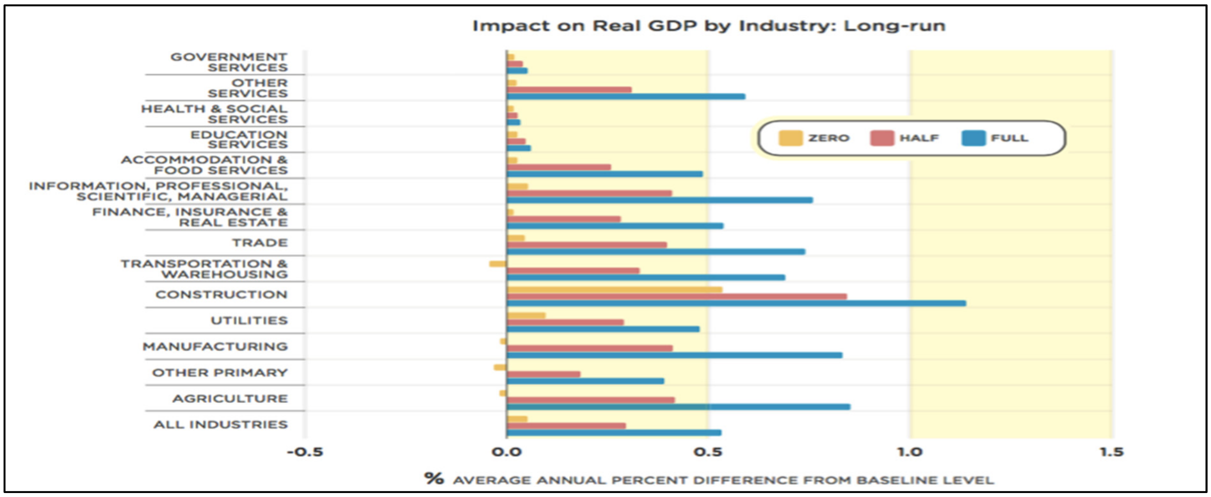

Figure 0.2 Long run Impact on Real GDP by Industry in Percentage (%)
Taken from Somerville (2015)

The primary driver of these investment returns is the multiplier effect generated from the infrastructure investments. Construction spending creates demand for raw materials, labor, supplies, fuel, manufacturing, etc., which in turn has a positive effect on the economy through increased successive spending of the same dollar (the Keynesian multiplier effect). Investment multipliers have been estimated to be around 1 to 3 for the short term and 3 to 7 at least six to eight years out (Wilson, 2013).

The need for road infrastructure in developing countries is large. The World Bank (Calderon and Serven, 2008) estimated the roads infrastructure investments needs for halving the gap in terms of roads quantity in Sub Saharan Africa (SSA) with other comparable countries outside of Africa as a percentage of GDP of over 6%, as shown in figure 0.3 below.

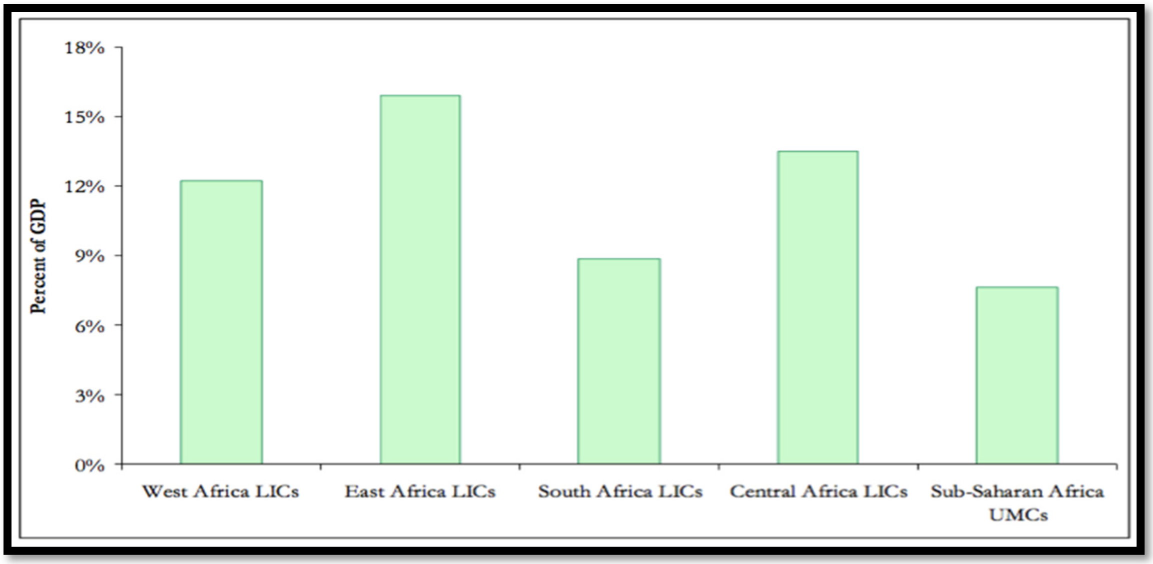

Figure 0.3 Cost of infrastructure catch-up in SSA as a percent of GDP
Taken from Calderon and Serven (2008)

Improving economic growth in poor countries through infrastructure investments is not just an investment in these countries' economic growth, but also an investment in the expanded opportunities of the people that live there. However, recent literature, which does not review MCC investments (Warner, 2014), suggests that large, publicly funded international road infrastructure investments **do not** appear to have delivered these types of results; rather, literature suggests that infrastructure investments *ex ante* socio-economic benefits fail to live up to the *ex post* socio-economic benefits due to misaligned incentives of key project stakeholders, coupled with poor data, non-existent design optimization and careless project-biased economic analysis. The question that arises is: what explains the infrastructure investment performance gap in developing countries relative to findings in developed countries?

The main objective of this research is to document, analyze, and provide a solution to reduce these shortcomings to deliver the benefits of infrastructure investments in developing countries.

The solution developed and validated for the roads sector and logically applicable to other civil infrastructure projects is three-fold**. Part I** of this thesis provides a road investment economic framework encompassing the entire or most of the road network, to select, in fast-track mode, the potentially most cost-effective candidate sections for further project-level assessment. **Part I** rapidly generates the needed potential high-investment return for donor agencies from which to select suitable investments with high economic returns.

Part II of this thesis addresses the project development and implementation cycle for the most cost-effective candidate sections, selected in **Part I. Part II** is focused on optimizing investment costs through the identification of the cause of deterioration for failed pavements in order to select the appropriate maintenance and rehabilitation (M&R) options that will deliver their expected performance at the lowest investment costs. This identification provides a technically sound and optimal engineering solution, as current efforts presently disregard the cause of failure. This is provided in an implementation performance monitoring graphic framework, or itinerary diagram that will simultaneously: 1) streamline donor agency oversight during construction to focus on the core engineering and economic drivers behind the investment; 2) develop the local road agency pavement management system in the collection of the key empirical based pavement design and management metrics to build local engineering know how; and 3) serve as the basis for the post project HDM-4 economic analysis and assumptions to improve donor transparency and accountability, including realistic assessments of maintenance and rehabilitation strategies based on the constructed product. These solutions have been introduced at MCC given the agency's goal to maximize economic returns on its investments, while improving overall quality, accountability and transparency.

Part III of this thesis is focused on developing a Bayesian statistical model that can be integrated into the itinerary diagrams and/or pavement management system to determine the most probable cause of deterioration; this model is meant to be a learning model that integrates other findings from across the network for similar families to help improve the pavement design process in developing countries.

The three parts as a whole were designed in line with each party's (donor and recipient) incentives in mind, while focusing on delivering higher *ex post* economic benefits for road projects in developing countries.

The thesis is organized as described below.

Chapter 1 provides a focused literature review analyzing major critiques of, limitations to and challenges of development assistance in road infrastructure, while delimitating the research scope. The literature review findings are meant to illustrate the entire whole of development assistance, rather than focusing on any one particular agency.

Chapter 2 formulates the objectives, defines the constraints, and establishes the methodology of this research.

Chapter 3 includes the essence of Part I, namely the road investment economic framework, encompassing the entire road network to select, in fast-track mode, the potentially most cost-effective candidate sections for further project level assessment. This chapter concludes with a validation of the system, wherein an MS Excel sheet is developed and tested on network level data from a sub-Saharan African country to select some 350 km of candidate sections with potential for higher investment returns to match an envelope of approximately one hundred million dollars. This innovative approach has been developed in this thesis to help identify more cost-effective road candidate sections for further study, which is consistent with the need to focus on economic evaluation throughout the project lifecycle.

Chapter 4 includes Part II and III by providing a graphical performance management dashboard, or itinerary diagrams, which are intended to help identify the cause of deterioration to deliver the most economically efficient engineering design to maximize economic benefits and also monitor and evaluate construction and post construction activities. This performance management framework is another innovation of this thesis that aims to set a new standard in overall economic evaluation of foreign aid investments to improve transparency and overall quality of these investments. A framework for developing a Bayesian statistical model is presented to complement the itinerary diagrams in the identification of the most probable cause(s) of deterioration as determined from other families of roads on the network, with the objective of improving pavement engineering design techniques in developing countries using an empirical approach.

Chapter 5 shows, using data collected in sub-Saharan Africa, how the concept of a graphical performance management dashboard proposed in Part III is useful to: 1) to determine the cause of any distress that would develop post-construction, and how this platform may be used in conjunction with Part II, and 2) determine the most proximate cause of deterioration during a project assessment phase to begin the design optimization process.

Chapter 6 concludes with a summary of the applicability, usefulness, and promises of these tools with reference to increasing the socio-economic benefits of large road investments, and provides a set of recommendations for future work.

CHAPTER 1

LITERATURE REVIEW, JUSTIFICATION AND SCOPE OF RESEARCH

1.1 Literature review

1.1.1 The promise of economic returns from infrastructure investment

Maximizing economic returns for road investments through improved economic, engineering, and construction information management requires a two-fold description of the problem. This chapter summarizes the literature on the technical and political economy considerations that need to be taken into account to understand the dynamics of road investments in a country-development context.

Since Roosevelt's New Deal, research has established that economic infrastructure such as roads, electricity and water/sanitation, is strongly interconnected with economic growth through activities such as higher employment, better health outcomes (Calderon, 2009, Bhattacharya et al, 2012, Leduc and Wilson, 2013, Inderst and Stewart, 2014), improvement in capital formation, material demand and fabrication, and other supporting services. (Dang and Sui Pheng, 2015).The role of infrastructure construction to the economy has been shown to increase as a country develops, as measured by GNP, but decline in relative terms as the country becomes mature; this is often referred to as the "Bon Curve" as shown in figure 1.1 below.

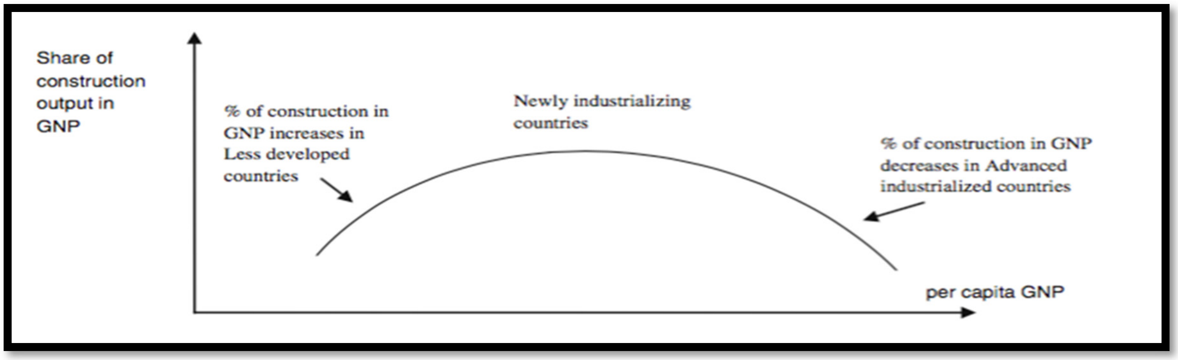

Figure1.1 Bon Curve for Infrastructure Development
Taken from Dang and Sui Pheng (2015)

It is estimated that 3.8% of world GDP has been spent on economic infrastructure, with annual spending trending down in advanced economies (3.6 to 2.8% from 1980 to 2008) and increasing in developing economies (3.5 to 5.7%) as shown in figure 1.2 below.

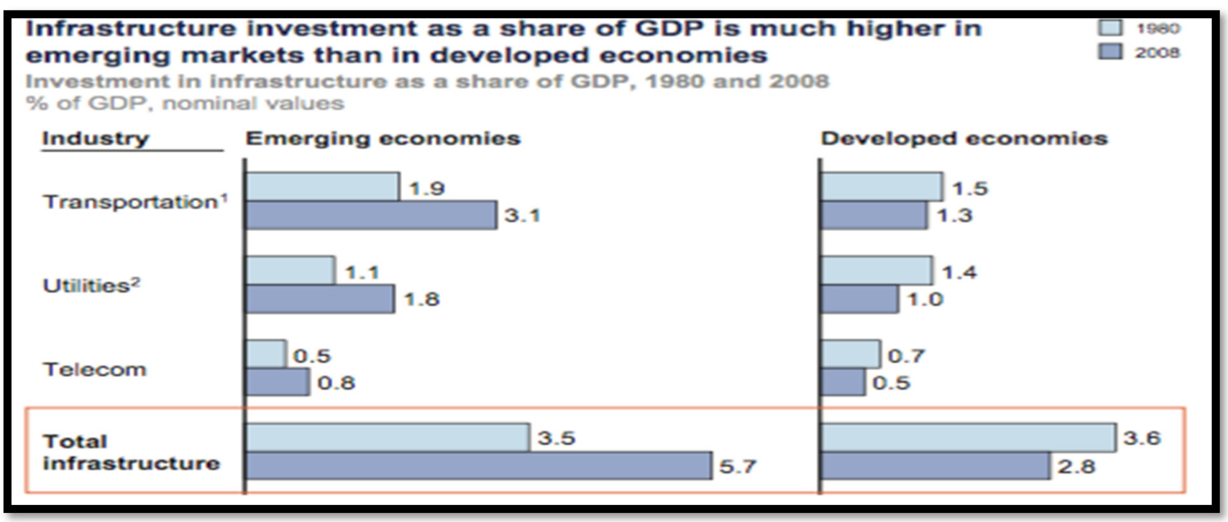

Figure 1.2 Infrastructure Investment as a percentage share of GDP
in Emerging and Developing Economies from 1980 to 2008
Taken from McKinsey (2010)

The estimated infrastructure growth trend in developing economies is 4% of global GDP per annum, or about $3 trillion, until 2030 (Inderst, 2016). Extrapolating from figure 1.3 below, the transport sector will account for between $300 to $600 billion dollars per annum globally with the overwhelming majority going to construction, mostly in East Asia in absolute terms, but relative to its GDP, sub-Saharan Africa will have a substantial share (Inderst and Stewart, 2014). The World Economic Forum, however, estimates that there will be a $1 trillion shortfall in meeting the estimated demand, or about 33% (World Economic Forum, 2014). The most efficient manner of obviating, or at least reducing, this financing shortfall is through increased infrastructure productivity gains, or optimized infrastructure investments.

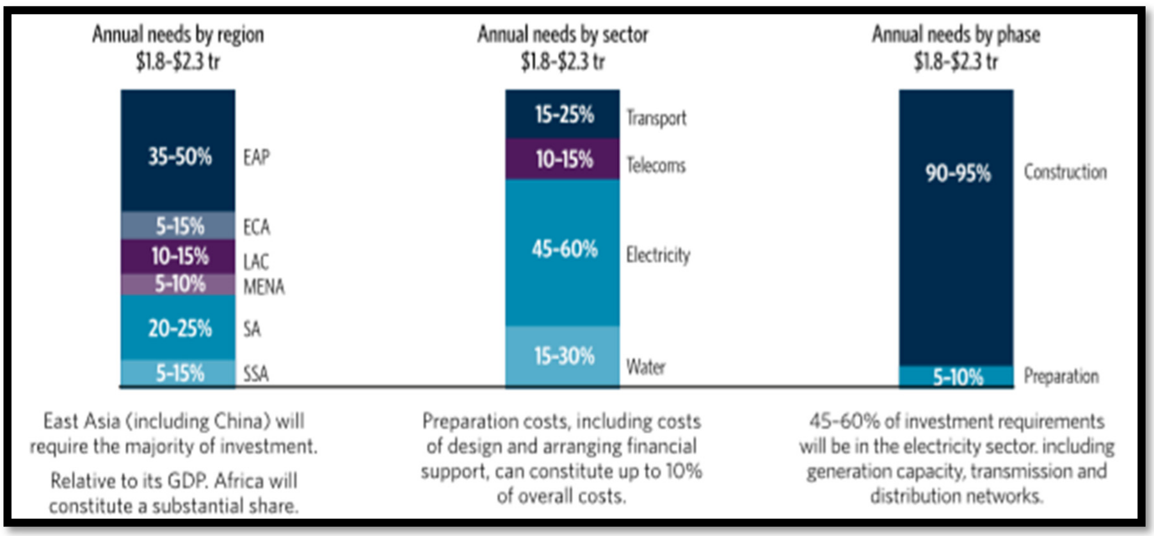

Figure 1.3 Estimated Infrastructure Investments
in Developing Countries over the next decade by region, sector and phase
Taken from Bhattacharya et al. (2012)

The situation in sub-Saharan Africa is even more dire, given the low level of overall development. The World Bank estimates that if all African countries were able to match the infrastructure stock and quality of Mauritius (the leader in the African group), their rate of economic growth would be higher by an average of 2.2% a year (Calderon, 2009), which could on average double a countries GDP in approximately 30 years alone.

1.1.2 Economic returns for infrastructure investments in developing countries are not promising

The question is how to invest when the published evidence to date suggests that *ex post* investment returns in foreign assistance countries are lower than *ex ante* investment returns (Yasin, 2003, Rajan and Subramanian, 2005, Easterly, 2007, Roodman, 2007, Deaton, 2013, Easterly, 2014, Warner, 2014). One study has reviewed 106 papers with over 1,217 estimates of growth based foreign assistance[1]and found "aid is positive but of no economic significance…with decades of research suggesting that aggregate development aid flows are ineffective at generating growth." (Doucouliagos and Paldam, 2010). The lesson to draw from this is that foreign aid requires a stringent economic evaluation framework within which projects are developed and implemented to help ensure economic impact.

One of the interesting metrics presented is related to Overseas Development Assistance (ODA) and its effect on growth ; the Nobel economist Angus Deaton has noted that countries like China, India and South Africa have prospered with a tenth of the amount of ODA as a percentage of national income, relative to 36 SSA countries with at least 10% or more, with some of these countries' budgets made up of up to 75% of ODA (Deaton, 2013). In other words, countries that received less development assistance seem to have done better than those that have received more development assistance.

Considering an estimated $4.6 trillion have been spent to date (Easterly and Williamson, 2011) on overseas development assistance with an estimated 36 to 40% of it devoted to technical assistance mostly provided by expatriates (Riddell, 2008), there is an urgent need to improve performance efficiency if one is to meet the challenge of funding more infrastructure going forward to promote economic growth while truly transferring technical assistance and know-how to these countries.

1.1.3 The primary problems and challenges behind poor economic returns to road infrastructure investment in developing countries

Looking forward, the challenge for the international development community is improving efficiency to deliver higher economic returns on these investments while making sure that projects put in place the needed environmental and social safeguards. Achieving optimal

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[1] Note this study did not include MCC-related investments.

outcomes requires a value engineering approach to optimize designs, maximize the use of readily available materials through recycling, and ensure requisite quality standards are met with the use of a simple graphical platform.

Figure 1.4 below outlines the major factors encountered in infrastructure projects from an extensive literature review of developing countries in two distinct phases: the planning stage and the implementation phase.

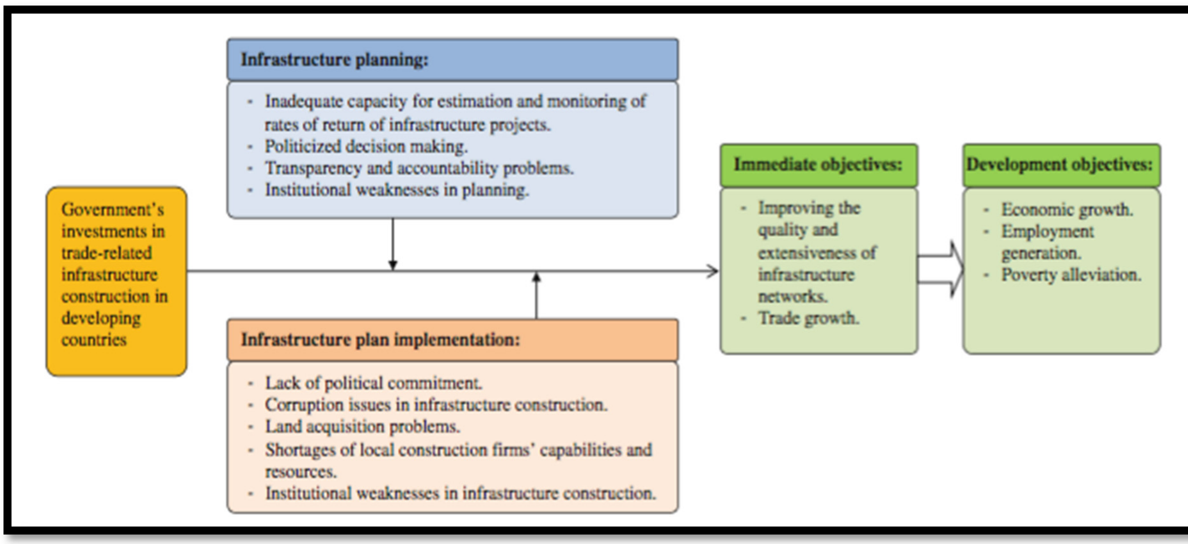


Figure 1.4 Factors affecting the efficient use of infrastructure investments
Taken from Dang and Sui Pheng (2015)

The planning phase mentioned by Dang and Sui (2015) in figure 1.4 above has several primary problems that will be discussed below, notably 1) a poor understanding of pavement asset management planning (inadequate capacity for estimation of rates of return for infrastructure projects and institutional weakness); and 2) political decision-making and a general lack of investment accountability and transparency in the planning and decision-making process (transparency and accountability). These are further described below.

1.1.3.1 Poor understanding/practice of pavement asset management fundamentals

The planning phase and the implementation phase both suffer from the same fundamental issues, notably the mismatch between pavement asset management fundamentals and local/donor capacity/willingness to understand and absorb these fundamentals in a locally appropriate manner with a focus on performance.

In order to prioritize network level investments (and their returns), one needs a solid pavement asset management system in place that responds to the technical capacity levels of the road agency, not the latest fads and most recent technological advances, which is where a lot of emphasis is placed by donor agencies (Wood and Metschies, 2006, Asian Development Bank, 2013). Figure 1.5 below illustrates the general spectrum of complexity of a Pavement Management System, however this does not account for the time it takes to build the institutional and educational awareness to progress from database development to the application of engineering logic and economics to simulate risk management models.

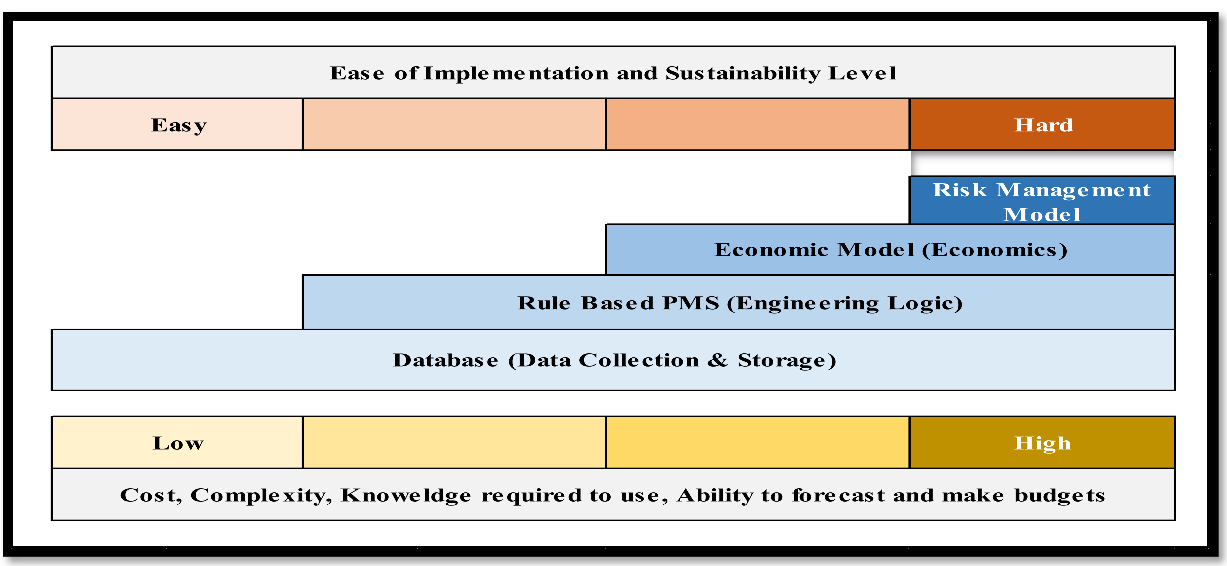


Figure 1.5 Information and decision support system,
Taken from Asian Development Bank (2013)

Dr. Bennett has noted that the successful implementation of a pavement asset management system occurs over a period of many years or decades, which does not necessarily match donor-financed programs, nor objectives in spending on large capital programs as indicated in figure 1.6 below.

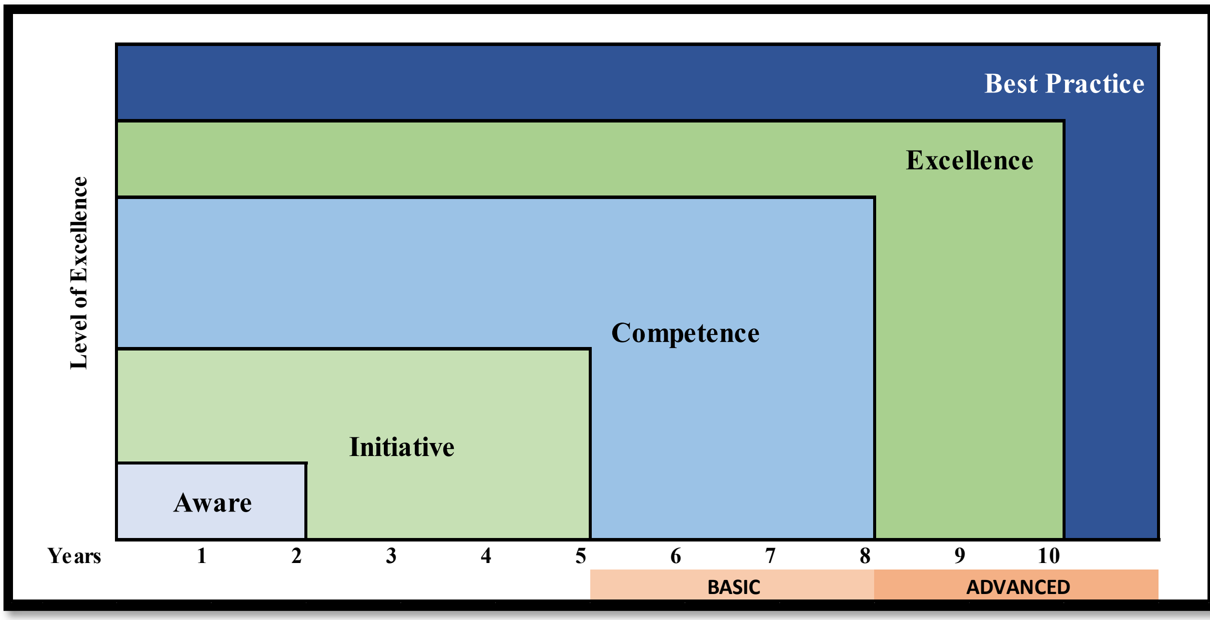


Figure 1.6 Indicative time scale (in years) to develop a Pavement Management System, Taken from Asian Development Bank (2013)

The indicative timeline assumes that the foreign recipient countries have bought into the idea behind road asset management and have true top-level management support with appropriate resources, which is not always the case. In 2012, the Sub-Saharan Africa Transport Program (SSATP) conducted a review of road management practices in seven sub-Saharan African countries and found that most road agencies surveyed have established some type of road asset management systems with varying levels of sophistication and capability. However, for various reasons, including problems with local calibration of the models, most countries have experienced difficulty in operating these systems in a reliable and sustainable manner. As a result, the agencies are unable to develop strategies for managing the road network in an optimal manner (Pinard, 2012).

An Asian Development Bank report noted few of the countries visited had the needed functional policy structures in place to efficiently allocate resources, much less the institutional and human capacity needed to support a road asset management system in line with higher GDP nations, especially with HDM4 planning and prioritization systems (Wood and Metschies, 2006).

For the transport sector in sub-Saharan Africa, the inability to prioritize network investments has left the overall network condition in 19 out of 21 countries less than "good" (See figure 1.7 below), which results in higher Vehicle Operating Costs (VOCs) for the users and higher infrastructure investment costs for the road agency.

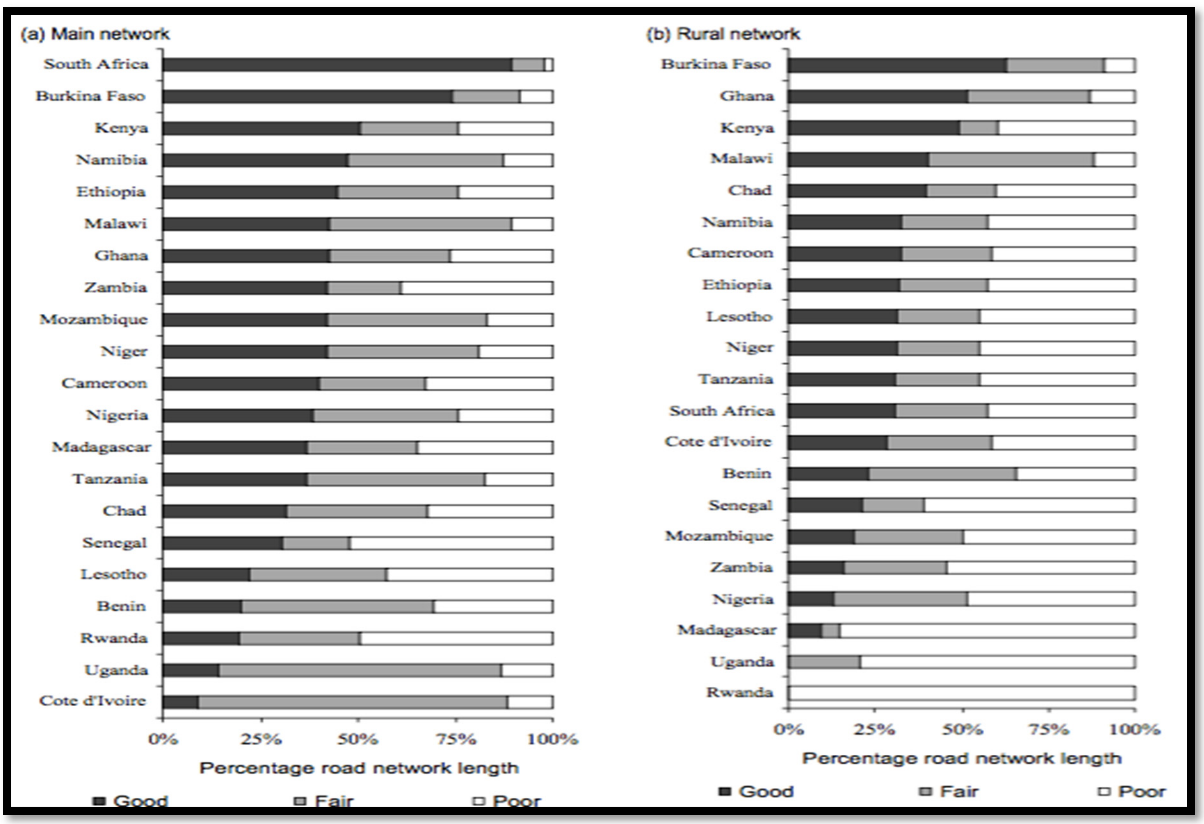


Figure 1.7 Sub-Saharan Africa road network class and condition by percentage of length, Taken from Gwilliam et al. (2008)

The World Bank estimates that at least half of the countries in sub-Saharan Africa are not providing adequate maintenance for the primary road network, with some not even spending enough for routine maintenance; the World Bank estimates that lower income countries underspend on maintenance, while the better off spend above the maintenance norm. See figure 1.8 below. (Gwilliam et al, 2008).

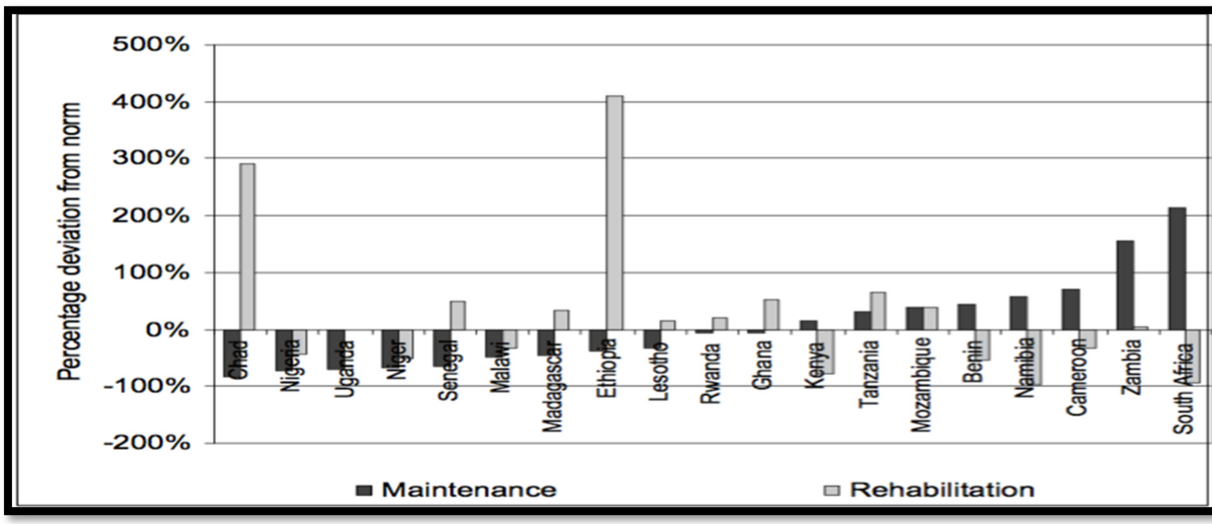


Figure 1.8 Percentage of maintenance and rehabilitation spending relative to "norms"
Taken from Gwilliam et al. (2008)

In a recent audit, the EU noted that countries generally prioritize rehabilitation and upgrading of the road network first, which leaves little money for maintenance, with the result that more rehabilitation work is needed in the future due to the lack of periodic maintenance (European Court of Auditors, 2012). Similar prioritization results were found for ADB financed projects. (Wood and Metschies, 2006) Prioritization of rehabilitation and reconstruction works is in direct contradiction to the principles of pavement asset management, which prioritize maintenance over rehabilitation given the higher economic overall returns to the road agency.

This vicious circle calls into question the economic efficiency of the donor investments in these countries as the prioritization of rehabilitation and upgrading is essentially burdening the country with a larger future liability and worse, increased dependency on limited donor funding. This is analogous to providing someone a brand new car, but no instructions on how and when to maintain the car, let alone assuring that the person has the financial resources available to pay for the maintenance and upkeep. Due to generally accepted accounting principles that require that an expense not be depreciable and therefore not be capitalized and amortized for over a year so as to justify a loan, donor agencies cannot justify a loan to support maintenance much like a borrower cannot easily borrow to pay a recurring expense. Donor agencies that provide grants may not be limited by these constraints and may invest in maintenance works, which supports the overall health of the countries' road networks and can complement those donor agencies that provide loans.

Secondly, there is also evidence to suggest that road investments are over-engineered relative to need, which "wastes" scare economic resources needed for these countries' development. The World Bank has noted that around 30% of the primary network surveyed indicated over-engineering relative to associated traffic levels, which is an inefficient use of scarce resources (Gwilliam et al, 2008); coupled with the lack of maintenance, an even larger inefficient use of resources as the over-engineered roads fail prematurely due to lack of maintenance.

In an extensive review of the Zambian Road Network, despite having a national transport policy mandating the "preservation of investments already made through maintenance as priority for sustainable national development…to promote national socio-economic development" (Zambia, 2002), the Government of Zambia recently undertook a program to increase its quantity of bituminous roads, mostly under 150 vehicles per day (i.e. over-engineered from a traffic perspective), by 8,000 km. This dramatic increase, effectively doubling the paved road network, worth an estimated $6 billion USD, effectively translates to an unfunded liability for the Government that is counter to proper road preservation as the country does not have the means to support the capital (borrowing) or maintenance needs (state budget) of the larger network. (Tembo, 2015) To provide a rough order of magnitude scale, assuming 200 vehicles per day at $0.10USD VOC savings per day per kilometer at 8,000 kilometers over a period of 20 years at 6% annual growth, the maximum benefits to be gained are $2.15 billion USD, which assumes no change to roughness over the 20 years, not to mention the generous VOC savings per vehicle attributed to the analysis, or any additional maintenance and rehabilitation/construction costs. Investing $6 billion USD to receive $2 billion USD user benefits is not an efficient use of scarce capital.

1.1.3.2 Political decision making and limited investment transparency and accountability

Robinson and Torvik (2005) have indicated that there are incentives for key stakeholders to misrepresent the costs and benefits of a project in order to secure funding. Robinson and Torvik have demonstrated that “white elephant projects” are politically attractive in order to influence voters who would otherwise not find them politically appealing; the argument is that socially efficient projects do not allow politicians a way to differentiate themselves from others; white elephants provide some politicians the ability to credibly promise some sort of redistribution to supporters as long as the political benefits are larger relative to the socially efficient projects’ surplus (Robinson and Torvik, 2005). The road agency, as an extension of the state or on its own volition, is incentivized to promote these projects, especially to donors that are not necessarily politically aware of what is occurring.

Reviewing donor performance in the road sector is difficult. The 2016 Aid Transparency Index performed by the International Aid Transparency Initiative found that only 25% of international aid donations are fully transparent (Sharman, 2016), which is also supported by development literature. (Riddell, 2008) One primary issue is that donor agencies’ primary beneficiaries provide minimal feedback (if any at all) and much less in a timely manner (Williamson, 2009) to affect donor behavior. Donor agencies typically rely on some sort of government agency to communicate the needs of the actual beneficiaries, which allows the host government to control the central messaging around the issue vis-a-vis the donor. This reliance on host government agents can be conflicting, especially in the case of state capture and/or corruption. As such, it is essential that any donor agency provide extensive diligence in checking and verifying the reliability of all data at all stages of the project lifecycle to ensure the viability of the investment, and also take appropriate measures to independently review all designs, tender preparation, procurement and execution so that quality, budgets, schedules and benefits are met.

There appears to be a consistent problem across donor agencies with access to high quality, timely and accurate data to make an informed investment decision. Data is hard to collect and the reliability of the data is not always promising. The results show that most donor agencies spend a large degree of time outsourcing the data collection and analysis without always fully verifying the resulting data quality, which leads to less than optimal outcomes in the field (Warner, 2010, GAO, 2012a, GAO, 2012b, Warner, 2014, Rose and Wiebe 2015). This finding suggests that an extensive, yet cost effective, data collection and verification approach is required; or to quote former U.S. President Ronald Reagan "trust, but verify."

Riddell argues that donors as a whole are more incentivized to show the short-term effects of aid working (number of people helped or served) as opposed to the extent to which they achieved the standards in aid delivery they pledged to meet. (Riddell, 2008) Verification of the investment decision calculations, both *ex post* and *ex ante*, are not possible, with some notable exceptions, as the full data sets are rarely provided to the public for review (Rose and Wiebe, 2015, Pritchett, 2002). The MCC model helps counter this problem with extensive post-compact assessments and data transparency requirements.

A thorough review of many economic assessments of road projects performed by numerous consultants in various developing countries show that the determinant assumptions used in the ERR calculations are not always provided, justified, documented or sourced.

One performance metric that donor agencies do use routinely is the level of disbursements relative to the planned or stated goal targets. Williamson notes that this is a rational bureaucratic outcome that is driven by the need to maintain or grow the donor agency budget (Williamson, 2009). Agencies that provide grants are incentivized to obligate funding to a certain country in a certain year to demonstrate the need for full or increased agency funding for future years (Rose and Wiebe, 2015). Agencies that provide loans are incentivized to make loans, which provide interest revenue for the agencies, regardless of investment decision criteria like a cost benefit analysis.(Klein and Harford, 2005) At the end of the day, donor agencies' ultimate decisions come down to their ability to spend the allotted money in each fiscal period to meet the agency needs; the problem is that they do not always know where the best investments are in each country. The primary takeaway is that donor agencies need a tool that helps them quickly identify the winner projects early-on to ensure sufficient financial and economic viability, but also provide a sufficient pool of high-quality investments that can adjust based on agency needs; Chapter 3 of this thesis provides one such mechanism.

Warner notes in his review of World Bank projects that the use of cost-benefit tools is made *ex post* investment decisions, which places a large amount of pressure on staff to reach supporting investment conclusions; this, in turn, downplays the importance of the tool in investment decisions (Warner, 2010).

It is important to remember that a lot of time and energy is spent by donor agency staff trying to put together an attractive portfolio, however there are institutional realities like long procurement periods, management check-ins, and the management of other portfolios that make finding a viable investment hard, especially if previous studies are not complete or the donor agency staff is overwhelmed.

This is not to say that these organizations are misplaced for trying to spend large sums of money in developing countries; the problem is in finding the right projects with which to invest these large sums of money, or identifying the venomous snakes from the non-venomous snakes to use the parlance of Pritchett, Woolcock and Andrews and the PDIA process (See section 1.1.4 below). These are the same types of pressures faced by hedge fund investment managers; finding the promising investments out of a thicket of poor investments. This thesis provides an approach, which is described in Chapter 3, of trying to overcome this problem by adapting a fast-track approach to weed out poor investments quickly.

The average cost overruns experienced on over 90 donor financed projects are about 19% from contract award to completion, and 2.35 times from the initial funding authorization phase to final completion, (Alexeeva et al, 2008, Chong and Hopkins, 2016) which suggest lower *ex* *post* economic returns relative to *ex ante* returns. A recent study of the transport sector covering over 258 international rail, fixed length and road projects found that project costs are underestimated in 9 out of 10 projects, with cost underestimations more pronounced in developing nations than in North America or Europe. The study has demonstrated the incentives found by rational actors to underestimating costs and overestimating benefits for large infrastructure projects in order to gain approval for their projects and its requisite funding; these projects generally generate the highest cost overruns and provide for larger benefit shortfalls resulting in what the author finds as the "survival of the un-fittest (sic) infrastructure projects" (Flyvbjerg, 2009, Sieber, 2012).

A recent report noted this problem, stating that locally produced models projected higher returns for desired investments compared with results from donor agencies' review that almost always lowered the estimated returns, sometimes to a point where the investment lacked economic justification (Rose and Wiebe, 2015). The author has had firsthand experience with engineering reports that overestimate certain drivers of the economic models like IRI and traffic; in one case, the stated IRI in the model was about twice the actual field measurement; the correction resulted in a dramatic decrease in the expected investment returns.

Flyvbjerg states that these kinds of cost overruns occur due to the lack of professional accountability or malpractice in project management, much like with doctors, lawyers and engineers. This lack of accountability in the project management profession leads to others, including donor agencies, noting that cost overruns are a normal part of engineering and construction projects, which is not always the case (Flyvbjerg, 2009). One step that MCC is taking to meet this cost overrun problem is to increase its visibility in the design and implementation process; this will be described in more detail in Chapters 4 and 5 of this thesis.

1.1.4 Misaligned incentives

In the roads business, the primary actor is the road agency, which holds more information about the roads sector than the potential investor. The donor agency has limited visibility into the road agency; will this be a venomous (out to fool the investor) or non-venomous (genuine intentions) road agency is hard for the donor agency and its experts to determine in the short period of time provided to bring the investment forward for decision. Secondly, there is the problem of premature loading, which is having people perform tasks that they are not capable of performing, like learning to run without having learned to walk first (Pritchett, 2002). The application of the Project Driven Iterative Adaption (PDIA) (Pritchett et al, 2010, Andrews, 2011, Andrews et al, 2012) technique to several developing country road agencies suggests the extension of that finding.

A pavement asset management system is primarily engineering know how, which is derived from high-quality education, instruction and experience, and a strong engineering culture to do better in a change-driven and rewarding environment to fight negligence, both of which may be found in small developing countries with limited governmental funding for universities coupled with fairly monopolistic engineering higher education institutions (and seats) with limited to no educational accreditation (Bordia, 2001). This results in a limited pool of engineers with various degrees of quality instruction, the best of which will either join the private sector, donor agency, or move internationally. In fact, in a recent discussion with a road agency official in sub-Saharan Africa, the official noted that the largest problem he faces when training and educating someone is that employee will become employed by the donor agency. There is simply not enough quality road engineering education being offered in developing countries.

Second, the instruction of pavement management principles and techniques is not universal to all engineering curriculums in industrialized economies, let alone emerging countries. Pavement management has only been around since the 1970s and has only really taken off in the industrialized economies over the last few decades. A recent visit to a sub-Saharan university, which is/was considered the most prestigious in the region, showed that pavement management is not a part of the curriculum; civil engineers are trained to do engineering calculations, rather than design an economically efficient engineering solution to a problem. This accords well with previous findings by others previously mentioned concerning the absence of advancement of the countries' road agencies; there is simply not enough engineering know how in pavement management.

1.1.5 Isomorphic mimicry and premature loading

That said a lot of road agencies (and donor agency officials) have learned to adapt to the "best practices," appropriate "forms" and jargon of the donor community and can demonstrate superficial understanding of the main principles and technologies in what is deemed isomorphic mimicry (Pritchett et al, 2010, Andrews, 2011, Andrews et al, 2012). This is the equivalent of creating a paper road agency; looks good on paper with some fancy tools and instruments, but lacks depth to perform the basic road management functions. Isomorphic mimicry allows…

> *…organizations to maintain legitimacy by adopting the forms of successful organizations and states even without their functions. Societal and institutional structures can create an ecosystem in which isomorphic mimicry is actually the optimal strategy for state organizations, leaders, and managers* (Pritchett et al, 2010).

By not understanding the actual level of technological capacity and the road agency organizational capacity, donors run the risk of overwhelming (overloading) the recipients to unsustainable levels, which ensures failure. Worse, premature loading too fast can encourage counterproductive behaviour through reduced morale and frustration and can actually turn the road agency from a service-providing agency to an extractive agency.

This latter behaviour can be reinforced by donor focus on project inputs (disbursements) over project outputs (quality of road constructed) (Pritchett et al, 2010); the road agency actors effectively change their behaviour (function) to match the incentives of the donor agencies (which is to develop a program in a specific timeline to ultimately spend money). The result is that many of these road agencies do not improve, as there is little incentive to perform, with the resulting degradation of the road network and lost returns to investment.

The problem leads to many good, bad options by donor agencies to "fix" the implementation failures with the good options being discarded as they are not "state of the art," or "ideal," or "too scaled down." (Pritchett et al, 2010) The authors point out that they key to resolving this persistent problem is the need to develop low-level performance before building longer-term capacity and performance. This is the equivalent of learning to fly a single engine Cessna before learning to fly a supersonic plane.

There is also a premature loading problem with some of the consultants/consulting firms hired by the donor agency to help assess the road investments; while these consultants have detailed resumes showing plenty of experience, few of them are capable of delivering as they have not been properly trained. It is very hard for donor agencies to discern the good from the bad candidates using existing procurement processes; it is not until the implementation phase that they realize the consultants' real capacity, by which time it is difficult to remove/replace the consultant.

For example, a consultant was hired by a donor agency to assess a basket of roads in a SSA country, upon which the consultant recommended pursing engineering designs and potential capital investments for the donor agency. These recommended investments from unpaved to paved, bituminous roads were estimated by the consultant to cost around $700,000/per kilometer with several of them having double digit traffic (AADT) levels. When asked to justify the investments, the consultant could not produce the IRI or AADT information, as it was not collected. The resulting ERRs would have been negative on many, if not all, of the proposed investments. While the consultant had attended a prestigious university at a PhD level and had notable experiences in pavement management, the consultant was unable to properly assist the donor agency as expected and would have resulted in a poor investment opportunity for the donor agency. Fortunately the donor agency was able to react quickly to find a more qualified consultant. Having an agency that is focused on learning, including from its past experiences, provides the needed feedback loop for continuous improvement.

1.1.6 Corruption eats away at economic benefits

A review of the incentives at play in the engineering and construction field is not complete without discussing the nefarious effects of corruption. The following section is an extensive review of the literature available. The primary definition of corruption is the misuse of public funds for private gain and or the misuse of public funds, goods, or office for private or political gain. Klitgaard defined corruption in formulaic terms, below:

Corruption = Monopoly + Discretion – Accountability (Klitgaard, 1991)

For the transport sector, monopoly concerns an individual monopoly of goods and services (like a government official), with the discretion to supply the goods or services with minimal or no transparency in the decision making process (World Bank, 2009). See figure 1.9 below. The only deterrent to corruption is the degree of accountability.

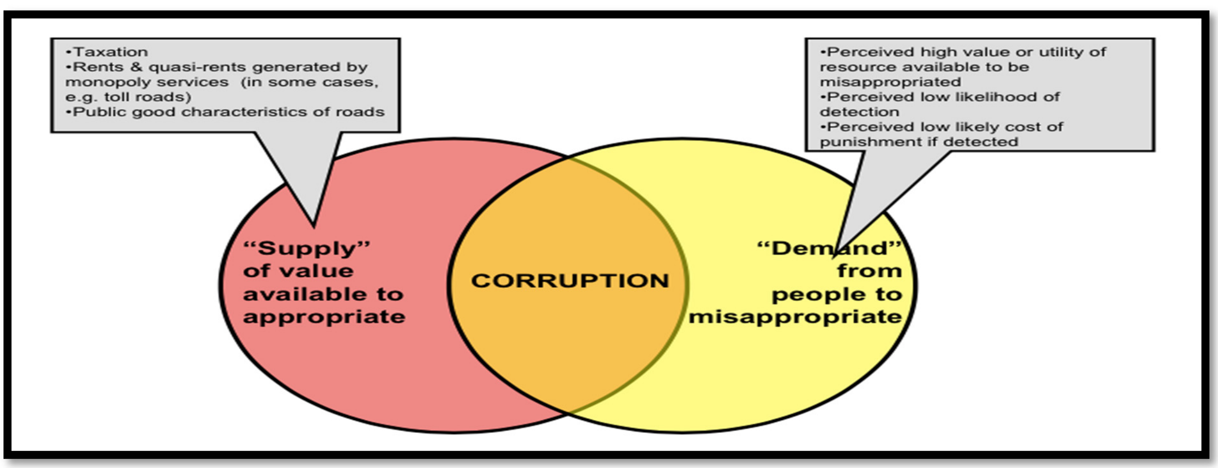


Figure 1.9 Causes of corruption,
Taken from World Bank (2009)

The global construction market is estimated to be over $3.2 trillion USD per year (Nordin et al, 2011) accounting for between 5% to 7% of GDP in most countries. Construction is estimated to contribute to about a third of gross capital formation with an undeniable role in economic development (Kenny, 2007). The global construction industry is consistently ranked as one of the most corrupt by Transparency International; annual corruption costs are estimated to be around $500 billion (de Jong et al, 2009, ASCE, 2015), which is larger than the entire GDP of the Quebec province or South Africa. A recent survey shows the percentage of reported bribery and corruption by industry in figure 1.10 below, with engineering and construction leading all industries at 49%.

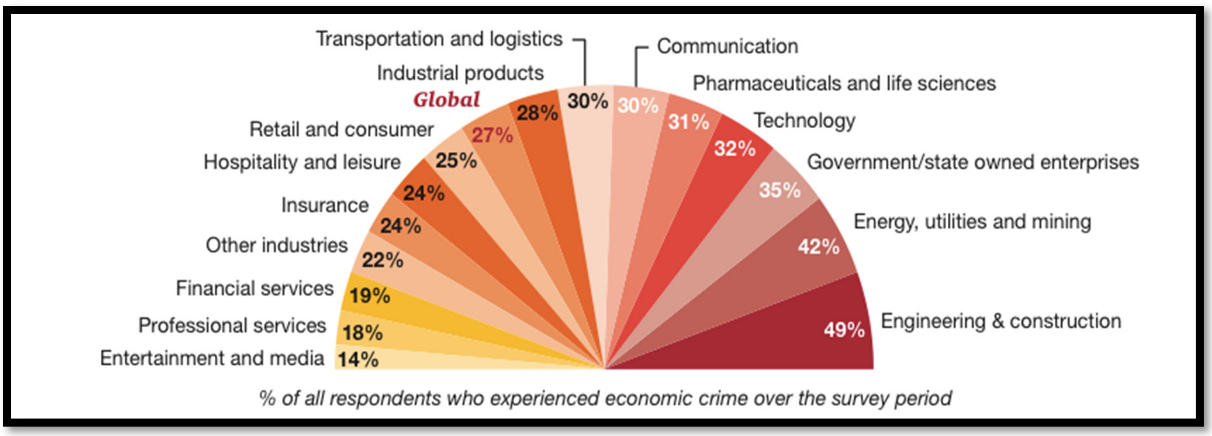


Figure 1.10 Percentage of reported bribery and corruption (economic crime) by industry
Taken from PWC (2014)

Transparency International provides annual corruption perception indexes to evaluate the extent of corruption in countries; the most recently available (2015) is shown in figure 1.1 below with red indicating more corrupt and yellow less corrupt. The developing countries that receive foreign assistance are various shades of red, or corrupt.

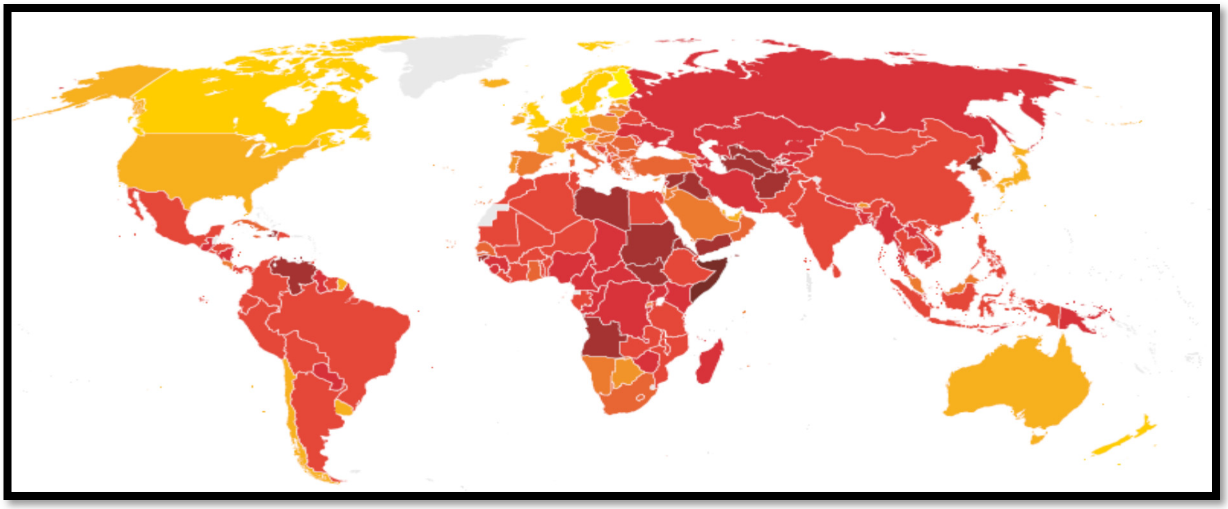


Figure 1.11 Corruption Perception Index 2015
Taken from Transparency International (2015)

The effects of corruption on the overall political economy are well-known. Corruption has been linked to increasing income inequality and poverty (Gupta et al, 2002), reduction in private investment (Mauro, 1995), and environmental degradation, (Sieber, 2012), all of which reduce economic growth. Corruption has also been shown to erode confidence in political leaders and institutions, effectively reducing public participation to coercion and force, which leads to civil unrest (Fantaye, 2004), erosion of the rule of law, and harm to the reputation of and trust in the state (Sieber, 2012). Others have shown that corruption can also lead to the formation of extremist parties like the Taliban and ISIS (Chayes, 2015). Corruption, if not properly checked, cannot only erode confidence in the government, but also destroy the government and any opportunities for sustainable economic growth.

Engineering and construction projects provide increased opportunities for rent-seeking from corrupt officials and individuals largely due to the large contract value (Robinson and Torvik, 2005, Wood and Metschies, 2006, Patterson and Chaudhuri, 2007, World Bank, 2009, Sieber, 2012). Donor agencies are aware of the problem and have produced numerous anti-corruption papers, research, and policies (Kenny, 2007, Kenny, 2009a, Kenny, 2009b, World Bank, 2009, World Bank Integrity Vice President, 2011, Sieber, 2012), as have the private sector and academia (Svensson, 2000, Fantaye, 2004, Olken, 2007, de Jong et al, 2009, Boyd and Padilla., 2009, PWC, 2009, Nordin et al, 2011, Bowen et al, 2012, Gillanders, 2013, PWC, 2013, PWC, 2014).

Moyo notes that the World Bank has estimated that as much as 85% of aid has been misappropriated from its intended use often to unproductive projects (Moyo, 2010). For the transport sector, an estimated 5% to 40% of allocations are estimated to be lost to corruption (Patterson and Chaudhuri, 2006). Olken determined that approximately 24% of the total cost of rural road projects in Indonesia was illicit. (Olken, 2007). It has been noted that after the Charbonneau commission began its hearings on potential corruption in public works contracts in Quebec, the cost of public construction contracts in Montreal decreased by some 20-30 percent (Binette, 2016).

Corruption networks are highly organized and efficient cartels, which operate much like the organized crime syndicates (Green, 2005, K&L Gates, 2014, Gyulai, 2014, Charbonneau and Lachance, 2015). They can control construction contracts, prices, and firm selection, and have shown to have ties to political elites, much as the Charbonneau Commission has uncovered in Quebec.

The standard symptoms of corruption in the transport sector are numerous and are shown in table 1.1 below.

Table 1.1 Symptoms of corruption in the transport sector at the network and project level Adapted from Tanzi and Davoodi (1997), Patterson and Pinki (2007), and Sieber (2012)

Network or Agency Level	**Project Level**
1) The disregard of an objective needs-based assessment planning and funding allocation process 2) Recurrent expenditures like maintenance directed to political supporters and away from an objective allocation scheme 3) Weak agency processes and controls 4) Personnel appointments that support the corruption	1) Deliberate overdesign by engineer for own interest (more work) or from political or vested interests that may benefit from overdesign 2) Land acquisition, social safeguards and environmental concerns deliberately underestimated 3) Benefit streams intentionally overstated with costs understated 4) Poor quality work 5) Variation Orders above 20% of the original contract 6) Time overruns more than 30% of the original contract 7) Poor oversight, monitoring and control of the works 8) Quantities billed but not placed

The donor agencies, which fund a large amount of roads investments in developing countries, are aware of the problem of corruption in their portfolios; the question is how they choose to manage it.

The first and major problem with many donor agency models is what is referred to as the principal agent issue; namely the donor agencies (principle) typically partner with a local government agency or group (agent) to implement the projects on their behalf with the private sector (firm) (Klitgaard, 1988, Hobbs, 2005). The problem arises with the agent's self-interest given his monopoly and discretionary role relative to his perception of accountability for transgression by the donor agency.

There are several primary motives behind the self-interest of the agent: Rose-Ackerman notes four primary incentives (Rose-Ackerman, 1997):

1. **Payments equate supply and demand:** As the sole (monopoly) provider of road contracts, the government may adjust supply (award of contracts) accordingly to determine the market willingness to pay. Incidentally this provides the unqualified firms higher willingness to pay than qualified firms; the bidders know they need to bribe to get the contract. In certain countries, local officials and engineers have few options but to play the game or risk future career opportunities in the transport sector. The same holds for engineering and construction firms (PWC, 2009, PWC, 2013, Gyulai, 2014, Hussain, 2015). Even if they all agree not to, Hobbs argues this places the bidders in a prisoner's dilemma, which means they need to bribe to win the bid as the other firms are incentivized to bribe (Hobbs, 2005). Svensson concluded, "firms with extensive dealings with the public sector is more likely to be under bureaucratic control and (therefore) faces a higher probability of having to pay bribes"(Svensson, 2003). This ultimately comes down to willingness to pay. For works contracts, bribes are paid upon award and are not detectable by any audit as they are built into the unit costs (Hobbs, 2005). Once the bribe is paid, the agent is incentivized to protect the firm.

2. **Bribes as Inventive Payments for Bureaucrats:** Firms and individuals may be willing to pay to expedite services that are controlled by the government. Once the award is made for a works contract, the contractor is in a conflict with the government agency that holds the performance security worth about 10 percent of contract value, which is only returned once all parties sign off on the work. (Hobbs, 2005)

3. **Bribes to reduce costs**: These are bribes that are paid to government officials to avoid regulations, taxes, and enforcement of criminal laws.

4. **Payments to Obtain Major Contracts, Concessions and Privatized Firms:** Unlike the first, this motive is related to higher-level officials (often immune from prosecution), and their ability to collect large payments in exchange for preferential contracts or concessions; the major issue is with the uncertainty of the agreement due to political turnover (new regime may not offer the old regimes deal) or the imposition of further demands once investments are sunk. The mobilization of large amounts of construction equipment into a country places the construction firm in a "sunk position," vis-à-vis the government.

Interestingly, recent work has demonstrated a market effect on bribery: Olken and Pande note that, "strategic interactions between corrupt officials affect the level of corruption – bidding down bribes if they compete against one another, and increasing bribes if multiple bribes are required and officials can't coordinate with one another"(Olken and Pande, 2012).

One of the major problems with corruption is the ability (or willingness) of the donor agency to detect corruption in a timely manner, let alone be able to satisfactorily address the problem. One problem is information and resource asymmetry: the donor agencies have limited access to information (the agents know how to manage the deals), let alone monitor any potential transgressions, which are rarely recorded and memorialized in documentation.

Hobbs noted that the donor agencies may not be properly incentivized to properly control corruption for two reasons: the first is that additional resources would be required out of its administrative budget (which is in short supply), and the second and most important is:

> *….that the (World) Bank recognizes that in order for its projects to be successful and delivered in a timely manner it must accept a certain amount of corruption; successful projects are crucial for the (World) Bank to continue to justify itself to creditor countries to ensure their support and financial contributions, but also to debtor countries to borrow its funds and maintain its existence.* (Hobbs, 2005).

Rose-Ackerman contends that the World Bank is actually less concerned with the projects' integrity as they are with the fiscal health of the borrowing government to repay the loan. Rose-

Ackerman notes that this bias was meant to be resolved through the provision of strong technical staff focused on economic rationality (Rose-Ackerman, 1997).

Hobbs noted through his interviews with former experienced contract managers that bribery was involved in all 22 contracts in 10 countries involved, with all but six subject to prior World Bank review and fiduciary audit review with no corrupt practices found by the Bank (Hobbs, 2005). Pande notes, “recent work has also shown that corrupt officials are resilient; over time, they adapt to changes in their environments, in some cases offsetting anti-corruption policies with new avenues for seeking out rents” (Olken and Pande, 2012).

Roads investments can provide tremendous economic benefits to developing countries; however, the investments need to be made in a manner more adapted to properly align the incentives surrounding the investment to maximize investment returns. Donor agencies need to be able to develop investment portfolios quickly and efficiently with a high degree of visibility (accountability) into the decision-making process, but also the implementation and oversight of the investments with a particular focus on long-term sustainability through building local capacity and technical know-how to not only manage the asset, but also develop locally appropriate technical solutions for the future. Accountability has been shown to have a positive effect not only on improving overall performance, but also on reducing the effects of corruption.

For example, the FHWA Construction Program Management and Inspection Guide makes note of the increased monies being spent by the federal government on the Interstate Highway System (great infrastructure spending program) and the charges of waste, fraud, and corruption during the 1950s and 60s. Rigorous inspections in depth (IIDs) were conducted by experienced engineers with strong construction backgrounds on behalf of the federal and state authorities in response to these charges in order to assure the public and to get the road agencies own house in order. (FHWA, 2004) These IIDs resulted in improved construction performance and public trust.

A recent experience in SSA has also supported the IID approach mentioned above. The use of itinerary diagrams showing the quality of the work performed relative to the specifications and the knowledge that verification was highly likely resulted in higher quality road investments than others made by other donors in the same country at the same time with the same road agency. Incidentally, it was this focus on quality that helped develop part of the idea of this thesis.

1.2 Justification and scope of research

The thesis aims to outline a framework that quickly identifies the most economically lucrative infrastructure investments in each country using simplified economic models and field data verification of the two primary benefit stream drivers to reduce the risk of making a poor investment decision, but also to identify a sufficient quantity of roads to meet donor-financing needs.

This easy to use, scaled down version of the HDM-4 network analysis tool based on an easy to use software application like MS Excel can be easily transferred to local conditions to help prioritize network investments. HDM-4 is much too complex for most of these road agencies, let alone more "developed" road agencies or even engineering consultants. This tool would need to be simple focusing on the key drivers of the investment benefit stream that requires minimal donor agency field verification before selecting a large pool of economically lucrative investments. This is referred to as **Part I-Fast Track Network Level Analysis** below.

The second need is for the development of a simplified, yet functional approach to build engineering know-how using the existing local engineering capacity to build out an appropriate pavement asset management system in line with capacity. This approach would need to marry the fundamentals of pavement engineering design, including the understanding of the cause(s) of deterioration, but also encouraging proper quality assurance and control throughout the design and construction process with a highly visible and understandable graphic orientation focused on accountability. The cause-based approach is referred to in **Part II-Technical**

Optimization below and the graphically oriented approach as **Part III- Graphical Data Representation Dashboard.**

1.2.1 Part I – Fast-track network level analysis

There are five methods for conducting economic analysis: Annual Cost method, the Net Present Value method, Rate of Return method, Benefit Cost Ratio method, and the Cost Effectiveness method (Haas, Hudson and Zaniewski, 1994). The most common method in use by donor agencies today is the Rate of Return model, which provides the discount rate at which the net present values and the net present costs are equal to zero.

One of the more ubiquitous rate of return models in use today is the Highway Development and Management Model, HDM-4, originally developed by the World Bank, and now licensed through the World Road Association (PIARC). The HDM-4 model is a software package that serves as the primary tool for road analysis, planning, management, and appraisal for road maintenance, improvements, and investment decisions (PIARC, 2015). The HDM-4 model has three levels of application: one level for high level network based analysis, a second level for program based analysis, and a third level for project specific level analysis (Kerali, 2000). This software can be used as part of a pavement management system to prioritize investments as well as conduct economic analysis on individual project-level investments.

Theoretically, the road agency would use the HDM-4 software to prioritize its road network investments through a needs-based approach based on economic prioritization of candidate sections. The optimal lifecycle cost strategy involves a frequent maintenance regime that intervenes early in the road investment in order to prevent or minimize deterioration, as maintenance is generally less expensive than rehabilitation and reconstruction. HDM-4 thus prioritizes maintenance works over rehabilitation work due to the lifecycle costs differences.

HDM-4 requires a large amount of country specific data in order to accurately model and predict pavement performance, which is affected by a multitude of factors including structural capacity, construction quality, traffic loading, vehicle operating costs, drainage, environmental conditions, and maintenance and rehabilitation practices (Li et al, 2004). There is a large amount of data that needs to be collected and verified for the HDM-4 software tool to perform as intended. This data collection effort requires a large degree of time and effort to collect, analyze and input into a separate road management database for HDM-4 to analyze based on the preferences of the user, or road agency.

The scope of Part I of this thesis is to perform the analysis, compile and verify whether the operating costs per kilometer, for different vehicles, performed in various countries are comparable, and if a simplified polynomial model may be considered for a given traffic and smoothness before and after rehabilitation to rapidly estimate the economic rate of return for each segment to inform the donor agency of the most lucrative economic investments.

This finding is very practical in a fast-track network level analysis requiring basically only AADT, percent of heavy trucks and IRI to identify cost-effective candidate sections and prioritize needs based on the highest return investments. Verification of these figures relative to those provided by the road agency will help validate the reliability of the road agency database and road agency capacity to collect and input quality data.

This network-level optimization method will provide a suitable pipeline of road investments for donor agencies to maintain their spending needs, but also reduce the possibility of “white elephant” projects or poorly defined benefit streams due to poor data.

1.2.2 Part II - Technical optimization

Pavement design attempts to model the behavior, namely strains of various soils, aggregates, binders, namely cement, lime, asphalt, in project-specific environment and geologic conditions under various loading patterns. The prediction of the pavement strains are, however, only one part of the design equation; seasons create variations in moisture and temperature, which significantly affect the rheological properties of pavement layers and subgrades under repeated and variable loads, all of which makes determination of the design life expressed as the cumulative number of allowable cycles or loadings, quite challenging. All of this is further complicated by the inherent variability of the construction process and materials (i.e. using soils from various sources, equipment with varying outputs, too much heat applied to the bitumen, insufficient compaction, etc.).

Monitoring and evaluation of the mechanical behavior of a specific pavement over time in response to its loading under varying climatic conditions is paramount in the determination of pavement performance. The monitoring and evaluation is performed at specified intervals over time to determine the pavement performance curve and resulting level of intervention. An example of a pavement performance curve is shown in figure 1.12 below with indicative levels of intervention.

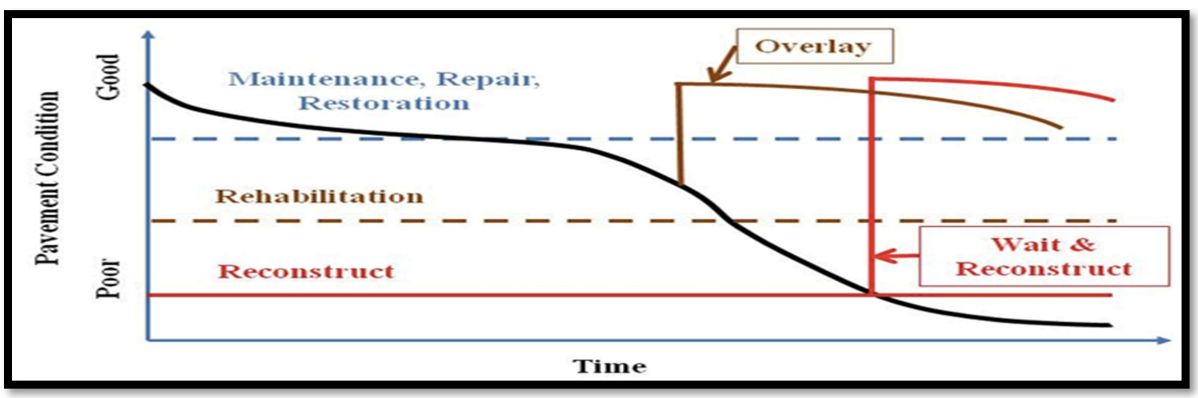


Figure 1.12 Pavement deterioration curve with levels of intervention
Taken from Elkins et al. (2013)

It is important to note that each pavement is affected by numerous random variables that can affect the shape of the curve over time like variations in loading, weather patterns, blocked drainage ditches, and poor construction techniques, such as poor compaction, thickness variations, and poor mix design. As such, each pavement should be routinely monitored to detect variations, or distress, that may lead to less than optimal performance over time. Earlier intervention to preserve the pavement is generally much more affordable than delaying treatment as previously shown. The idea is generally referred to as pavement preservation and is the underlying principle behind road maintenance; early action preserves pavement assets longer for less money resulting in lower agency costs and higher user savings (increased vehicle operating cost savings).

Once the distress is observed, the primary cause behind the distress should be identified and verified in order to properly treat and prevent the problem from coming back in the future. This approach incorporates the structural deterioration factors as well as other deterioration factors like materials deterioration; freeze thaw, shrinkage and creeping, and bitumen/aggregate problems (Assaf, 1993) that may affect the pavement performance curve. Unfortunately, this elementary concept is mostly missed in modern pavement management, which focuses more on structural deterioration.

Pavement design is either based on an empirical approach, the mechanistic approach or a combination of the two. The primary appeal of empirical performance prediction models is that they are developed from actual field performance results, which include the placement and performance of materials, under actual loading conditions, in lieu of the analytical mechanistic models that are more theoretical, based on simplified assumptions, and most importantly do not predict pavement performance, but rather behavior. (Haas et al, 2007, Yoder and Witczak, 1975, Haas and Hudson, 2015).

In Francophone West Africa, for example, the primary pavement design manual in use, *le Manuel pour le renforcement des chaussées souples en pays tropicaux*, evaluates the pavement structurally via Benkelman beam deflections and “functionally” via an assessment of the cracking and distortions. This manual was based on empirical observations made in the region during the 1970s and early 1980s. The structural assessment is based on a mechanistic verification based on Burmister’s multi-layer model.

The deflection measurements are taken and characterized by the average deflection (m) at a 90 percent confidence interval to arrive at a characteristic deflection (dc), or $dc = m + 1.3\ \sigma$. The characteristic deflection measurements are then broken down into zones and labeled d1 (satisfactory) or d2 (not satisfactory; serious structural defects), with an intermediate zone (not labeled) in between as shown in table 1.2 below. Note that the deflection ranges are provided locally for the varying climatic conditions, generally based on a rule of thumb approach as opposed to the pavements historical loading conditions.

Table 2.2 Deflection assessment matrix
Adapted from Autret et al. (1985)

Deflection	**Low D1**		**High D2**
Strength	High	Mediocre	Weak
Quality of Structure	Good	Dubious	Poor

Cracking, defined as pavement fatigue, shrinkage and structural quality related, and distortions, defined as depressions, settlement and rutting, are evaluated based on quality assessment ratings shown in table 1.3 below:

Table 2.3 Composite score for cracking and distorsions matrix and condition assessment
Adapted from Autret et al. (1985)

Cracks	**Q1 (<10%)**	**Q2 (10-50%)**	**Q3 (>50%)**
Distortions			
Q1 (<10%)	1	2	3
Q2 (10-50%)	3	4	5
Q3 (>50%)	5	6	7

The cracking and distortion composite scores are then compared to the deflection scores to determine the level of intervention, with Q1 and Q2 indicating maintenance such as primary surface layer activities and resurfacing, Q3 indicating resurfacing with corrective layer as needed, and Q4 and Q5, "strengthening or *reinforcement,*" correction of structural faults with an additional layer(s) as per Table 1.4 below.

Table 2.4 Final composite score calculation
Adapted from Autret et al. (1985)

Deflection	**Low D1**		**High D2**
Condition (Score)			
Good (1)	Q1	Q2	Q3
Cracked by not deformed (2-3)	Q2	Q3	Q4
Deformed and Cracked (4-7)	Q3	Q4	Q5

The idea behind this approach is to provide a basic, yet structured methodology to improve pavement design techniques for maintenance, rehabilitation and reconstruction; however, this methodology does not address in any way the underlying cause that leads to the intervention, which represents a major handicap.

Proper identification of the actual cause(s) of deterioration of each pavement is also critical to improving the predictive accuracy of the pavement performance curve, the effectiveness of the maintenance and/or rehabilitation intervention, and also the improvement of the design process by effectively isolating the key pavement behavior variables from the other "noise." This is the essential element behind feedback loops, which are missing in the pavement design process; that is, a full understanding of why the pavement structure has behaved in order to identify, treat and hopefully avoid it in the future through adjustments in specifications and requirements.

For instance, in West Africa, the tropical sun oxidizes asphalt pavements very quickly. The resulting brittle asphalt cracks easier and earlier than would be expected in more temperate European climates, which is the basis for some pavement design in West Africa. Cracks will then allow water into the base course with the resulting destruction of the pavement structure. Through the identification of the cause of deterioration, the road agency would theoretically be able to adapt its asphalt mixture for higher temperature environments, or program more proactive preservation maintenance techniques to rejuvenate the asphalt with solvents, thereby providing a renewed surface. This would also hopefully lead to the adoption of more improved bitumen testing methods such as SUPERPAVE as compared to the traditional Marshal test, as the former accounts for environmental temperature effects, while the latter does not.

This thesis provides a structured framework to identify the causes of deterioration and proposes a Bayesian model to help road agencies better predict the cause(s) of deterioration to optimize any maintenance and rehabilitation interventions in a timely and cost effective manner. The pavement response variables will be broken down into homogenous, or dynamic sections, to properly identify intervention sections. The model attempts to develop a more empirically based, cause-determinate pavement design architecture for replication that can be **fully integrated** into the road agency Pavement Management System (PMS) and serve as a learning database for the road agency and others going forward. With minimal training, local road agencies can use the PMS to learn about their road network and develop appropriate designs for their conditions.

In fact, this later point is one of the primary weaknesses of the AASHTO Mechanistic Empirical Pavement Design Guide, or MEPDG, which has used empirical data from the North American Long Term Pavement Performance (LTPP) database to establish a "*factorial statistical analysis to define the influence trends of the basic factors while minimizing the effect of errors in any specific measurement*." (Haas and Hudson, 2015). The MEPDG's primary weakness is that it is trying to develop a model based on numerous sources, with various levels of quality and completeness, that requires extensive calibration data (over 300 plus) to use, which are not fully integrated or adapted to a road agencies PMS (Haas and Hudson, 2015).

While the MEPDG does recommend that investigations be undertaken during the condition assessment to understand the causes of pavement deterioration in order to best determine its rehabilitation needs (NCHRP, 2004), it does not provide any framework or indications on how to do this fundamental exercise. This again highlights the scope of Part II of this thesis, which is to provide a structured framework on what to collect and what are the causes of deterioration in flexible pavements, and what are the appropriate tests to confirm the proximate cause(s) of deterioration.

It is worthy to note that the LTPP Distress Identification Manual provides an excellent source of these pavement distress descriptions, severity levels, and methods for measurement; however, it does not indicate the possible cause of each distress nor does it provide the appropriate tests to conduct in order to confirm these causes. Needless to say that a MEPDG-based rehabilitation study is in vain should it not include the recognition of the cause and a tailored solution that addresses it before the MEPDG structural capacity assessment and reinforcement needs are conducted.

The value added of Part II of the proposed thesis would be to use the collected condition assessment data in conjunction with the cause of deterioration to quantify the needed confirmation tests based on the most probable cause(s) of deterioration.

As the system is used over time with the road agency PMS, the system would ideally begin to learn through increased probabilistic determination how to better predict the cause(s) within the network to better enable the road agency plan for maintenance and rehabilitation expenditures and improve its pavement design techniques within the road agency and others if the know how is automatically generated and shared. This will most likely require an adaptation of the agency PMS architecture, which will make it more responsive to the pavement design and management needs.

The fundamental principle of a PMS is to provide the best possible value for money while maintaining the stated objectives of the road agency (Haas, Hudson and Zaniewski, 1994). A PMS helps road agencies develop multi-year investment programs to maintain a road network at a certain level (or condition) based on funding availability (Kulkarni and Miller, 2003). Originally conceived as a project assessment tool, the PMS has expanded over the last 30 years to include network assessments. A PMS helps the road agency properly collect, store, and manage pavement data to predict pavement performance in order to provide an economically optimal prioritization to leverage every investment dollar.

The primary activities of a functional PMS are shown in table 1.5 below by network and project levels.

Table 2.5 Summary of activities and decisions within a PMS
Adapted from Haas and Hudson (2015)

Basic Block of Activities	**Network Management Level**	**Project Management Level**
A. Data	1. Sectioning 2. Data a. Field Inventory (roughness, surface distress, friction, deflection, geometrics) b. Other (traffic, unit costs) 3. Data processing	1. Detailed data structural, materials, traffic, climate, and unit costs. 2. Sub-sectioning 3. Data processing
B. Criteria	1. Minimum serviceability, friction, structural adequacy, max. distress 2. Maximum user costs, maintenance costs 3. Maximum program costs 4. Selection criteria (max of benefits and max. cost effectiveness)	1. Max. as built roughness; minimum structural adequacy and friction 2. Maximum project costs 3. Maximum traffic interruption 4. Selection criteria (such as least total costs)

Basic Block of Activities	**Network Management Level**	**Project Management Level**
C. Analyses	1. Network needs (now) 2. Performance predictions and future needs 3. Maintenance and rehabilitation alternatives 4. Technical and economic evaluation 5. Priority analysis 6. Evaluation of alternative budget levels	1. Within project alternatives 2. Testing and technical analysis (performance and distress predictions) 3. Lifecycle economic analysis
D. Selection	1. Final priority program of capital projects 2. Final maintenance program	1. Best within-project alternative (rehab or new pavement) 2. Maintenance treatments for various sections of networks
E. Implementation	1. Schedule, contracts 2. Program monitoring 3.Budget and financial planning updates	1. Construction activities, contract control, and as built records 2. Maintenance activities, maintenance management, and records.

At the core of the PMS is the database. The database houses the key pavement management and design variables, which would ideally create a feedback loop throughout the project level process (the design, construction, maintenance and rehabilitation are all monitored and evaluated to optimize performance), as well as influence network-level analysis activities like programming, planning, and budgeting (Haas and Hudson, 2011). By maintaining and updating the database, the road agency is able to modify its pavement prediction models over time and continue to build on what works through investigation of pavement sections that perform better than predicted just as much as those that perform worse than predicted in order to fine tune the empirical design approaches. The key is to have a PMS architecture that facilitates this level of analysis.

The fundamental concept behind pavement management is to provide a functional and structurally acceptable pavement that minimizes agency and/or user costs (depending on agency) in order to efficiently move goods and people. Figure 1.13 below illustrates the basic concept, with a simplified pavement deterioration curve, over time. The PMS functional capacity should allow the user to model the pavement deterioration curve over time using similar homogenous sections from the network.

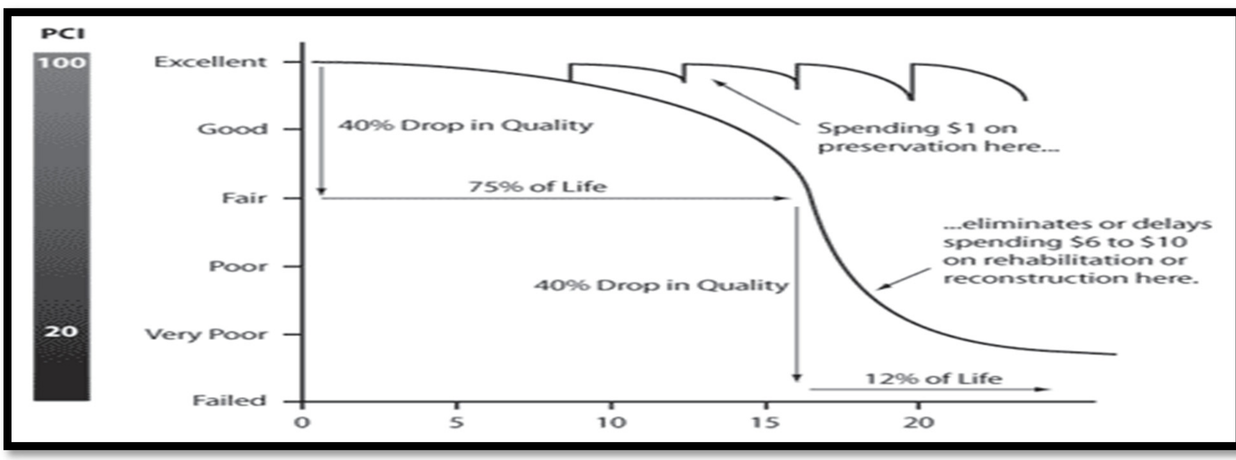


Figure 1.13 Pavement Option Curve by PCI over time,
Taken from Galehouse et al. (2015)

The pavement deterioration curve is then used to determine the maintenance and/or rehabilitation planning over time. As newly collected data from periodic condition assessments are input into the PMS, the curve should adjust accordingly, moving in step with the modeled curve (meaning the pavement behaves like the other homogenous sections) or deviating in either direction, which suggests further investigation to understand why.

The modeling of a future pavement deterioration curve is paramount to the precision of the PMS and its optimization as pavement deterioration curves behavior is influenced by numerous factors, including climate, traffic (loading), materials and various degrees of construction quality and workmanship. The PMS is (or should be) nothing more than a database that allows the road agency to model the behavior of its road assets to efficiently manage the appropriate levels of intervention in a timely manner. The pavement behavior determines, no drives, the pavement design process, which requires a PMS that is designed to collect, analyze, and understand the differing behaviors of each pavement family to continuously learn and improve.

This is the basis for the itinerary diagrams approach that are designed to identify the major elements of the pavement deterioration curve in graphical manner, which can be integrated with the Bayesian prediction models identifying the cause(s) of deterioration.

1.2.3 Part III – Graphical data representation dashboard

The itinerary diagram approach is not new; it has been used in road engineering for quite some time (Luhr, 2015, Autret et al, 1985), especially in Francophone countries. A sample itinerary diagram is shown in figure 1.14 below; however, the proposed approach will also include aerial imagery with a Digital Terrain Model to account for the hydrology around the road investment.

Figure 1.14 Sample itinerary diagram (strip map representation) from South Africa
Taken from SANRA (2014)

This itinerary diagrams concept is useful in Part II of this research to identify the cause of deterioration of an existing pavement in need for rehabilitation since all the data required to pose a diagnosis as to the most probable cause of deterioration is in the diagram, which in turn may point towards additional tests as needed. Based on the itinerary diagram approach, the scope of Part III is to develop a concept to monitor and evaluate if projects are delivered in accordance with the contractual specifications, which reflect stakeholders' requirements. This is important for donors and lending agencies to verify in a snapshot whether the roads are up to the standards upon which payment was based. The concept is even more useful post-construction, for both the road agency in providing suitable performance maintenance management and the development of soils fatigue curves, but also for the donor agency in monitoring the effectiveness of its investment over time with direct accountability.

In fact, with all the data collected during design and construction saved on one graphical platform, it is easy for the analyst to identify the cause of failure at any specific point in time (after construction) or space (position on the road) simply by observing what parameters are different where the distress is observed. Applying this across other similar road sections would thus trigger preventive and proactive interventions before the distress has manifested.

In order to properly determine each pavement performance curve, the pavements would need to be grouped into families based on their similarities as shown in the indicative figure 1.15 below.

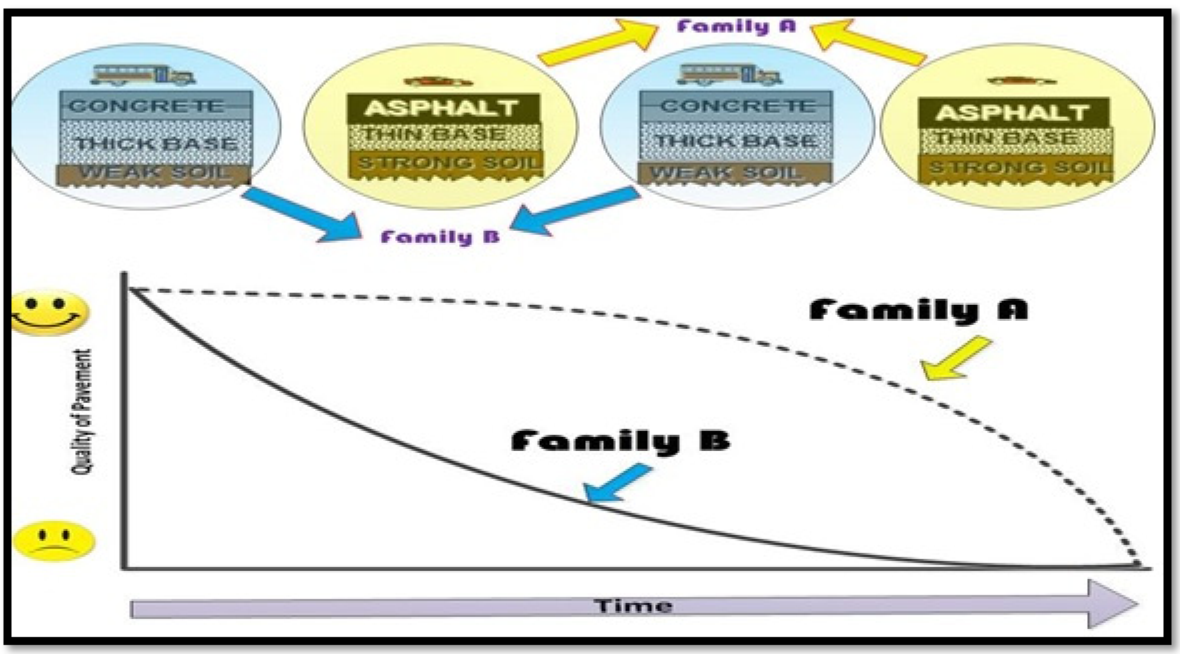


Figure 1.15 Indicative pavement family classification approach by pavement condition over time

Within each family, further refinement based on homogenous, or dynamic, sectioning of the pavement response data is required. Dynamic sectioning is an approach that allows each pavement response to be shown over its respective distance in lieu of being averaged over a fixed length, which allows for a more refined analysis of the key variables to optimize the intervention(s), as shown in the figure 1.16 below. (Assaf, 1993, Bennett and Paterson, 2000)

Figure 1.16 Dynamic Sectioning versus fixed sectioning approach
Taken from Bennett and Paterson (2000)

The implication on design of treatment solutions and optimization of resources becomes more apparent as shown in figure 1.17 below, which shows a clear break in the pavement response for section A1 and A2.

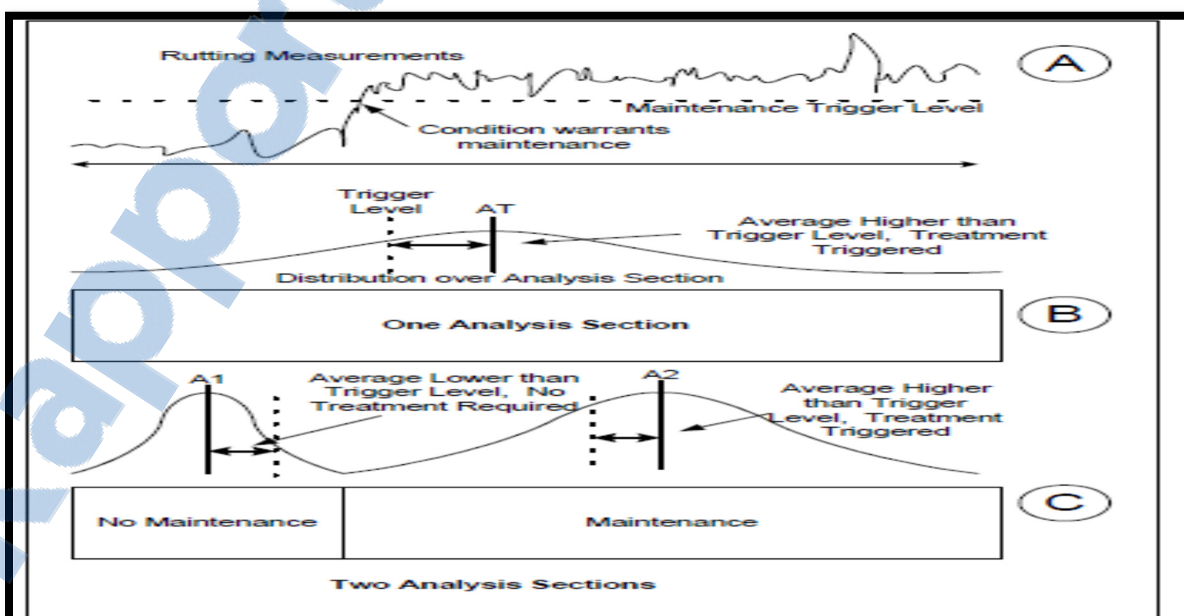


Figure 1.17 Implications of homogenous sectioning
Taken from Bennett (2004)

In order to determine the actual analysis sections for each pavement response, or breaking points, there are several approaches available including the Cumulative Differences Approach (AASHTO, 1993), the Bayesian approach (Thomas, 2005), a classification and regression tree (CART) approach (Misra and Das, 2003), to moving averages. One approach that has been developed by cartographers and is used extensively in GIS (ESRI based software) is the Jenks Optimization method or Natural Breaks classification method, which classifies data based on its distribution by reducing the variance within groups and maximizing variance between groups.(Assaf, 1993, Baz, Geymen and Er, 2008, ESRI, 2015). This method is illustrated in figure 1.18 below.

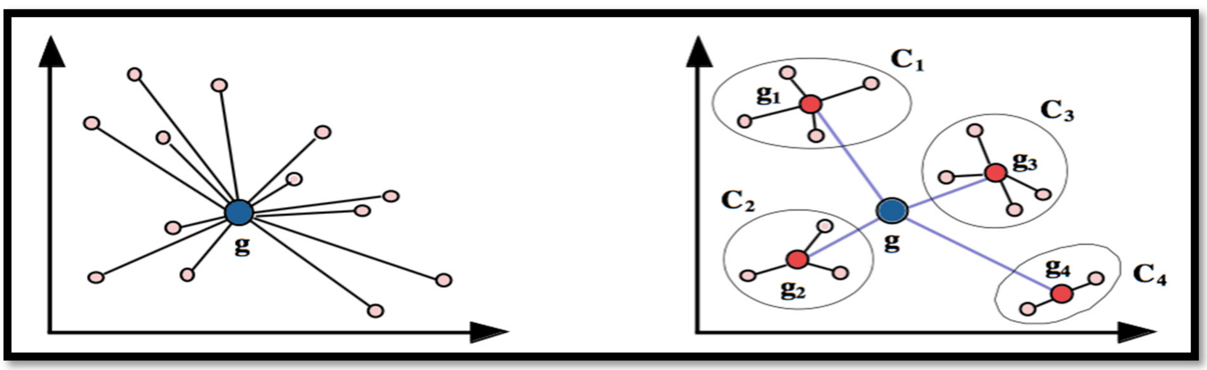


Figure 1.18 Graphical Representation of the Jenks Optimization
Taken from Gasso and LeRay (2014)

In the initial dataset, *g*, represents the mean value with one data class or group; by clustering the data through the Jenks Optimization approach, one would find four data classes or groups with individual means. For those road agencies that do not have the means, a more straightforward Excel-based approach may be better suited. This approach determines the sectioning by calculating the average pavement response variable for all points on the left of a data point and on the right to determine the highest difference between the left and right variables. The sum of the highest difference point represents the cut-off section.

The novelty of the proposed approach is the modification of the itinerary diagrams to integrate the behaviour of key factors of pavement deterioration throughout a pavements lifecycle (construction, rehabilitation and service periods) to modify and improve pavement deterioration curves and by extension pavement fatigue curves.

Using the previous design methodologies as an example, they both require routine pavement condition assessments to determine the levels of intervention; the MEPDGs through a mechanistic modeling of the pavement deterioration curve based on national data that may or may not be properly and fully calibrated to local conditions (Haas and Hudson, 2015); the francophone West African Pavement Design Manual uses a simplistic qualitative and quantitative assessment of cracking/deformations and structural capacity at a specific time, which do not rely on the determination of an empirically based pavement deterioration curve per se. Both examples demonstrate the inefficient use of (expensive) pavement condition data over time to drive the development of the pavement deterioration curves for specific families of pavements.

Secondly, pavement deterioration curves are an integral component of any economic analysis based on lifecycle costing. A standard approach used by most public agencies is to use some form of economic analysis to justify/prioritize investments. The economic analysis considers all the estimated agency costs user costs associated with the project over its lifetime (lifecycle); these include, but are not limited to, preliminary engineering costs, construction and supervision costs, maintenance and rehabilitation costs, land costs, agency overhead costs, and the salvage value at the end of the evaluation period. The user costs include vehicle operating costs (VOCs), travel time costs, and accident/costs. The user costs are generally calculated as a savings (or benefit stream) from performing a project versus the existing condition (Haas, Hudson and Zaniewski, 1994, Kerali, 2000, New Zealand Transport Agency 2013, Pavement Interactive, 2016).

In addition, in order for the HDM-4 model to produce credible results, a calibration of the model to local conditions is required. (Bennett and Paterson, 2000, Kerali, 2008). When properly calibrated and manipulated, HDM-4 has been shown to be fairly accurate in its predictive function for flexible pavements, although less effective for rigid pavements (Paterson and Bennett 1999, Li et al, 2004). Figure 1.19 below shows the differences between the default HDM-4 conditions and the actual observed results for Road User Effects (RUE), which shows significant operating cost differences for different vehicle types. Using the example below, the difference in the economic rate of return results would be quite significant, with the default values overstating the reality for five and seven axle trucks, but understating for two axle trucks.

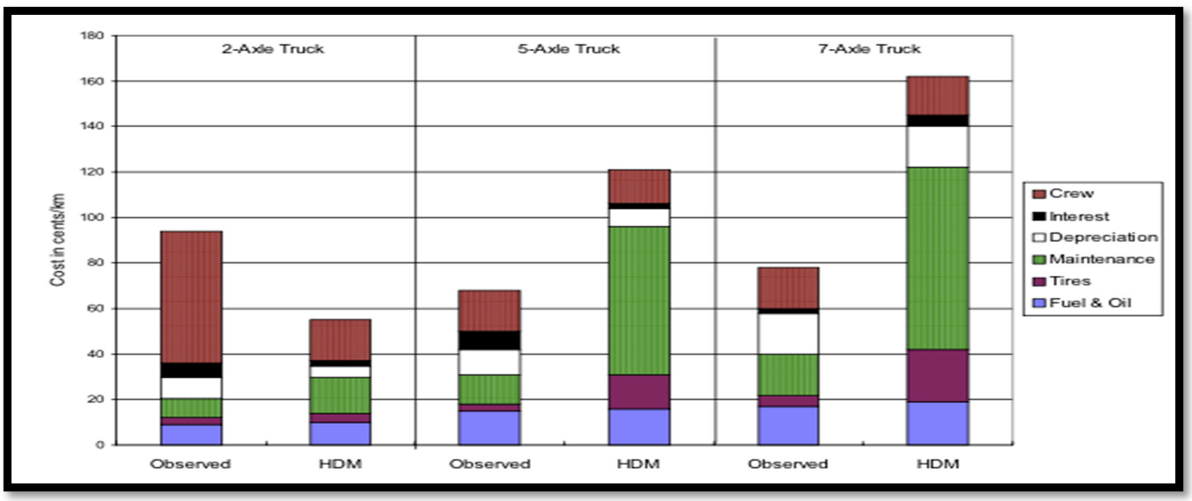


Figure 1.19 Comparison between observed and non-calibrated HDM RUE models
Taken from Bennett and Paterson (2000)

The flexible pavement deterioration curves used in HDM-4 are useful (when calibrated) for road agencies that have limited or poor pavement asset data; however, it is important to note that these deterioration curves were developed from numerous field studies. There is an apparent need to help refine these pavement deterioration curves based on each agency's own pavement conditions and environment.

The proposed itinerary diagram approach coupled with the Bayesian approach will assist the road agency in the development of their own pavement deterioration curves that can be used by HDM4 to more accurately predict pavement performance and thus performance management of the road network at lower capital investment costs.

CHAPTER 2

RESEARCH OBJECTIVES AND METHODOLOGY

2.1 Research objectives

The objectives of this research are as follows:

1) Develop a network-level prioritization model to rapidly ascertain cost-effective road project candidates for periodic maintenance or rehabilitation;

2) Develop a project-level optimization model to visually integrate all the relevant road engineering and economic information for multi-disciplinary project representation based on a graphical itinerary diagram; this will facilitate the recognition of the cause of deterioration, while providing a data visualization tool that assists the donor agency in maintaining transparency into the investment and provide the road agency with an as built file that can be integrated into their pavement management system; and

3) Develop a Bayesian statistical model using the itinerary diagram approach to "learn" from past and ongoing engineering investigations on similar pavement families of the most probable cause(s) of deterioration in order to improve pavement design techniques and asset management in developing countries.

2.2 Research methodology

The proposed methodology is threefold:

2.2.1 Network level prioritization model

The primary contribution is the development of a simple and straightforward approach to performing a network level prioritization model under limited time constraints. A calibrated

HDM4 model will develop a polynomial vehicle operating cost (VOC) curve for each vehicle class as a function of roughness, or IRI. As part of this thesis, a simplified model will be proposed using MS Excel using previous VOC curves developed by the World Bank (Archonodo-Callao, 2006) in over 44 countries, including Latin America and the Caribbean, Asia, Africa, and Eastern Europe and the former Soviet Union countries to determine through simulation an appropriate VOC range for each vehicle class that can be quickly adapted and modified over time. Note that the simulations performed under the World Bank study assumed paved roads on a flat terrain.

The second aspect that will be evaluated is pavement deterioration curves over time to adjust the IRI over the analysis timeframe. The IRI generally deteriorates over time, affecting the VOC savings. This will be performed through simulations using HDM-4 and supplemented with other previous work by others to determine the optimal pavement deterioration curve. With these two curves established, an MS Excel-based program will be developed to quickly simulate projected ERRs without spending significant time, money, and effort calibrating HDM-4. The easy-to-use program will be validated with engineering and economics data from other countries available within the MCC database on completed road projects.

2.2.2 Project level design technical optimization

An updated graphical representation of road data in the form of an itinerary diagram and dynamic sectioning of the road in homogeneous sections will be developed that incorporates a methodology to determine the cause of deterioration, based on the visual inspection of the pavement structure distress. The engineering process envisioned will provide the appropriate tests to conduct in order to confirm the preliminary cause of deterioration that was established based on the visual distress observations.

The itinerary diagram approach is modeled to facilitate transfer of the key field collected data into the road agency pavement management system database to begin building out the needed pavement performance curves for improved pavement design; this same approach feeds into an implementation monitoring and evaluation framework for the donor and road agency.

A case study of a previous project conducted in two sub Saharan African countries will be analyzed to validate the project level design optimization and highlight the benefits of the optimization cause-based approach relative to the status quo approach.

2.2.3 bayesian model to determine the most likely cause of deterioration

A Bayesian statistical model will be developed to integrate into the itinerary diagrams and road agency pavement management system to help identify the most probable cause(s) of pavement deterioration based on previous and ongoing engineering investigations on the network of similar pavement families. The objective of the model is to integrate a learning function in the pavement asset management approach that can help improve pavement engineering design in developing countries.

CHAPTER 3

FAST TRACK NETWORK LEVEL PRIORITIZATION MODEL

The objective of a network analysis is to identify and economically prioritize road investments over a medium- to long-term horizon based on funding constraints. A network prioritization requires a large amount of data, which may or may not be available, much less reliable, in developing countries. This creates a problem for donor or lending agencies, which have to make investment decisions in a short time period with limited available resources.

Donor agencies and lending institutions are at a disadvantage vis-à-vis the road agency in that the road agency knows more about its roads and is in a potential position to either misrepresent (purposefully or not) data or to provide poor quality data, which can lead to an overstating of traffic, or higher roughness values (IRI), etc. to make the road project investment more appealing for donor financing.

This issue is exacerbated when the economic feasibility is performed with a complex system like HDM-4 that requires a large number of pavement response variables, calibrations and adaptations, which makes it difficult to appreciate the reasonableness of the results.

With this problem in mind, it became apparent that a more streamlined approach is needed for donor agencies to quickly identify economically lucrative candidates for further engineering study. This network level approach, can be applied on the whole network or on a subsection of the network, only requires the most recent IRI and AADT, in addition to any VOC surveys that might have been performed. The only concern at this stage is to ensure that the data is reliable through spot checking. All of which will be verified by an independent consultant (hired by the donor agency) and prioritized using an Excel-based HDM-4 adapted model. The prioritization will rank the road projects from the most economically efficient investments for the donor agency to pursue down to the poorest, all of which can be performed in a short period of time, such as two months or so. Like HDM4, the model compares the “without” project scenario to the “with” project scenario using all the same assumptions (i.e. traffic growth, annual IRI deterioration), and addresses all the national, regional and/or subset of those roads.

3.1 Vehicle operating costs

Maximizing road investments economic returns requires an optimization of the lifetime user and road agency benefits and costs. The primary lifecycle benefit stream is comprised of VOCs as a function of the road roughness; higher traffic volumes, expressed as Average Annual Daily Traffic (AADT), mean cumulative higher vehicle operating cost savings, especially with higher percentage of trucks as a proportion of AADT. The typical components and their percentage contribution to vehicle operating costs are shown in table 3.1 below.

Table 3.1 Components of vehicle operating costs and relative contributions, Adapted from World Bank (2005)

Component	**Percentage Contribution (%)**	
	Private Cars	**Trucks**
Fuel	10-35	10-30
Lubricating Oil	<2	<2
Spare Parts	10-40	10-30
Maintenance (Labor)	<6	<8
Tires	5-10	5-15
Depreciation	15-40	10-40
Crew Costs	0	5-50
Other Costs and Overheads	10-15	5-20

The World Bank has noted that “operating cost relationships for road vehicles are far more generic and transferable between countries (World Bank, 2005);” as such, the vehicle fleet economic (ex-taxes) characteristics relative to roughness should be more or less comparable across countries, with an expected higher vehicle operating costs due to higher labor and overhead costs (North America, Western Europe) relative to fleets with lower labor and overhead costs (Sub-Saharan Africa, South Asia).

The World Bank collected vehicle fleet economic unit data from 44 countries covering Latin America and the Caribbean, Asia, Africa, and Eastern Europe and the former Soviet Union countries as tabulated in table 3.2 below.

Table 3.2 Average of 44 World Bank HDM-4 studies for developing countries vehicle fleet economic unit costs in 2005 US$
Adapted from Archonodo-Callao (2006)

	Motor_ cycle	Small Car	Medium Car	Delivery Vehicle	Four-Wheel Drive	Light Truck	Medium Truck	Heavy Truck	Articulated Truck	Small Bus	Medium Bus	Large Bus
Economic Unit Costs												
New Vehicle Cost (US$/vehicle)	1,400	6,000	13,000	15,000	29,000	22,000	40,000	65,000	90,000	15,000	70,000	80,000
New Tire Cost (US$/tire)	13.0	25.0	60.0	75.0	95.0	160.0	240.0	290.0	340.0	55.0	230.0	360.0
Fuel Cost (US$/liter)	0.34	0.34	0.34	0.34	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Lubricant Cost (US$/liter)	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10
Maintenance Labor Cost (US$/hour)	0.81	2.14	3.36	3.84	3.84	3.44	3.77	3.81	4.66	2.08	3.72	4.17
Crew Cost (US$/hour)	0.15	0.00	0.46	1.67	0.46	3.66	3.51	4.06	4.63	1.45	3.73	4.57
Overhead (US$/year)	40	110	150	55	270	410	1000	1260	6500	140	230	7000
Interest Rate (%)	12	12	12	12	12	12	12	12	12	12	12	12
Working Passenger Time (US$/hour)	0.50	1.50	1.50	1.50	1.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Non-working Passenger Time (US$/hour)	0.25	0.75	0.75	0.75	0.75	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Cargo Delay (US$/hour)	0.00	0.00	0.00	0.00	0.00	0.11	0.11	0.11	0.11	0.00	0.00	0.00
Basic Characteristics												
Kilometers Driven per Year (km)	14000	22000	22000	34000	34000	45000	55000	70000	82000	52000	73000	81000
Hours Driven per Year (hr)	700	700	700	1200	1200	1500	1700	2000	2200	1600	2000	2200
Service Life (years)	9	13	10	9	9	10	11	11	11	9	10	11
Percent Private Use (%)	100.0	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of Passengers (#)	1.0	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0	12.0	30.0	40.0
Work Related Passenger-Trips (%)	75.0	75.0	75.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	75.0	75.0
Gross Vehicle Weight (tons)	0.3	1.1	1.3	2.2	2.0	4.2	10.3	19.6	33.3	3.0	9.3	12.2

The 44-country World Bank average economic unit costs adjusted for inflation (Consumer Price Index, or CPI) to show 2015 US dollars and were input into the HDM-4 Road User Costs Model version 1.20 (03/03/2007) to derive the cubic polynomial function for each vehicle class. All default parameters of the program were maintained with the exception of the inflation adjusted economic unit costs.

The 2015 inflation adjusted vehicle operating cost curves as a function of IRI by class of vehicle is shown in figure 3.1 below.

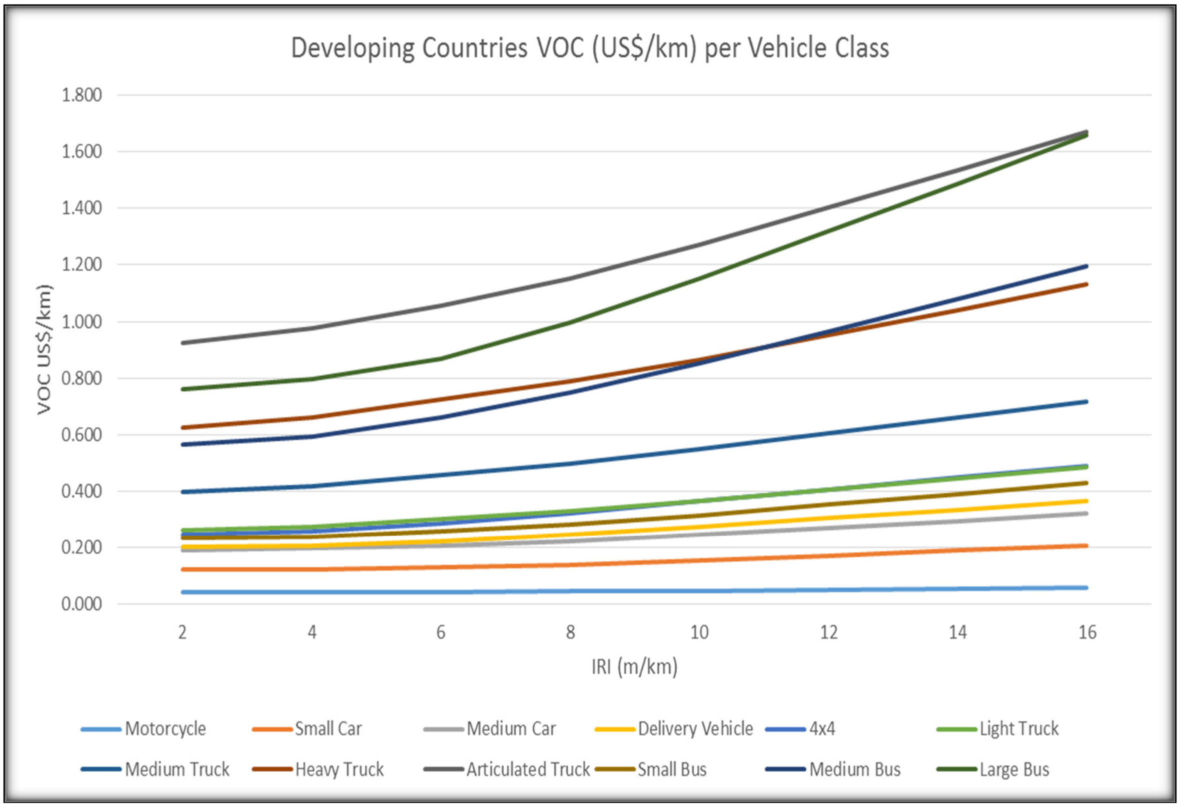


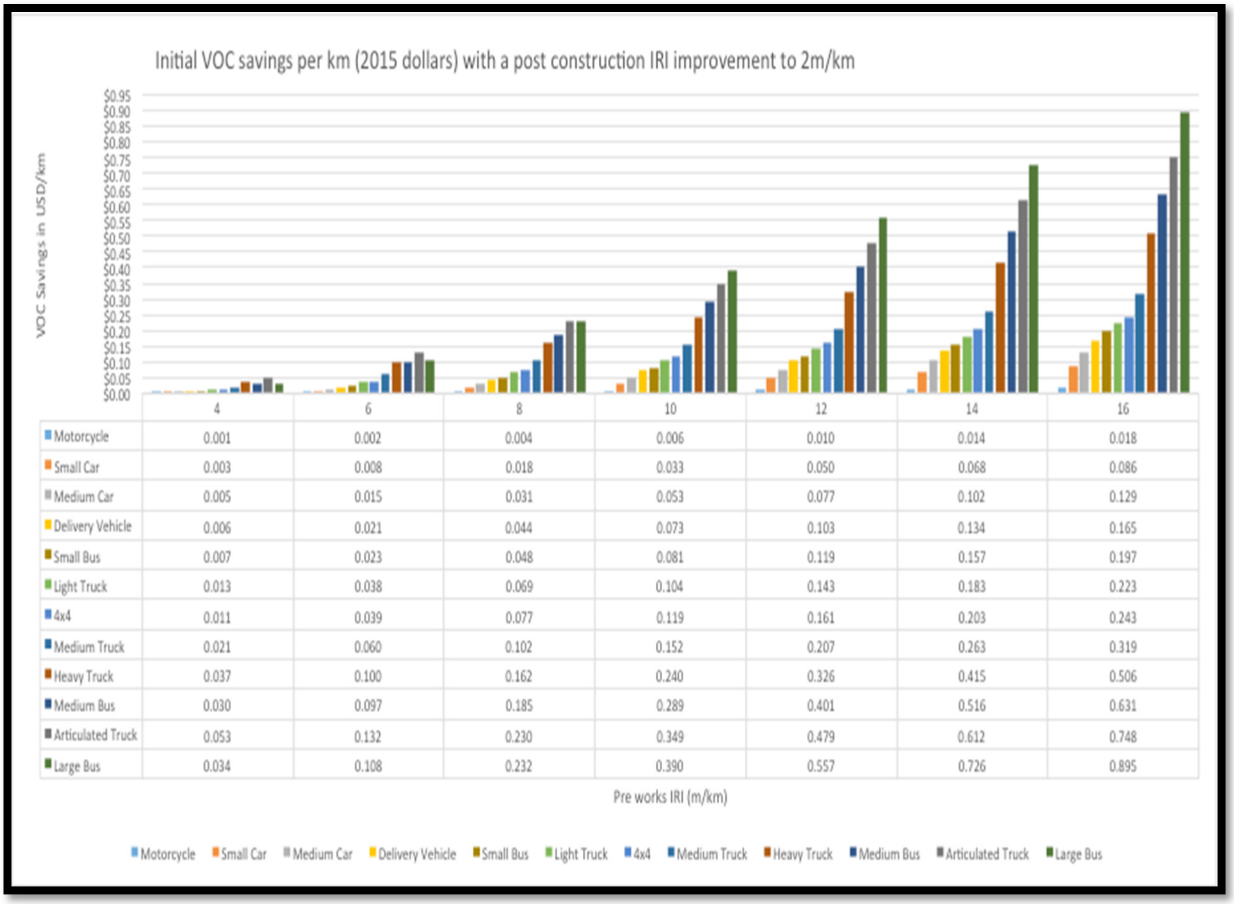
Figure 3.1 Developing countries VOC (US$/km)
per vehicle class in 2015 inflation adjusted US$ by IRI (m/km)
Taken from Archonodo-Callao (2006)

The functions for each vehicle class for developing countries VOCs as a function of IRI is shown in table 3.3 below:

Table 3.3 World Bank's 44 country average 2015 US$ inflation adjusted vehicle fleet cubic polynomial functions as calculated by the HDM-4 Road User Costs Model Version 1.20 (03/03/2007)

Unit Road User Costs ($/vehicle-km) = a0 + a1 * IRI + a2 * IRI^2 + a3 * IRI^3													
Coefficient	Motor_ cycle	Small Car	Medium Car	Delivery Vehicle	Four-Wheel Drive	Light Truck	Medium Truck	Heavy Truck	Articulated Truck	Small Bus	Medium Bus	Large Bus	Average Vehicle Fleet
a0	0.04275	0.12590	0.19565	0.22672	0.28726	0.25992	0.39663	0.61630	0.92363	0.28795	0.53564	0.77154	0.30498
a1	-0.00078	-0.00381	-0.00409	-0.00646	-0.00493	0.00052	0.00300	0.00777	0.00183	-0.00921	-0.00300	-0.02216	-0.00197
a2	0.00016	0.00083	0.00114	0.00194	0.00260	0.00132	0.00173	0.00229	0.00425	0.00237	0.00409	0.00757	0.00176
a3	0.00000	-0.00002	-0.00002	-0.00005	-0.00007	-0.00003	-0.00004	-0.00005	-0.00009	-0.00005	-0.00009	-0.00018	-0.00004

These VOC curves are used to determine the vehicle operating cost savings per kilometer for a proposed project intervention; the change in the pre works IRI to the expected post works IRI is the primary data point per vehicle class. Figure 3.2 below shows the VOC savings per km for various IRI levels ranging from 4 to 16 m/km, assuming the IRI is reduced to 2 m/km as a result of the works performed.



	4	6	8	10	12	14	16
Motorcycle	0.001	0.002	0.004	0.006	0.010	0.014	0.018
Small Car	0.003	0.008	0.018	0.033	0.050	0.068	0.086
Medium Car	0.005	0.015	0.031	0.053	0.077	0.102	0.129
Delivery Vehicle	0.006	0.021	0.044	0.073	0.103	0.134	0.165
Small Bus	0.007	0.023	0.048	0.081	0.119	0.157	0.197
Light Truck	0.013	0.038	0.069	0.104	0.143	0.183	0.223
4x4	0.011	0.039	0.077	0.119	0.161	0.203	0.243
Medium Truck	0.021	0.060	0.102	0.152	0.207	0.263	0.319
Heavy Truck	0.037	0.100	0.162	0.240	0.326	0.415	0.506
Medium Bus	0.030	0.097	0.185	0.289	0.401	0.516	0.631
Articulated Truck	0.053	0.132	0.230	0.349	0.479	0.612	0.748
Large Bus	0.034	0.108	0.232	0.390	0.557	0.726	0.895

Figure 3.2 Initial VOC savings per km (2015 US$) with a post construction
IRI improvement to 2m/km in Developing Countries by IRI (m/km)
Taken from Archonodo-Callao (2006)

For example using figure 3.2 above, the VOC savings generated from an improvement of the IRI from a 16m/km to a 2m/km for an articulated truck is approximately $0.75 per kilometer and $0.13 per kilometer for a medium car.

In many developing countries, the Average Annual Daily Traffic (AADT) is generally reported with the percent trucks given the importance of trucks to pavement design calculations. This coincides with the importance of trucks relative to passenger vehicles in terms of vehicle operating costs savings.

As such, the cubic polynomials have been grouped into two distinctive functions; automobiles and trucks. Automobiles are comprised of the HDM-4 categories “Small Car,” “Medium Car,” Delivery Vehicle,” “Small Bus,” and “Light Truck.” The trucks category is comprised of “Medium Trucks,” “Heavy Trucks,” “Articulated Trucks,” “Medium Bus,” and “Large Bus.” Note that grouping of the available vehicular classes was made through the review of the VOC savings per interval of roughness; the distribution of each categories into automobiles and trucks was based on the approximate equivalent single axle load (ESAL), with typical ESAL values below 1 grouped in automobiles and above 1 into trucks. The distribution of these VOCs by roughness is shown in Table 3.4 below and is about a multiple of 3 difference, which corresponds to previous literature findings (Barnes and Langworthy, 2003).

Table 3.4 Average VOCs for automobiles and trucks for 44 developing countries in 2015 US$ by IRI (m/km)

Roughness (IRI, m/km)	**Automobiles (in 2015 US$)**	**Trucks (in 2015 US$)**	**Ratio of Truck to Automobile VOCs**
2	$0.22	$0.66	2.99
4	$0.23	$0.70	3.05
6	$0.24	$0.76	3.10
8	$0.27	$0.84	3.09
10	$0.31	$0.93	3.06
12	$0.34	$1.04	3.04
14	$0.38	$1.15	3.03
16	$0.42	$1.26	3.02
18	$0.45	$1.37	3.01
20	$0.49	$1.48	3.02

The average 2015 inflation adjusted vehicle-operating costs (in USD$) for both automobiles and trucks in the 44 developing countries per IRI unit (m/km) is shown in figure 3.3 below.

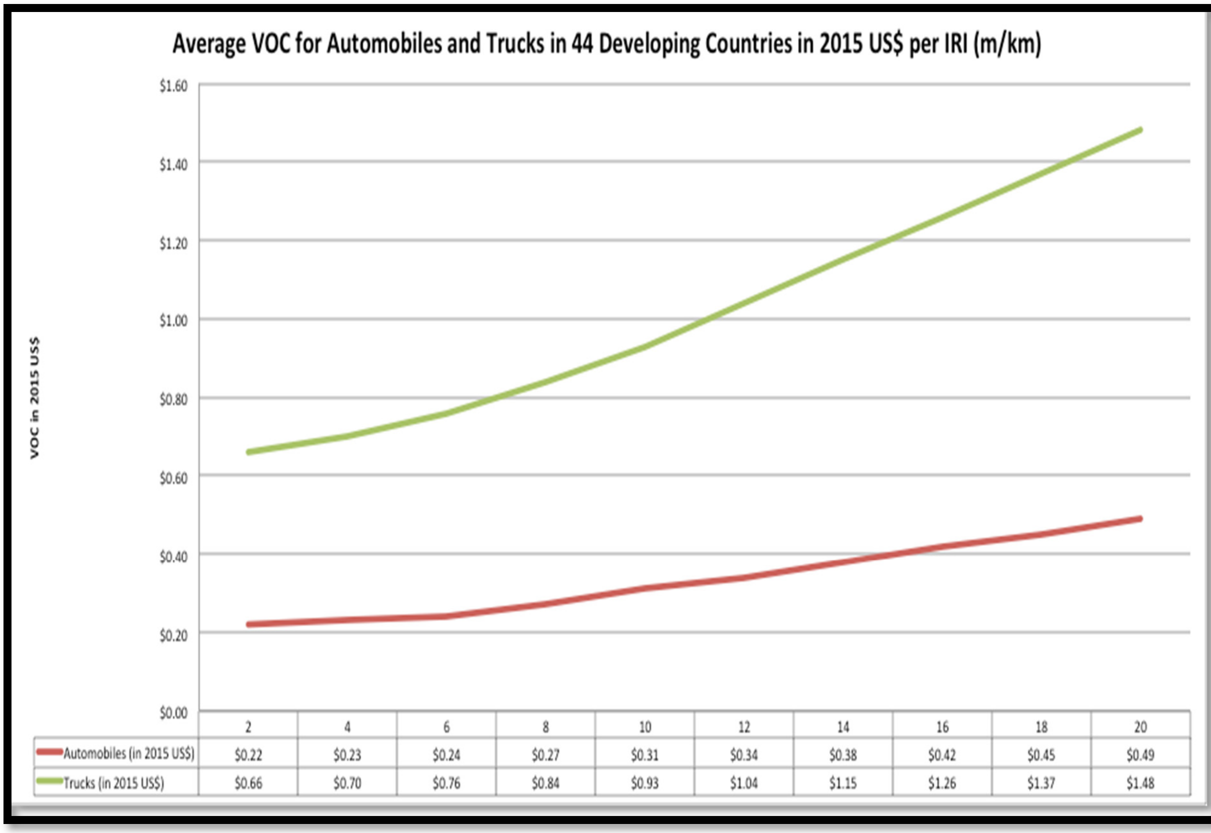


Figure 3.3 Average VOC for automobiles and trucks in 44 developing by IRI (m/km) countries in 2015 inflation adjusted US$

The derived cubic polynomials from the HDM-4 Road User Costs Model version 1.20 (03/03/2007) are as follows:

Automobiles User Costs ($/vehicle-km) = -0.00004 x IRI^3 + 0.00178 x IRI^2 -0.00570 x IRI + 0.23057

Trucks User Costs ($/vehicle-km) = -0.00008 x IRI^3 + 0.00354 x IRI^2 -0.00201 x IRI + 0.64875

With these two curves established, the VOC savings from the no project and the project scenario can be determined with the initial IRI and AADT with percent trucks for the first year. For subsequent years, assumptions on the rate of roughness deterioration need to be made.

3.2 IRI

The two primary IRI elements to consider for this model are the annual IRI deterioration rate and the collection of the IRI data in the field.

3.2.1 Annual IRI deterioration rate

Ideally, the deterioration of the IRI over time could be determined with the road agency's PMS; however, this information may not be available, and if available, the information may not be reliable. The HDM-4 model for IRI deterioration is built off of the HDM III component incremental model (i.e. various factors affect the IRI and should be modeled as such), comprising of structural deformation effects (loading), rutting, cracking, potholing and environmental conditions effects. The only major change between the two versions was an updating of the potholing effect (Morosiuk, Riley and Odoki, 2004).

The formula is written as follows (Morosiuk, Riley and Odoki, 2004):

$$\Delta RI = \Delta RI_s + \Delta RI_c + \Delta RI_r + \Delta RI_p + \Delta RI_e$$

ΔRI = total incremental change in annual roughness (IRI as $\left(\frac{m}{km}\right)$)

ΔRI_s = annual change in roughness due to structural effects

ΔRI_c = annual change in roughness due to cracking effects

ΔRI_r = annual change in roughness due to rutting effects

ΔRI_p = annual change in roughness due to potholing effects

ΔRI_e = annual change in roughness due to environmental effects

Cracking in HDM-4 plays a large role influencing rutting, potholing and roughness as shown by figure 3.4 below. Raveling is built into the potholing equation.

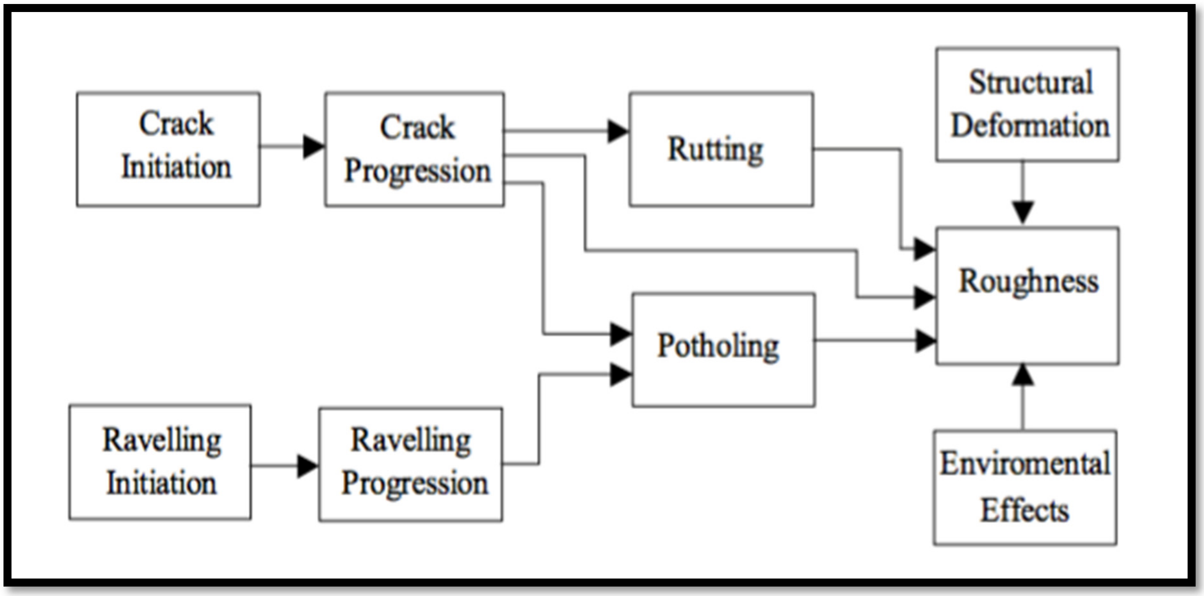


Figure 3.4 HDM-4 factors determining overall roughness
Taken from Li et al. (2004)

As the model is comprised of five influential models, the effect of each on the total roughness will vary. The difference between a low traffic, weaker (SNP) and thinner pavement (5cm asphalt overlay) is illustrated in figure 3.5 relative to a higher traffic, stiffer (SNP) and thicker pavement (10cm asphalt overlay) illustrated in figure 3.6. The total annual linearized roughness change shown in figure 3.5 is approximately 0.2m/km, while in figure 3.6 about 0.3m/km.

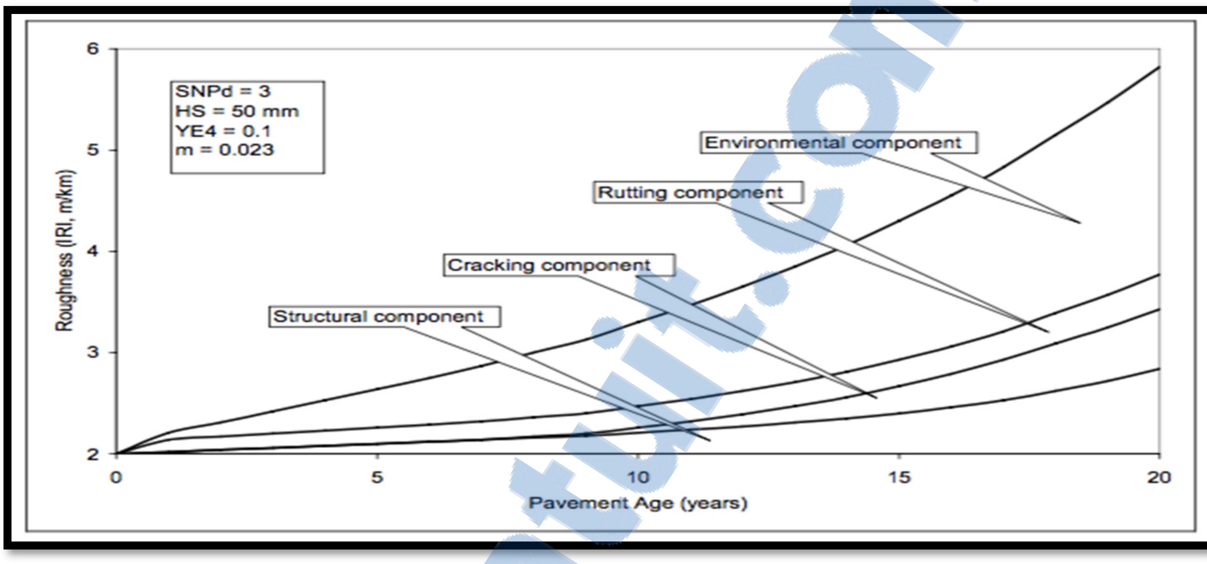


Figure 3.5 Roughness Progression for a low traffic (YE4) over time
thin pavement (5cm asphalt overlay)
Taken from Morosiuk, Riley and Odoki (2004)

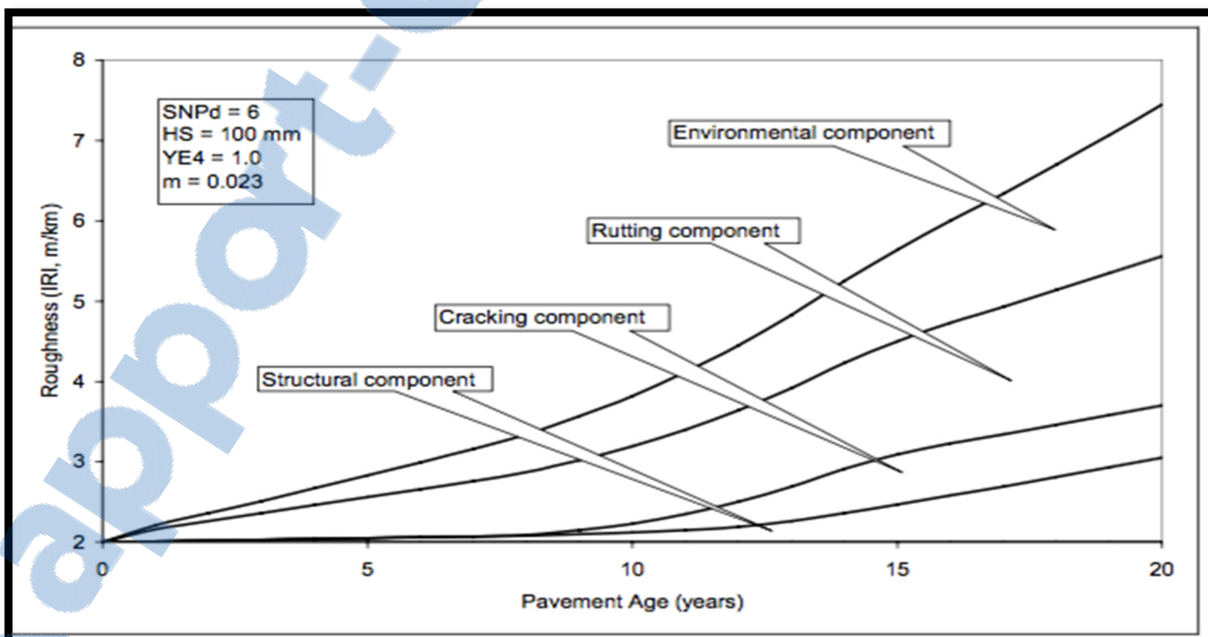


Figure 3.6 Roughness Progression for a high traffic (YE4) over time
thicker pavement (10cm asphalt overlay)
Taken from Morosiuk, Riley and Odoki (2004)

The HDM-4 roughness deterioration appears fairly consistent with other roughness models. Figure 3.7 below illustrates the progression of the IRI over time, which follow a mostly linear degradation until the road is too degraded, beyond which the deterioration rate accelerates, with ranges from 0.1m/km to 0.24 m/km. This in itself supports the point for early proactive preventive maintenance rather than reactive curative and costly rehabilitation.

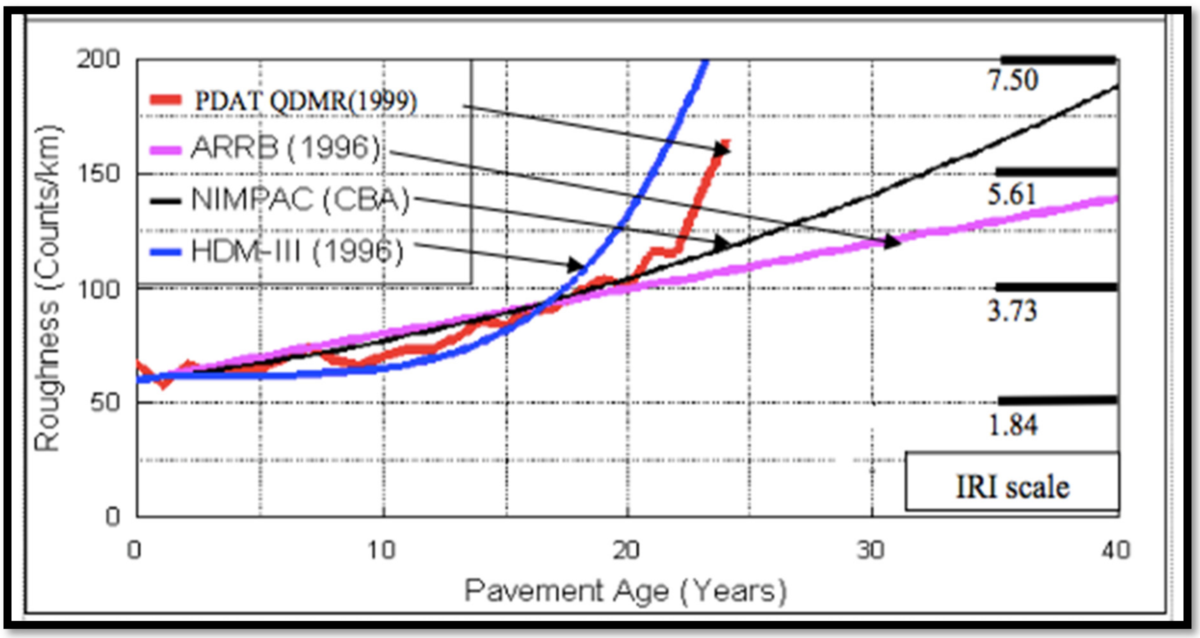


Figure 3.7 Comparison of the age/roughness relationship for four roughness progression models over time Taken from Hunt and Bunker (2002)

Dong and Huang (Dong and Huang, 2012) found the following relationships using LTPP data using the following formula:

$$IRI = k \times AGE + b \quad (3.1)$$

Table 3.5 below shows the slope (k), or the rate of pavement deterioration per year, for each pavement, with the range between 0.16 m/km and 0.33 m/km for the pre model and 0.01 m/km to 0.05 m/km for the post work. This assumes adequate maintenance is performed.

Table 3.5 IRI pre work and post work results from LTPP Analysis
Adapted from Dong and Huang (2012)

Number	Type	KESAL per year	Overlay thickness (in.)	Total pavement thickness (in.)	Premodel k_1	Premodel b_1	Postmodel k_2	Postmodel b_2	Pre-IRI	Post-IRI	IRI drop	Benefit by year	Benefit by traffic
1	51	53	13.5	84.1			0.01	0.52	1.25	0.55	0.69		
2	19	395	11.4	73.4	0.16	2.25	0.02	0.50	2.22	0.52	1.70	16	2,612
3	19	339	6.6	86.9	0.33	1.99	0.01	0.38	1.75	0.45	1.30	17	4,534
4	51	64	14.0	92.2			0.05	0.43	1.02	0.65	0.37		
5	19	77	3.8	36.3	0.22	1.88	0.02	0.77	1.78	0.77	1.01	13	717
…													
Counts	519		515	519	192	192	511	511	429	516	429	154	154

Note: KESAL = kilo–ESAL; k_1 and b_1 = slope and intercept of prehabilitation linear performance curve, respectively; b_1 = prehabilitation pavement serviceability index (PSI); k_2 and b_2 = slope and intercept of postrehabilitation linear performance curve, respectively.

Martin (Martin, 2004) of AUSTROADS has estimated the following roughness deterioration rates using data from Australia calibrated to HDM-4; the annual roughness deterioration range is approximately between 0.05m/km to 0.01m/km as shown in figure 3.8 below.

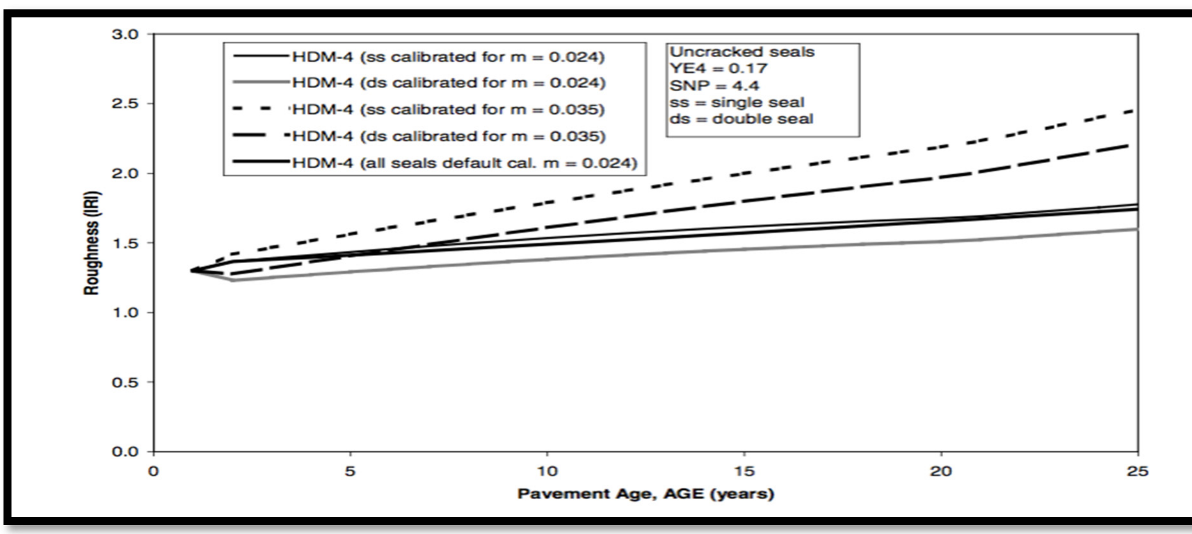


Figure 3.8 IRI (m/km) as a function of pavement age
Taken from Martin (2004)

Table 3.6 recapitulates the annual estimated IRI linear deterioration rates from the various sources and literature review.

Table 3.6 Summary table of annual estimated IRI linear deterioration rates

Source	**Annual estimated IRI Linear Deterioration Rates (m/km)**
HDM4 Low Traffic (Morosiuk, Riley and Odoki, 2004)	0.2 m/km
HDM4 High Traffic (Morosiuk, Riley and Odoki, 2004)	0.3 m/km
HDM III (Hunt and Bunker, 2002)	0.24 m/km
PDAT (Hunt and Bunker, 2002)	0.15 m/km
NIMPAC (Hunt and Bunker, 2002)	0.14 m/km
ARRB (Hunt and Bunker, 2002)	0.1 m/km
LTPP (Dong and Huang, 2012)	0.16 to 0.33 m/km
AUSTROADS (Martin, 2004)	0.01 to 0.05 m/km

To maintain a degree of conservatism, the IRI deterioration rate is estimated at an annual linear deterioration of 0.25 m/km; however, this can be modified to meet country specific needs and experience. The sensitivity is fairly low with regards the ERR; changes of 1 to 2 percentage points over the life of the investment. Note that the annual linear IRI deterioration rate is assumed to be the same for the "without" project and the "with" project scenario.

3.2.2 Collection of IRI data

The verification of the IRI data provided by the road agency is one of the most critical steps in the process. The donor agency will recruit a consulting engineer to properly measure the IRI on the proposed network using a World Bank Class III or better device in full compliance with proper procedures (i.e. ASTM E1364-95 for the Level and Rod Calibration section and ASTM E950M-09 for and Inertial Road Profiler), for proper calibration of precision and bias.

Once the data is collected, it needs to be analyzed and sorted into homogenous sections; there are many manners in which to section the IRI measurements (as previously discussed in the literature review), however the objective is to arrive at a manageable number of homogenous sections, as these will become the basis for the prioritization. An example performed on an 82 km section of road is shown in figure 3.9 below with five homogenous sections.

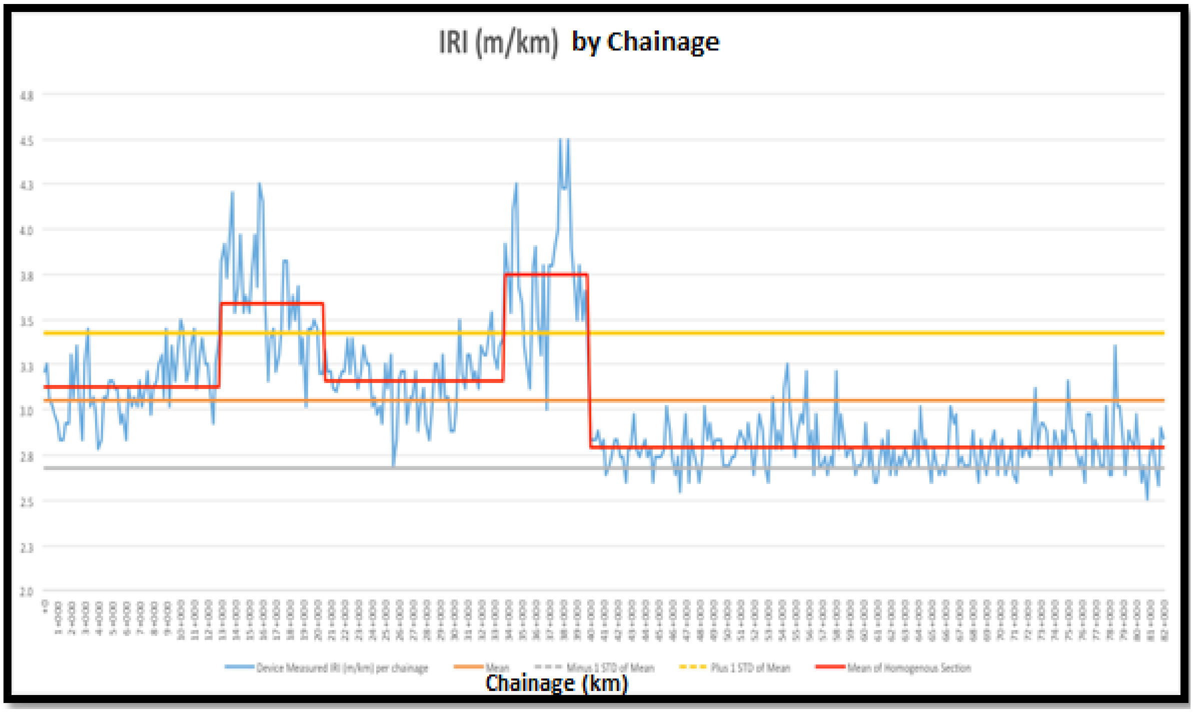


Figure 3.9 Homogenous sectioning for IRI through mean analysis by chainage

For large datasets, sectioning for the IRI can be calculated by taking the average IRI measurement for all points on the left of a data point and on the right to determine the greatest difference between the left and right variables. The best cut-off point is when the difference in averages left and right of the cut-off point is the highest.

Once the analysis is complete, the results should be compared to the road agency provided figures and analyzed for any differences. Significant differences indicate the need for improvement in data collection and analysis techniques at the road agency and serve as a baseline performance objective for road agency improvement.

3.3 Capital and maintenance costs

The major components of the road agency costs are the capital expenditure, routine, and periodic maintenance requirements. A basic rule of thumb developed over several countries is to provision 2% of the capital costs annually for routine maintenance; this is confirmed (conservatively) by the World Bank data below for rehabilitation works (majority of work proposed for donors); the mean annual routine maintenance cost of $3,130 divided by the mean rehabilitation cost of $251, 882 provides 1.25%.

Periodic maintenance costs can be estimated with the general assumption used in the model as the provision of a structural overlay (say mill and fill) at US$90,000 every 8 years to correct the IRI by 1 m/km. This assumption can be modified in the model if the country has significant capacity to provide further IRI reduction.

In general, these costs are available in country; however, the costs from the World Bank have been provided in 2015 US dollars for reference (adjusted with CPI Inflation Calculator provided by the Bureau of Labour Statistics) in table 3.7 below.

Table 3.7 Maintenance costs for two lane roads in 2015 US$ (CPI)
from World Bank ROCKs database
Adapted from Burningham and Stankevich (2005)

Work Class	**Work Type**	**Work Activity**	**Minimum**	**Maximum**	**Mean**
Routine	Routine Maintenance	Unsealed 2 lane Highway	$394	$2475	$1,407
		Bituminous 2 lane Highway	$933	$7,940	$3,130
Periodic	Grading	Light Grading	$73	$291	$156
		Heavy Grading	$460	$1,250	$740
	Gravel Resurfacing	Re-gravelling	$2,840	$92,527	$21,800
	Bituminous Pavement	Fog Seal	$3,990	$22,450	$12,700
	Unsealed	Unsealed Preventive Treatment	$2,860	$22,500	$6,007
	Surface Treatment Resurfacing	Slurry Seal or Cape Seal	$6,475	$39,150	$139,200
		Single Surface Treatment	$7,553	$55,000	$26,940
		Double Surface Treatment	$15,450	$64,414	$38,470
	Asphalt Mix	Asphalt Overlay < 40mm	$18,321	$117,115	$54,200
	Resurfacing	Asphalt Overlay 40 to 59mm	$29,905	$179,440	$97,756

Additionally, the average and median rehabilitation and construction costs from the World Bank adjusted to 2015 US$ via the CPI is shown in table 3.8 below for reference.

Table 3.8 World Bank road works costs per km in 2015 US$ (CPI)
Adapted from Archondo-Callao (2000)

Works Classification	Average Cost (2015 US$)	Median Cost (2015 US$)
Rehabilitation	$294,551	$251,882
Construction	$1,191,967	$1,319,973

3.4 Traffic

The two major components of traffic for this model are the annual traffic growth rate and the verification of the Annual Average Daily Traffic (AADT).

3.4.1 Annual traffic growth rate

The annual traffic growth rate is assumed to be 3 percent for the entire fleet for the purposes of this model. A higher growth rate, especially for higher truck traffic, will have a correspondingly higher effect on the ERR. The MS Excel worksheet does allow for adjustments of the traffic growth rate, however. The annual traffic growth rate may also be available with the local road agency.

3.4.2 Annual average daily traffic (AADT)

As AADT figures have been provided by the road agency, the principal objective at this stage is to verify that the provided AADT figures are within an acceptable range, rather than to conduct full traffic count survey using the same vehicle classification as the road agency. One approach is the "Moving Observer Survey," which is intended to categorize traffic into broad survey bands. The survey should be conducted for at least one hour using a mobile vehicle. The commonly used formula proposed for conversion of a count for a particular period to daily flow is:

$$\text{Daily Traffic} = w * (x+y+z) / t \quad (3.2)$$

Where:

w = average number of hours of traffic operation generally observed (12-18 hours)

x = number of vehicles travelling in opposite direction

y = number of vehicles overtaking the observer

z = number of vehicles overtaken by the observer

t = time in hours.

The moving observer approach is meant to quickly validate the appropriate traffic range and vehicle classification percentages along a road segment, with the road agency AADT figures used if validated. Significant deviations from the road agency model may require additional traffic counts to confirm.

The road segments under consideration will need to be broken up into homogenous sections, especially as traffic flows can change from segment to segment depending on industry, commercial or residential traffic usage patterns. Road agencies generally take the changes in traffic volume into consideration with the placement of traffic counting posts, however instances have been found where the traffic posts where placed at a convenient (for the traffic counting team) over the most appropriate location that properly accounts for traffic patterns (say outside of urban or semi-urban areas).

Once the road segments are divided into sections by AADT, then further sub-sectioning by IRI can be performed. Sectioning for the IRI can be calculated by taking the average IRI measurement for all points on the left of a data point and on the right to determine the greatest difference between the left and right variables. The best cut-off point is when the difference in averages left and right of the cut-off point is the highest.

3.5 Validation of the err MS Excel-based model

In order to validate the MS Excel-based model, comparisons with actual HDM-4 runs were made and evaluated. Previous work performed by an independent consultant "A"[2] in a developing country with an HDM-4 Level 1 calibrated workspace was used; in particular 32 independent runs were compared, with the results shown in table 3.9 below.

Table 3.9 Comparative ERR results between HDM-4 and the proposed model

Section ID	Distance (kms)	AADT	% Trucks	IRI (m/km)	Cost/km (US$)	HDM 4 Runs	Excel Model	Decision Based on HDM4	Decision Based on Excel	Validation of Excel Model to HDM4
Section 8.1.4	0.5	6683	42%	3.3	$ 420,000	18%	-33%	TRUE	FALSE	No
Section 3.2.3	12.6	14098	10%	4.2	$ 653,968	10%	-20%	FALSE	FALSE	Yes
Section 9.3.3	11.1	2177	42%	6.4	$ 418,018	7%	-17%	FALSE	FALSE	Yes
Section 9.3.1	27.4	2177	42%	6.8	$ 478,248	24%	-17%	TRUE	FALSE	No
Section 22.2	3.7	2632	12%	6.5	$ 256,757	60%	-8%	TRUE	FALSE	No
Section 3.1.1	1.6	21305	10%	4.2	$ 650,000	17%	-8%	TRUE	FALSE	No
Section 8.1.1	24.8	6683	42%	5.2	$ 418,145	13%	4%	TRUE	FALSE	No
Section 3.2.4	6	14098	10%	5.6	$ 653,333	8%	4%	FALSE	FALSE	Yes
Section 3.1.2	1.5	21305	10%	5.4	$ 833,333	9%	7%	FALSE	FALSE	Yes
Section 15.6	1.5	3350	15%	9	$ 420,000	2%	10%	FALSE	FALSE	Yes
Section 9.3.2	49.9	2177	42%	9.7	$ 418,156	6%	12%	FALSE	FALSE	Yes
Section 8.1.2	17.6	6683	42%	6.1	$ 418,182	12%	19%	FALSE	TRUE	No
Section 3.2.2	2.9	14098	10%	5.6	$ 417,241	7%	23%	FALSE	TRUE	No
Section 8.1.3	33.8	6683	42%	6.7	$ 418,047	10%	29%	FALSE	TRUE	No
Section 22.1	15.9	2632	12%	13.5	$ 420,126	36%	32%	TRUE	TRUE	Yes
Section 29.4	13.8	2879	12%	11	$ 257,246	69%	44%	TRUE	TRUE	Yes
Section 15.1	6.25	3350	15%	10	$ 257,600	77%	45%	TRUE	TRUE	Yes
Section 15.3	14.2	3350	15%	11	$ 257,042	77%	57%	TRUE	TRUE	Yes
Section 29.1	17.8	2879	12%	12.5	$ 256,742	70%	60%	TRUE	TRUE	Yes
Section 3.1.3	1.2	21305	10%	6.3	$ 416,667	14%	65%	TRUE	TRUE	Yes
Section 29.3	9.4	2879	12%	13.5	$ 257,447	68%	70%	TRUE	TRUE	Yes
Section 3.2.1	1.1	14098	10%	7.8	$ 418,182	5%	70%	FALSE	TRUE	No
Section 1.1.1	7.1	32388	12%	5.5	$ 418,310	18%	74%	TRUE	TRUE	Yes
Section 15.5	2.8	3350	15%	12.5	$ 257,143	84%	75%	TRUE	TRUE	Yes
Section 29.2	4.6	2879	12%	15	$ 256,522	70%	86%	TRUE	TRUE	Yes
Section 15.4	1.6	3350	15%	14	$ 256,250	71%	94%	TRUE	TRUE	Yes
Section 15.2	0.75	3350	15%	16	$ 253,333	77%	118%	TRUE	TRUE	Yes
Section 1.1.2	2.9	32388	12%	7	$ 417,241	13%	138%	TRUE	TRUE	Yes
Section 14.6.1	11.9	9914	10%	12	$ 350,420	108%	148%	TRUE	TRUE	Yes
Section 3.1.4	2.1	21305	10%	9.3	$ 419,048	8%	162%	FALSE	TRUE	No
Section 14.6.3	3.6	9914	10%	12	$ 236,111	93%	220%	TRUE	TRUE	Yes
Section 14.6.2	10.3	9914	10%	16	$ 360,194	71%	235%	TRUE	TRUE	Yes

[2] The name of the consultant and the country are identified respectively as A and C for confidentiality.

The MS Excel based model results and the HDM-4 model results were compared against each other with a minimum 12% investment threshold in mind. The green boxes labeled "yes" indicate both models were in agreement, while the red boxes labeled "no" indicated disagreement between the two models.

The results indicate that: 1) the proposed Excel based model matches the HDM-4 overall investment decision result 69 percent of the time; 2) the accuracy of the model in selecting lucrative projects increases with the ERR, tending towards 90 percent at high ERR levels (30 percent and above). Figure 3.10 below summarizes the findings in graphic format.

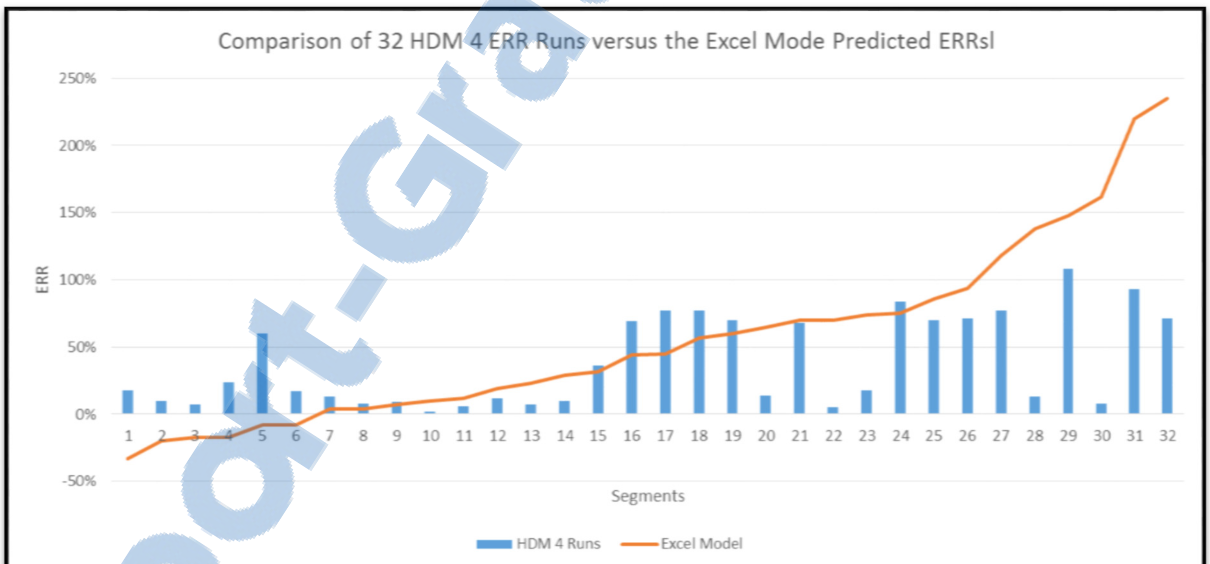


Figure 3.10 Comparison of 32 HDM-4 runs with the proposed MS Excel model

It should be noted that the HDM-4 results might be skewed relative to the MS Excel model due to a limitation in HDM-4 to consider atypical (to HDM-4) designs, which were used under these HDM-4 runs. In this case, a 5cm thick fiber reinforced and polymerized asphalt concrete (assumed 4000 MPa) was used on a 30cm, 7 percent-cement reclaimed base course (assumed 3000 MPa) on the existing well-compacted subbase estimated at an assumed 300 MPa (CBR of 30-50%) as result of good lateral drainage to avoid it from being soaked.

The addition of the polymer with fiber into the asphalt concrete to reduce fatigue cracking and rutting is not taken into account in the HDM-4 models, which are largely based on previous studies in developing countries that had not used this technology. The use of a modified high performance asphalt concrete will result in a much less temperature susceptible Hot Mix Asphalt (HMA) mix, which is important in hot climates, as the modified HMA mix will deploy a much higher modulus at hot temperatures relative to traditional non-modified HMA mixes. The HDM-4 model, however has not been adjusted, or calibrated, to account for these technological advances in HMA mix design. HDM-4 adopted the traditional AASHTO Structural Number approach, which assigns a stiffness coefficient to each layer based on material and thickness as shown in table 3.10 below.

Table 3.10 HDM-4 adopted pavement layer coefficients the surface layer
type coefficients for surface treatments (ST) and Asphaltic Mix (AM)
Adapted from Morosiuk, Riley and Odoki (2004)

Layer	Layer Type	Condition	Coefficient
Surfacing	ST	Usually 0.2	a_i = 0.20 to 0.40
	AM	h_i < 30 mm, low stability and cold mixes	a_i = 0.20
		h_i > 30 mm, MR_{30} = 1500 MPa	a_i = 0.30
		h_i > 30 mm, MR_{30} = 2500 MPa	a_i = 0.40
		h_i > 30 mm, MR_{30} ≥ 4000 MPa	a_i = 0.45
Base	GB	Default	$a_i = (29.14\ CBR - 0.1977\ CBR^2 + 0.00045\ CBR^3)\ 10^{-4}$
		CBR > 70, cemented sub-base	$a_i = 1.6\ (29.14\ CBR - 0.1977\ CBR^2 + 0.00045\ CBR^3)\ 10^{-4}$
		CBR < 60, max. axle load > 80kN	a_i = 0
	AB, AP	Dense graded with high stiffness	a_i = 0.32
	SB	Lime or cement	$a_i = 0.075 + 0.039\ UCS - 0.00088(UCS)^2$
Sub-base		Granular	$a_j = -0.075 + 0.184(\log_{10} CBR) - 0.0444(\log_{10} CBR)^2$
		Cemented UCS > 0.7 MPa	a_j = 0.14

The modified HMAs structural coefficient, however, has been shown to be a bit higher (22 percent), or stiffer, with an initial 18.5% reduction in thickness per figure 3.11 below. While the additional cost of the modified bitumen will result in about a 10-15 percent cost increase

(Buncher and Rosenberger, 2005), this is largely compensated with better performance, and therefore less maintenance and a prolonged life.

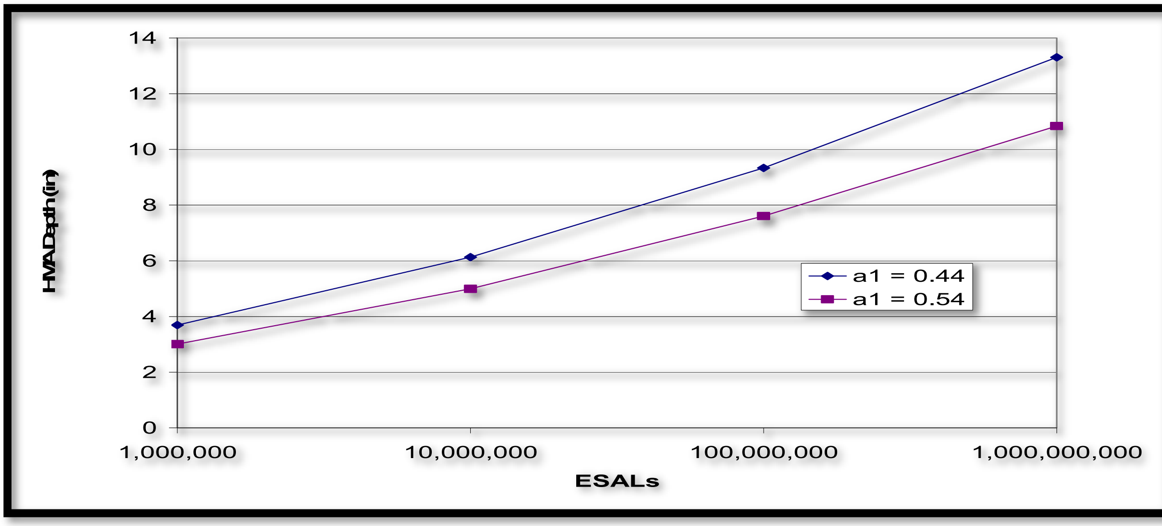


Figure 3.11 Effect of Modified Pavement Mixes (lower, purple line) relative to traditional Pavement Mixes (higher, blue line) on the AASHTO Structural coefficient (a1)
Taken fron Peter-Davies and Timm (2009)

Secondly, the fibers are known to increase the indirect tensile strength of the asphalt concrete by upwards of 20 to 30 percent, which reduces the effects of fatigue cracking and rutting. The resistance to fatigue cracking with the addition of fibers as a percentage of the bitumen is shown in figure 3.12 below.

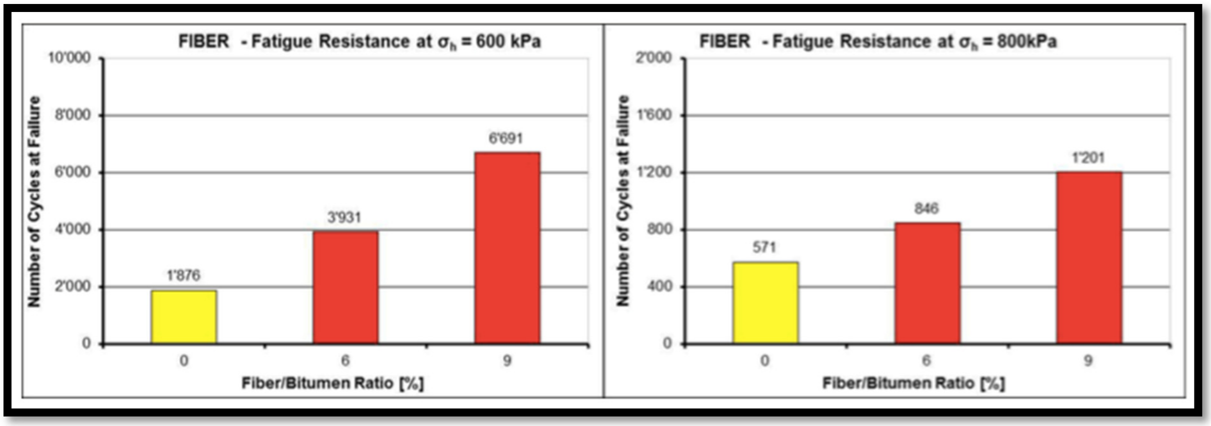


Figure 3.12 Fatigue resistance of bitumen at two frequencies as a ratio of fiber to bitumen
Taken from Montanelli (2013)

In effect, the use of fiber reinforced asphalt concrete requires further calibration of the HDM-4 roughness coefficients for cracking initiation, rutting and potholing; the effect would be an improved roughness model with higher vehicle operating cost savings as cracking initiation is delayed due to the higher stiffness and resistance to oxidation of the modified HMA.

In conducting the application in the country example above, one interesting additional finding came out to support the theory of isomorphic mimicry (See literature review and PDIA reference) and potentially premature loading. Specifically, VOC curves were collected and normalized to 2015 US$ and plotted together by vehicle class. Theoretically the VOC curves should have similar slopes with the various movements along the y axis a function of labor rates in the country as all other costs are economic costs, or similar (for example tires, spare parts, fuel cost, etc.). The HDM-4 model calculates the difference in moving from one IRI unit to another as a result of an intervention, so slopes are important.

The isomorphic mimicry occurs as the consultant that was hired to perform the VOC survey appeared very competent, had specific experience in the region working for a reputable international engineering firm, yet established a VOC curve for the country that began $2 per vehicle per km (on the y-intercept) higher than comparable vehicles in North America and much higher than the World Bank average for SSA.

Worse, the slopes were shown to increase dramatically relative to the other countries; the result was a very significantly overestimated benefit stream. As previously mentioned, the consultant has an incentive to provide higher ERRs on projects to please the donor; a happy donor with robust results can translate into future work opportunities, including supervising the execution of the works. Secondly, the consultant may inflate the benefit stream to compensate for their poor non-optimal design, which provides more safety (in terms of reliability) but also pleases the host country by inflating the project cost and therefore its short-term benefits (more materials used, more work, more expenditures, more political benefits and potential rent seeking).

In this case, the consultant proposed very expensive solutions that were several times larger than needed. The higher benefit stream, however, allowed the consultant to show suitable economic returns thus masking the poor engineering and design capacities of the firm and its disregard to optimize the donors return on investment, intentionally or not, yet misleading the donor organization into believing the investment is a good one.

It should be noted that consultant's work was revised (and corrected) by an experienced transport engineer with the VOC curves fitting nicely into the category average.

The premature loading (see PDIA under the literature review) was the ability of the consultant to perform this work without proper training and instruction; the consultant was hired and expected to perform, when in reality the consultant was learning on the job at the client's expense. Most donors or owners don't have access to HDM-4 or are not fluent in its use. Therefore, they rely on the consultant's know how and engineering ethics. This clearly leaves a lack of accountability in the profession, in the absence of a supervisory body that enforces accountability and certification.

As a result of this, the MS Excel sheet represents an additional tool for donor agencies and owners to collect and compare VOCs by vehicle fleet composition to help quickly identify this type of problem in the future.

CHAPTER 4

USING ITINERARY DIAGRAMS AND STATISTICAL ANALYSIS TO DETERMINE THE CAUSE OF DETERIORATION TO PROVIDE AN OPTIMAL ENGINEERING DESIGN SOLUTION

Once a road segment is selected through a network level analysis, the effort then shifts to understanding the road segment condition, or health, in order to engineer the most economically efficient, responsive engineering design on a life cycle cost basis wherein both the cost of maintenance and rehabilitation and the user costs are taken into account.

Data collection is the first step in understanding the road segment condition, which is guided by the same principles used in other professions, such as medicine, that look at the symptoms or distress experienced by the road segment to determine the proximate cause(s) of distress. Other data, such as environmental, social and resettlement data, are also required and need to be integrated into a complete whole to make the most informed pavement design decision. This can be performed either by monetizing all the input, or with a multi-criteria approach.

The specific objective of this chapter is to illustrate the process from the initial road condition survey including a statistical based model to help identify the most likely cause(s) of deterioration while developing a streamlined itinerary diagram that can be used to monitor performance during and after construction as an integral part of a pavement management system. As will be demonstrated in this chapter, this is paramount to identify the proper engineering treatment (design) on a life-cycle basis, while integrating other critical design considerations such as hydrology, topography, resettlement and environmental characteristics in one visual, graphic based document. Again, proper and timely *(i.e. efficient)* data collection and an easy-to-appreciate representation of the data to convey the information, provides the donor agency with a proper, easy to understand, transparent, baseline of the existing road investment, which can also be easily adapted to the road agency needs. This approach is equally important to properly and accurately justify the capital investments through a rigorous engineering design methodology, while reducing opportunities for mismanagement and/or fraud and corruption in both the engineering design and construction phases, while providing a high degree of donor agency accountability to the public.

This chapter therefore justifies, develops, and validates two innovative ideas, integrated in one project-level tool: 1) the development of a graphical itinerary diagram framework that integrates all relevant pavement design, environmental, and resettlement issues into one usable space for design, decision making, monitoring, and evaluation during construction, and long-term pavement performance monitoring that can be integrated into a pavement management system; and 2) the use of Bayesian statistical modeling to determine the most probable cause of deterioration using the itinerary diagram approach.

4.1 Data management, analysis and the concept of itinerary diagrams

The graphical itinerary diagram's primary purpose is to integrate the relevant engineering/environmental and resettlement data points into an easy to visualize, graphic format to properly identify the causes affecting the deterioration of the road, but also to analyze the other impacts affecting the investment (environmental and resettlement), while providing a transparent investment tool/mechanism that provides the donor with increased visibility and accounting to support the investment decision. The assembly of the relevant information into this format should reduce the opportunities for engineering error and/or malfeasance through misdiagnosis and costly engineering design solution. This format is also designed to be easily integrated into the road agency pavement management system as a platform to easily integrate as built data for long-term pavement performance modeling.

By providing all the relevant data upfront in one format, decision making by multiple stakeholders becomes much easier. Considering that engineering files are generally multiple volumes (one for geotechnical, one for hydraulic, one for topography, one for environmental, one for resettlement, one for alignment, one for economic analysis, etc.) and hundreds of pages long, this approach not only represents a dramatic time savings for design review, but also forces the integration of these disciplines to work together to produce one coherent format for the project.

This approach also provides valuable information to both the donor and road agency. The donor agency is provided with complete file to serve as the baseline and justification for all economic analysis *ex ante* and *ex post*. The primary HDM-4 elements, like the IRI, deflections, road condition, geometry and traffic elements, are visible and properly broken down into representative or homogenous sections (which is how HDM-4 is designed), with clearly visible environmental and resettlement impacts/mitigation measures.

A sample itinerary diagram showing the HDM-4 elements is shown in figure 4.1 below, which highlights the traffic, % trucks, calculated ESALs in year 1 and year 20 (analysis period is 20 years), the mean altitude (determined using satellite imagery and field based survey points). A recent satellite image was provided at the top of the itinerary diagram, which can be replaced by more precise aerial imagery during the more detailed design phase to visually assess and represent the resettlement, environmental and social aspects Below the imagery, both the functional (IRI), structural (deflection) and condition assessment characteristics (as per HDM4) with the road agency condition assessment classification. Any road agency thicknesses can be shown as well as the horizontal and vertical geometric data per HDM4. Below all of this data, which are sub sectioned in 200 meter increments, still capture video is shown for each segment to provide a representative view of each section. Using a web based GIS system, these links can be made to run for the entire segment as needed.

Once the data is collected into 200 meter segments, a larger effort to organize the data into homogenous sections will occur in terms of IRI and deflection measurements.

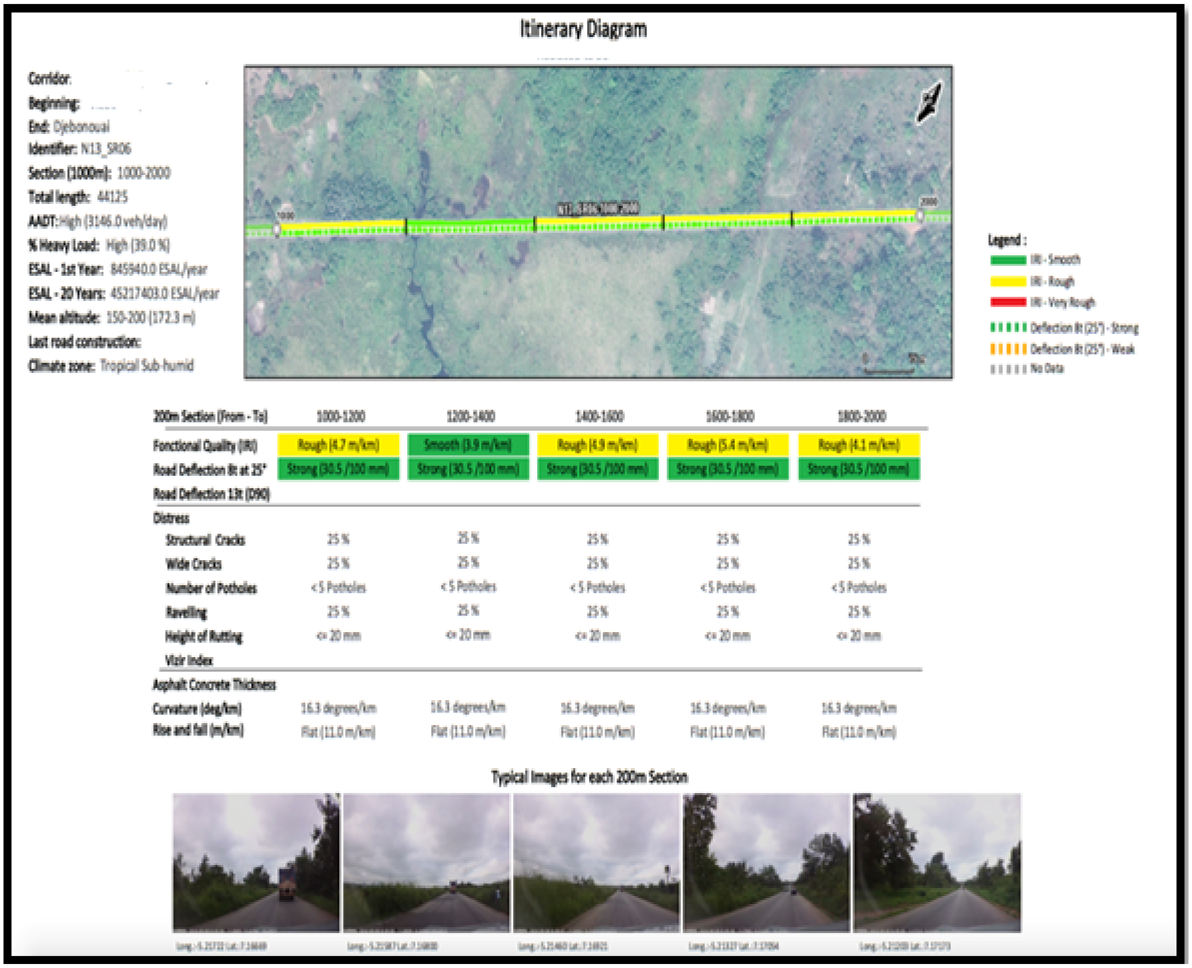


Figure 4.1 Sample itinerary diagram output showing all engineering related data during pre-project evaluation
Taken from WSP (2016)

The itinerary diagram approach is also valuable information for the donor agency to evaluate the robustness of the road agency data collection and analysis work by field checking the IRI, deflections, road condition surveys, and traffic counting procedures against those provided by the road agency. The donor agency can then target specific capacity-building or technical assistance programs within the road agency to begin correcting any data collection weakness. In very short order, the donor agency can not only collect project relevant information, but also determine how robust the road agency's database is structured and the quality of its data, which is the first step in building a PMS. This also helps the donor agency build a more tailored program that helps identify potential isomorphic mimicry and avoids premature loading.

As the project progresses to the implementation phase, the itinerary diagram approach becomes the platform for project monitoring and evaluation as well as the road agency as-built file. There are numerous field inspection and lab tests performed on each road project with a resulting mountain of data to process, review and analyze to ensure conformity with the stakeholders requirements. For example, table 4.1 below shows the number of tests performed on a 120 km road project in Africa per the road agency requirements.

Table 4.1 Total number of tests performed on a road project in SSA
Adapted from SGS (2015a)

	Compaction	**Swiss Plaque**	**Deflection**	**Plasticity Index**	**CBR**	**Thickness**	**Marshall Stability**	**Creep**	**IRI**	**Brazilian Test**
AC	464	NA	122	NA	NA	464	153	153	246	6
Base	2,361	1,162	2,361	237	237	NA	NA	NA	NA	NA
Subbase	1,953	1,953	3,319	178	178	NA	NA	NA	NA	NA
Subgrade	972	963	3,673	94	94	NA	NA	NA	NA	NA

Under the itinerary diagram approach, the data points are collected and represented in a graphical format along the road chainage as shown in figure 4.2 below, which constitute 9,475 data points. By representing the data in such fashion, the engineer, road agency and donor agency are better able to monitor and evaluate construction quality progress against technical requirements.

Figure 4.2 also provides additional post construction information for the road agency with the presence of the two yellow bars; the chainage in between the two yellow bars indicate that the deflection measurements on the base course were taken during the rainy season. This may help future road agency officials better identify any potential causes of failure and discrepancies in data.

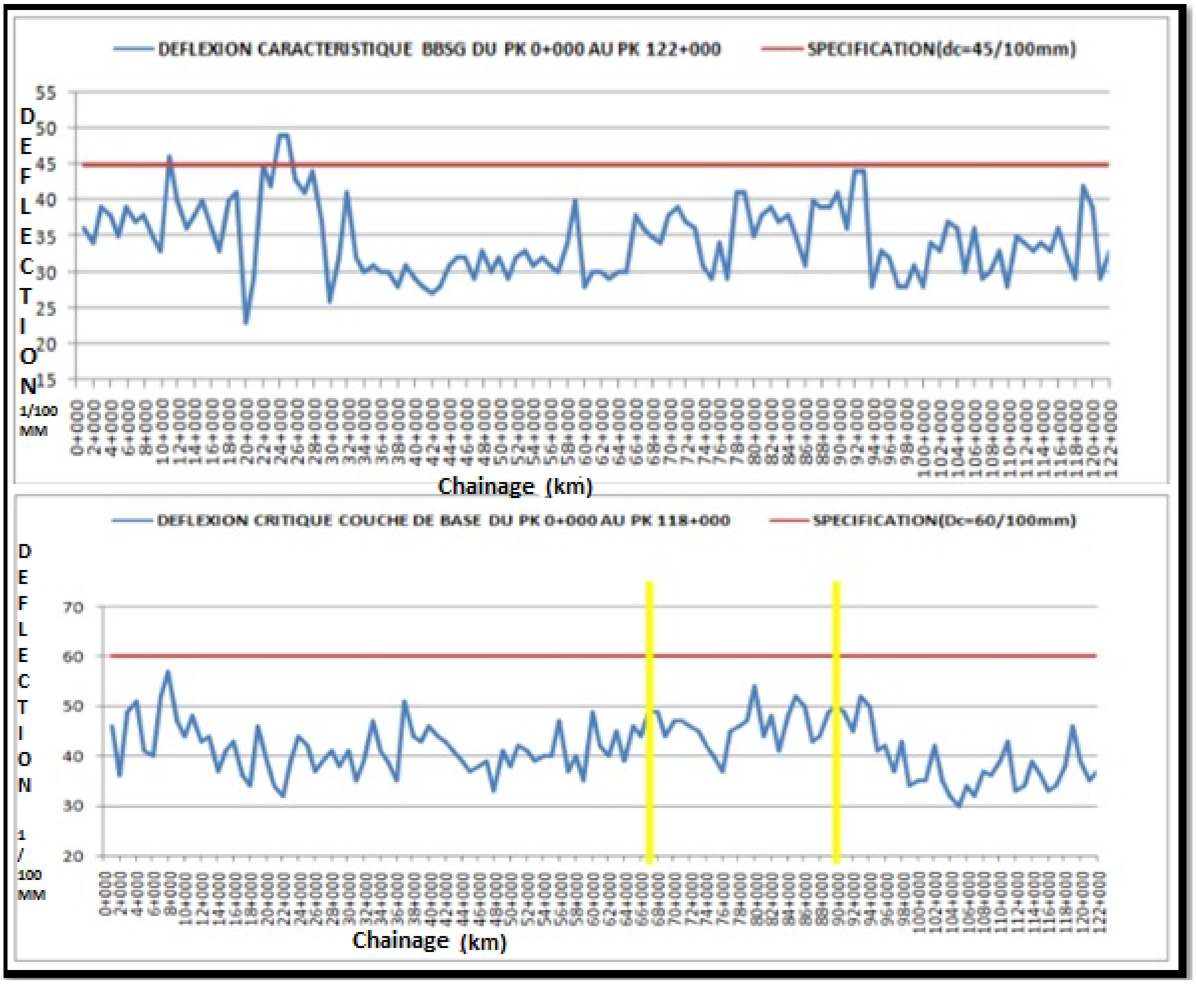


Figure 4.2 Characteristic Deflections (in 100mm) for the Asphalt Concrete and Base course layers in itinerary diagram format on a recent donor project in Africa by chainage, Taken from SGS (2015a)

The use of the itinerary diagram approach also helps the donor and road agency make adjustments during the execution of works as well. For example, on a recent donor-funded project in Africa, the contract specifications required an IRI of less than 1.5m/km to receive a bonus payment, which the contractor was hoping to achieve as he had invested in a new paving machine, which he figured could be paid for by the bonus payment. The results from the first 20 kilometers showed a much higher IRI than the contractor wished, and after some additional research, the contractor invested in some additional guidance equipment for the paver and improved GPS guided grading of the base course. These actions resulted in an improved overall performance and the payment of the performance bonus to the contractor.

The itinerary diagram format is also integral to monitor progress during implementation. The economic analysis performed to justify the initial investment is standardized via this approach, which makes post-project completion economic analysis much easier to compare, both within the donor agency as supporting documentation and outside the agency as visual evidence of accountable foreign assistance that provides invaluable open data for the public. An example is shown in figure 4.3. More interestingly, all of this data and representation can be used as the project is implemented to provide the donor agency real-time project quality and progress updates, with which to justify quarterly or yearly expenditures. In fact, depending on the rigor of the monitoring and evaluation program and perceived incentives to manipulate data during the construction process, a separate third party testing laboratory with no current or future business interests in the country could be hired to validate the posted results, much in the spirit of Ronald Regan's maxim of "trust, but verify."

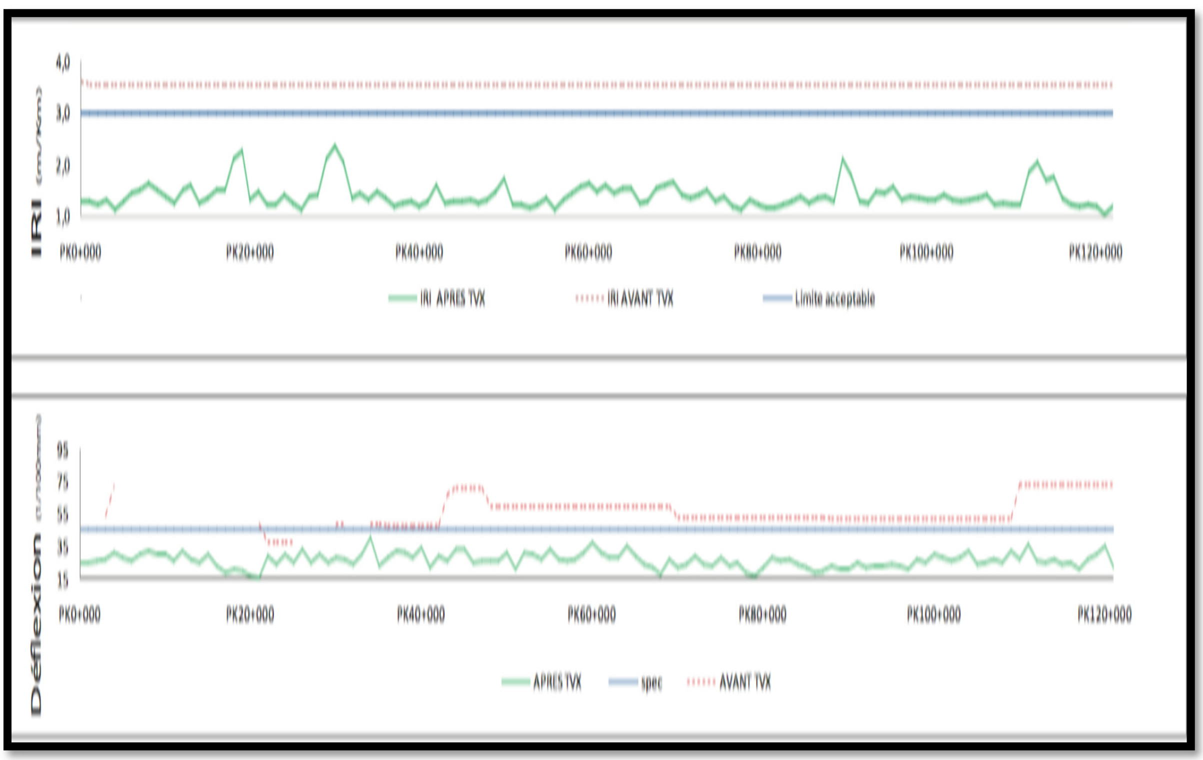


Figure 4.3 Example Itinerary Diagrams for a recent road project in Africa showing pre-project and post project IRI and deflection measurements (Green indicates post works, Blue the contract specification and Red the pre project values)
Taken from SGS (2015b)

Collecting the data in itself is a huge task, but it is the analysis of this data, both during the execution phase, but also *ex post* that is the most valuable to the road agency as this data will assist the road agency in developing a database to begin developing their own materials fatigue curves to meet their own requirements as opposed to importing standards and fatigue curves from other countries/regions. This is the basis of a properly functioning PMS.

In fact, as this database grows over time with new project data and the annual and semi-annual road survey data, the road agency will begin the process of building the necessary data relationships to determine the probabilities used in the Bayesian approach (to be discussed later in the Chapter) to determine the most probable cause of road deterioration. Donor and road agencies can begin to use this data to develop more robust engineering design approaches and methods to minimize materials usage and investment costs through improved research and testing using this data, much like the LTPP data is used in North America. This is where the transfer of engineering knowhow can really benefit a developing country and spur economic growth: by learning from past empirical results, pavements can be more efficiently designed with lower investment and maintenance costs, which allows for a more optimal management of scarce financial resources to maintain and expand the road network in the country.

Ideally the donor agency would be advised to adopt a standard approach across all donor agencies for each particular region in order to begin to develop the needed "learning" database required to run the Bayesian model. With an appropriate "learning" database at hand, the engineering consultant can identify the most likely testing requirements to confirm the cause(s) of deterioration and modify any new specifications as needed based on the findings (i.e. using a higher performance grade mix).

One of the primary advantages of this approach (with or without the Bayesian approach) is that it will begin the process of optimizing the engineering efforts away from only structural deterioration solutions to include materials deterioration, thermal deterioration, and design/construction deterioration, which will reduce investments costs while improving engineering knowledge and know how. This perspective is crucial for the donor agency to adopt as the hired engineering consultants and country representative's interests may not be fully aligned with the donors.

The engineering consultants wish to not only satisfy their clients (generally the donor country), but also maximize their revenues. Revenue maximization can occur in several ways, some of which include billing higher "international" rates, yet filling the position with lower wage labour and collecting the difference; providing very conservative (and costly) engineering designs to cover their engineering weakness (may be related to previous point); and providing an over engineered solution to please the donor country (in the attempt to generate future business) as the local road agency may prefer higher investment costs to maximize rent seeking behaviour.

From the donor's perspective, this itinerary diagram approach is not only a check on potential nefarious activities, but more importantly it allows for an improved technology and capacity-building transfer to the local road agency, all while providing the donor with more assurance that its investments are better optimized to generate higher economic returns to society.

4.2 Pavement engineering fundamentals for the itinerary diagrams

Determining data collection requirements to properly engineer the most economically efficient pavement structure requires an understanding of how the pavement works and is modeled through economic analysis.

There are four primary deterioration agents that directly affect pavements: structural deterioration through traffic, materials deterioration due to environmental effects, thermal deterioration (shrinkage, creeping, freeze thaw), and the asphalt mix design and placement issues. The figure below illustrates these agents' effects on the pavement structure. The pavement's ability to withstand fatigue depends directly on traffic loading; the pavement's materials' stiffness, or ability to resist loading, will change depending on the amount of water in the structure (water reduces the pavement's stiffness), and the climate. Thus keeping water out of the pavement is key. This is obtained with adequate surface and subsurface drainage and a properly mixed and placed asphalt surface to repel water whilst maintaining its integrity by being temperature resistant. The yellow boxes in figure 4.4 below highlight the primary structural engineering data needs, notably the loading, or traffic distribution over seasons, and the resulting deflections over these seasons of the pavement layers. The effects of water, temperature, and climate, and their interaction with the pavement structure are equally important, as these factors will determine the cause of deterioration.

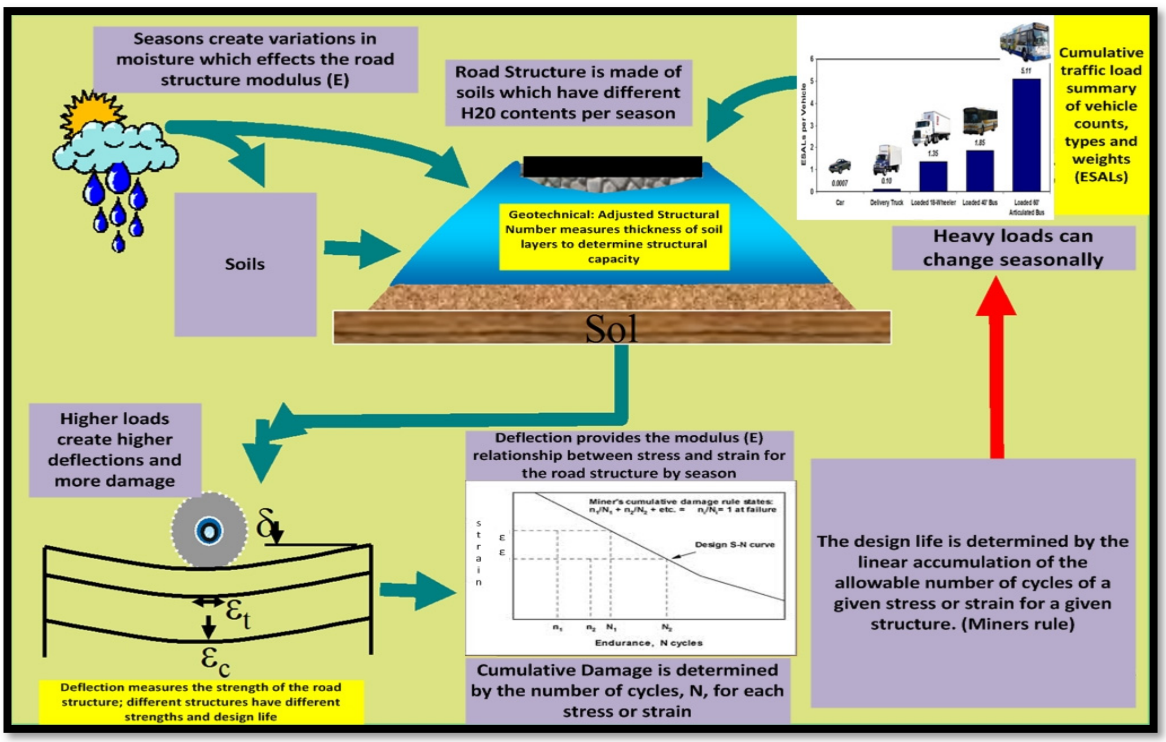


Figure 4.4 Interaction of the pavement structure with climate and loading
Taken from Towles et al. (2014)

4.3 Data needs for the itinerary diagrams

The next section describes the list of data required and how they may be integrated into itinerary diagrams so as to determine the prevalent cause of deterioration of the road.

Other information, such as environmental considerations, associated resettlement needs determination and management, and road imagery integration, that is equally important in determining needs are also added in subsequent sections. All historical data from the road agency is required and shall be part of the itinerary diagram approach.

4.3.1 Traffic volume and loading levels assessment

Traffic survey needs required to assess the feasibility of a road rehabilitation project depend on the accuracy and timeliness of the traffic counts provided by the road agency. For roads with high investment costs, a minimum three-day count is required during the weekdays to verify, with a seven-day count preferred, with potential road widening projects at least seven day counting. The road agency seasonal adjustment factors can be used to convert to AADT.

One aspect of the traffic counting that is required is the determination of the Equivalent Single Axle Loadings (ESAL) to determine the structural design need. The calculation of the ESAL relies on the determination of the load equivalency factor (LEF), which converts different axle loads and their damage to the pavement structure into equivalent damage units based on a standard axle load, as it was determined under the AASHO Road Tests that higher axle loadings cause exponentially higher damage than lower axle loadings.

The LEF is calculated as the Measured Axle Load divided by the Standard Axle load to the power n, where n is the damage exponent, which is typically a 4 (Pavement Interactive, 2007). The damage factor (n), which is generally represented as a 4 from the AASHTO Road Test, will vary depending on the base/subbase used. For example, the South Africans use the following ranges shown in table 4.2, which were derived over years of pavement performance evaluation in South Africa:

Table 4.2 South African suggested values for the relative damage exponent
Adapted from SANRA (2013)

Base/Subbase Combination	Range of Values (Recommended Values)
Granular/granular	3-6 (4)
Granular/cemented	2-4 (3)
Cemented/granular (pre-cracked)	4-10 (5)
Cemented/granular (post-cracked)	3-6 (5)
Cemented/cemented (pre-cracked)	3-6 (4-5)
Cemented/cemented (post-cracked)	2-5 (4-5)
BSM/granular	2-6 (4)
HMA/cemented	2-5 (4)
Concrete	(4.5)

The total number of ESALs can be determined for the projected lifetime of the road, which is needed for the structural assessment below. Care should be taken to ensure that the ESALs are shown in both the local country equivalent and the HDM4 equivalent of 80kN, or 8 tones.

4.3.2 Structural assessment

The structural assessment is determined by deflection measurements using the Benkelman Beam, as this instrument is fairly universally well known, easy to use, and quite reliable. These deflection measurements, preferably wet season at 100 meter intervals in alternating wheel paths, are then compared to the total ESALS expected during the project lifetime (present and future traffic) and materials fatigue curve. If a materials fatigue curve is not available, the recommended approach is to use the approach developed by Bert Wilkins from the Canadian Good Roads Association, or CGRA (Canadian Good Roads Association, 1965).

The approach is described in six steps, with the first four steps outlined in table 4.3 below:

Step 1: Identification of the functional class;

Step 2: Identification of the AADT;

Step 3: Identification of the Truck Traffic or Percent Trucks;

Step 4: Identification of the permitted deflection;

Table 4.3 CGRA Identification of the permitted deflections for 8 ton loadings
Adapted from Canadian Good Roads Association (1965)

Road Functional Class	Traffic (AADT)	Truck Traffic	Permitted Deflection (0.01mm) with 8 ton loadings
Interstate			75
Primary	0-500	0-10%	140
		10 to 20%	125
		>20%	115
	500-1000	0-10%	115
		10 to 20%	115
		>20%	100
	1000-3000	0-10%	100
		10 to 20%	100
		>20%	90
	>3000	0-10%	90
		10 to 20%	75
		>20%	75
Secondary	0-500	0-10%	150
		10 to 20%	140
		>20%	125
	500-1000	0-10%	125
		10 to 20%	125
		>20%	115
	1000-3000	0-10%	115
		10 to 20%	115
		>20%	100
	>3000	0-10%	100
		10 to 20%	90
		>20%	90

The last two steps are used to characterize the deflection data already collected per homogenous sectioning.

Step 5: Identification of the mean and standard deviation with an appropriate "k" value to determine the characteristic deflection (dc) from table 4.4 below;

Table 4.4 CGRA determination of the "k" value
Adapted from Canadian Good Roads Association (1965)

Number of deflection measurements per homogenous zone	**K value**
100 or more	1.3
50	1.7
30	1.66
20	1.8
10	2.06
North America	2.0

Step 6: Compare the characteristic deflection (dc) to permitted deflection (dp). If dc<dp, no structural reinforcement needed; if dc>dp, structural reinforcement is needed.

An example of this analysis using the itinerary diagram approach is provided in figure 4.5 below:

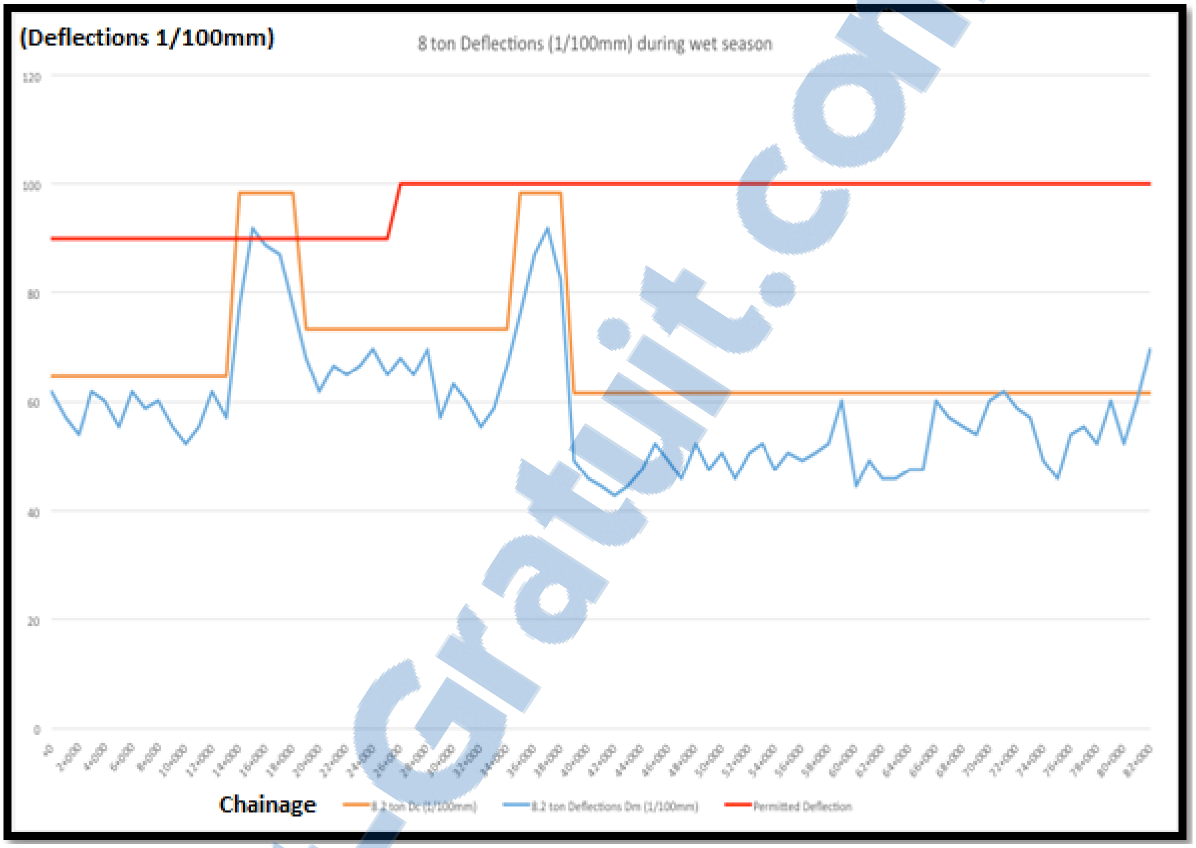


Figure 4.5 Permitted deflection characteristic deflection (1/100mm)

The graphic identifies one section between STA14+000 and 18+000 that needs structural reinforcement. Note the change in permitted deflections at STA 26+000 due to the change in traffic loading from the previous section.

In addition, the dynamic cone penetrometer (DCP) should be used to determine the thickness of the pavement layers to calculate the associated moduli per layer, check the Benkelman Beam deflections in performing a pavement structural analysis, and provide the actual thickness measurements needed for the calculation of the Structural Number (SNP) in HDM-4.

4.3.3 Road condition assessment

The first objective of the road condition assessment is to properly classify each distress and its severity for cracking, patching/potholing, surface deformation, surface defects, and any other miscellaneous defects observed. The road condition assessment shall be performed using the homogenous sectioning approach previously defined.

For road distress, the type of cracking, severity, and locations shall be identified using an established methodology such as the "Distress Identification Manual for the Long-Term Pavement Performance Program" (Miller and Bellinger, 2014). There are a fair amount of methodologies for classifying distresses; however, note that whichever methodology is selected, a proper conversion will be required for use in the HDM-4 model, if applicable as the HDM-4 model does not recognize (or model) all forms of distress equally. The table below illustrates the difference between the "Distress Identification Manual for the Long-Term Pavement Performance Program" (Miller and Bellinger, 2014) and HDM-4 for cracking. The LTPP approach considers nine types of distinct cracking, while the HDM-4 model uses three types of cracking as shown in table 4.5 below.

Table 4.5 Cracking distress and measurement between LTPP and HDM-4
Adapted from Odoki and Kerali (2000)

LTPP Distress Type (measurement)[3]	**HDM-4 Distress (measurement)**
Transverse (Thermal) Cracking (number, meters)	Transverse thermal Cracking (meters/km)
Edge Cracking (meters)	Edge Break (square meters)
Fatigue Cracking (square meters)	Structural cracking is defined as load and age/environment associated cracking (Odoki and Kerali, 2000), with extent measured as follows: 1) All Cracking (Narrow of 1-3mm width) 2) Wide Cracking (Wider than 3mm crack width, with spalling)
Block Cracking (square meters)	
Wheel Path Longitudinal Cracking (meters)	
Non Wheel Path Longitudinal Cracking (meters)	
Reflection Cracking at Joints (not measured)	
Transverse Reflection Cracking (not measured)	
Longitudinal Reflection Cracking (not measured)	

There are numerous methods for conducting the distress survey; however, the essential element is to properly identify the affected areas and location along the roadway chainage, rather than highlighting every crack and its individual severity.

This is also another opportunity to verify the road agency capacity to properly conduct road condition assessments by comparing the results from the donor agency engineer and the road agency. The donor agency is able to tailor any capacity-building work directly toward remedying any of these gaps.

[3] Note that LTPP considers three distinct levels for extent of cracking: Low, Medium, and High.

4.3.4 Road widening needs assessment

One of the major issues affecting road infrastructure investments is the need to widen the existing roadway, which has major implications for investment, environmental, and resettlement costs. From an investment perspective, traffic demand drives the decision making process, which is modeled in figure 4.6 below. The S1, S2 and S3 represent the free speed (or speed the driver wishes to safely drive given roughness, grades and curvatures). The Snom is the typical mean speed of a slow vehicle with Sult the minimum speed under heavy traffic conditions.

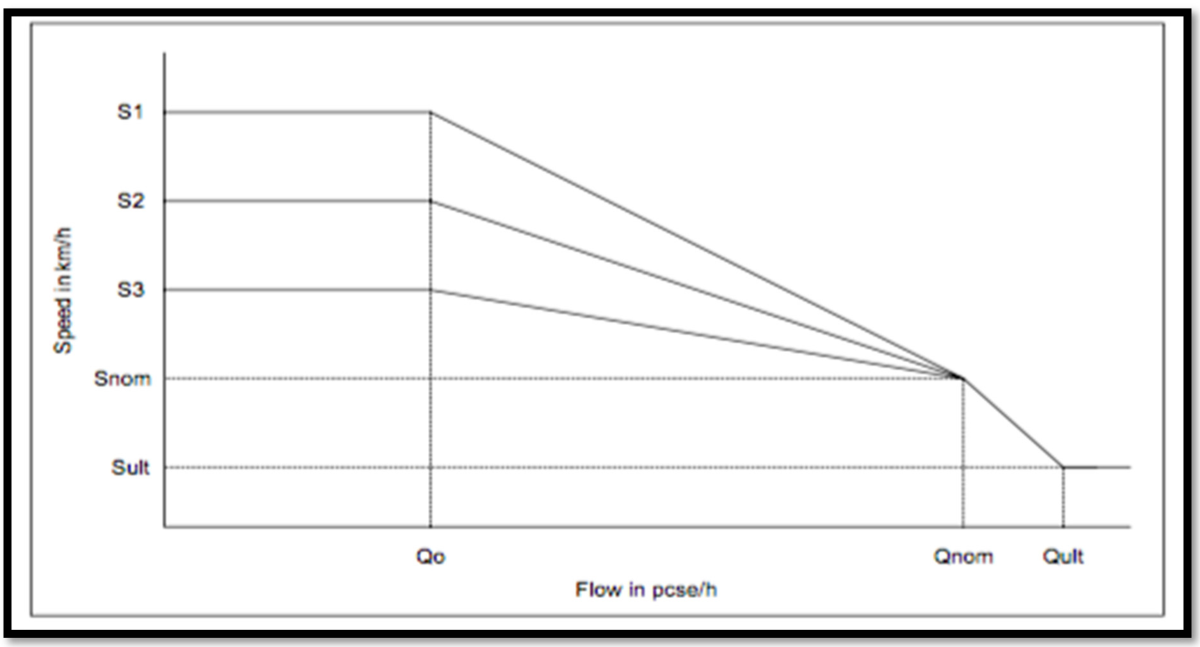


Figure 4.6 HDM Speed-Volume Model (speed in km/hr by Flow in pcse/hr)
Taken from Bennett and Greenwood (2004)

The model harmonizes vehicle sizes into once unit called a Passenger Car Space Equivalent, with a standard passenger vehicle as 1.0 and other vehicles adjusted accordingly by road type as per table 4.6 below.

Table 4.6 Passenger Car Space Equivalents (PCSE) by road type
Adapted from Hoban, Reilly and Archondo-Callao (1994)

Road Type	**Car**	**Pickup**	**Bus**	**Light Truck**	**Med Truck**	**Heavy Truck**	**Articulated Truck**
Single Lane	1.0	1.0	2.2	1.5	1.8	2.4	3.0
Intermediate	1.0	1.0	2.0	1.4	1.6	2.0	2.6
Two Lane	1.0	1.0	1.8	1.3	1.5	1.8	2.2
Wide Two Lane	1.0	1.0	1.8	1.3	1.5	1.8	2.2
Four Lanes	1.0	1.0	1.8	1.3	1.5	1.8	2.2

The suggested traffic flows, or Q, are provided in Table 4.7 below, which provides indicative ranges for discussion on road widening justification. For example, widening of an existing two-lane road would require traffic flows (Q) of 140 PCSEs[4]/hour/lane to begin having an effect on reducing the free flow speeds and 1,260 PCSEs/hour/lane for all vehicles to reach the same mean speed (but not slow speeds with high congestion).

Table 4.7 Example speed-flow-capacity parameters by road type
Adapted from Hoban, Reilly and Archondo-Callao (1994)

Road Type	**Width (m)**	**Qo/Qult**	**Qnom/Qult**	**Qult (PCSE/h)**	**Sult (km/h)**
Single Lane	<4	0.0	0.70	600	10
Intermediate	4 to 5.5	0.0	0.70	1800	20
Two Lane	5.5 to 9	0.1	0.90	2800	25
Wide Two Lane	9 to 12	0.2	0.90	3200	30
Four Lane	>12	0.4	0.95	8000	40

[4] Take 2800PCSE/hour / 2 lanes = 1400PCSE/hr/lane * 0.10 (Q0/Qult)

The understanding of traffic flow and its relation to road widening is a crucial element for the donor agencies to appreciate insomuch as this understanding assists the donor agency to better leverage its scarce investment dollars relative to the huge economic need for high quality roads in developing countries. There may be a fair amount of pressure applied on donor agencies in certain countries to widen roads for political or rent-seeking reasons (higher cost projects can mean larger payouts) and or both. As a result, this type of analysis, built into the HDM framework, provides sufficient rationale and technical justification for not widening a road, using scarce environmental resources (materials) and moving people that would be considered in the right of way of the widened roadway.

4.3.5 High-resolution imagery

High-resolution imagery (approximately 3-5cm per pixel resolution) captured aerially provide significant advantages for advancing donor investments over previous survey and satellite methods. From an engineering perspective, the primary advantages are the ability to collect road survey data in x, y and z (with orthophoto rectification) with sufficient precision to determine contour lines for sufficient hydraulic analysis and the coordinates of the existing road and all other road furniture. The visual representation of the hydraulic channels along the roadway, used in conjunction with the pavement distress, IRI and deflections survey results provides a much more complete picture of the elements that may be causing deterioration in and along the roadway. An example of a recent donor captured image showing hydraulic directional flow is shown in figure 4.7 below (blue arrows).

Figure 4.7 Aerial imagery showing hydraulic flow directions
on a recent donor project in SSA
Taken from MCC (2015)

The full collection of the survey data at the outset also provides an accurate baseline survey for the donor agency to reduce engineering survey costs (and time), but also to use in comparison with the final built product. Not only is the imagery clean and crisp enough for publications, but this also allows the donors the ability to effectively oversee that the quantities paid for were placed on large volume works. For example, if the recommended engineering design calls for an additional placement of base material and Asphalt Concrete upon the existing structure, the pre-project aerial imagery can be compared with the post-project imagery elevations to validate the quantities paid for by the donor. In other words, these aerial images allow the donor agency the ability to confirm that its investment dollars were being spent properly (minimal corruption through the billing for quantities not placed) and in a fully transparent manner that can be shared with the public to build confidence that the donor agency monies are being spent wisely.

4.3.6 Integration of environmental and resettlement aspects

Environmental and Resettlement aspects are an integral part of any project design, with the objective of minimal disturbance as possible and only due to justifiable, economic needs. Satellite imagery has been used for some time to conduct these analysis; however, with the use of aerial imagery for the engineering work, the same images can be used to show the relevant environmental and resettlement issues/concerns during all phases of the project process. The primary advantage from an engineering/construction perspective is the ability to visualize the actual zones of disturbance for an accurate description and extent of lost assets based on changes in the current alignment.

4.4 Determining the causes of deterioration

Once all this data has been collected and placed into the itinerary diagrams, the next step is the engineering analysis and the real value added of this approach, where the cause of deterioration is determined and engineering solution identified to treat the identified cause(s).

The four primary types of deterioration are 1) structural deterioration, 2) materials deterioration, 3) thermal deterioration, and 4) mix design and placement related deterioration. Within these four types of deterioration, there are 27 known causes of pavement deterioration. These causes (C) have been provided below with the associated distress and the needed testing to confirm the cause(s) of deterioration (Assaf, 1988, Assaf, 1993, Towles et al, 2014).

4.4.1 type i: structural deterioration (traffic based)

- **C1: Fatigue failure at the bottom of the asphalt concrete (tensile failure) and/or at the top of the subgrade (compression);**

a. Associated distress: Wheel Path Cracking, Alligator Cracking, Blowout; Rutting;
b. Testing: Deflection testing to assess structural capacity and ability to support traffic;

- **C2: Slope failure (such as on a side hill cut);**

a. Associated distress: Edge Cracking, Settlement;
b. Testing: Visual confirmation;

- **C3: lateral (tangential) shear failure due to frequent braking and cornering;**

a. Associated Distress: Edge Cracking, Settlement;
b. Testing: Visual confirmation of narrow lane; need to verify adequate side slope, surface drainage and edge compaction (if not narrow lane), unpaved shoulder prone to water infiltration on the edges.

4.4.2 type ii: materials deterioration (water and environment)

- **C4: Hydraulic movement of the cement treated base due to curing;**

a. Associated distress: Transverse or wheel path Cracking;
b. Testing: Cores to verify rigidity of the base course acting in flexure;

- **C5: Asphalt oxidation and aging;**

a. Associated distress: Alligator Cracking, Transverse Cracking, Polished Aggregate, Block Cracking;
b. Testing: Verification of residual penetration on extracted bitumen to verify that bitumen is too hard and lost its ability to deform without rupture;

- **C6: Sub material reflective cracking;**

a. Associated distress: Longitudinal Cracking, Transverse Cracking;
b. Testing: Performing core samples to verify that the Asphalt Concrete Layer is not reflecting its cracks upwards; for concrete base courses, confirm slab size relative to spacing of transverse and longitudinal cracks on the asphalt surface;

- **C7: Water infiltration from edges;**

a. Associated distress: Settlement;
b. Testing: Visual confirmation for non-paved shoulders with distress on edges of road; perform deflection testing on rainy and dry days and compare;

- **C8: Water infiltration from cracks;**

a. Associated distress: Settlement;
b. Testing: Visual confirmation; perform deflection testing on rainy and dry days and compare;

- **C9: weakening of granular materials due to seasonal changes;**

a. Associated distress: Blowout, Rutting;
b. Testing: Performing deflection tests in fall (dry season) and spring (rainy season) to determine change due to increased moisture;

4.4.3 type iii: thermal deterioration (water, temperature and fines)

- **C10: asphalt shrinkage due to colder temperatures;**

a. Associated distress: Longitudinal Cracking, Transverse Cracking;
b. Testing: Verification of constant spacing between transverse cracks with some cores to confirm no reflective cracking. Additional Residual Penetration Tests needed to confirm bitumen is not too hard

- **C11: Differential frost penetration;**

a. Associated distress: Upheaval;
b. Testing: Consulting with the district engineers on non plowed roads versus plowed roads as snow covered roads will not heave;

- **C12: Frost heaving;**

a. Associated distress: Edge Cracking, Upheaval/Swelling;

b. Testing: Confirmed by measuring roughness and/or crack widths in winter and summer months to compare differences;

4.4.4 type iv: mix design and placement deterioration (bitumen and aggregates)

- **C13: Overheated asphalt during construction;**

a. Associated distress: Alligator Cracking;

b. Testing: Verification of residual penetration on extracted bitumen to verify that bitumen is too hard and lost ability to deform w/o rupture;

- **C14: Temperature sensitive bitumen;**

a. Associated distress: Rutting, Bleeding;

b. Testing: Extracting and characterizing the mix formula in the lab and establishing a penetration-viscosity versus temperature curve to assess the pen-vis number (PVN).

- **C15: Vertical movement of poorly compacted materials;**

a. Associated distress: Edge Cracking, Settlement, Blowout, Rutting, Potholes, Bleeding;

b. Testing: checking construction reports and engineering records with additional compaction tests to verify if problem remains;

- **C16: Water suction into pavement;**

a. Associated distress: Edge Cracking, Alligator Cracking, Settlement, Blowout, Rutting, Potholes, Corrugations/Shoving, Upheval/Swelling;

b. Testing: confirmed by characterizing the subgrade, subbase and base materials for fines, liquid limit and plasticity index;

- **C17: Low bitumen content;**

a. Associated distress: Block Cracking, Loss of Aggregate on Surface Treatments;
b. Testing: Lab mix characterization;

- **C18: Excessive bitumen content;**

a. Associated distress: Rutting, Block Cracking, Corrugations and Shoving, Raveling, Bleeding;
b. Testing: Lab mix characterization;

- **C19: Low voids in the asphalt mix;**

a. Associated distress: Corrugations and Shoving, Bleeding, Slippage Cracks;
b. Testing: Lab mix characterization;

- **C20: Excessive voids in the asphalt mix;**

a. Associated distress: Rutting;
b. Testing: Lab mix characterization;

- **C21: Chemical compatibility between the bitumen and aggregate in the asphalt mix;**

a. Associated distress: Block Cracking, Raveling, Peeling, Loss of Aggregate on Surface Treatments;
b. Testing: Visual assessment of the aggregate and binder;

- **C22: Improper binding course (tack coat);**

a. Associated distress: Bleeding, Slippage Cracking, Loss of Aggregate on Surface Treatments;
b. Testing: Visual assessment when peeling is present;

- **C23: Rounded aggregates;**

a. Associated distress: Rutting, Corrugation and Shoving;
b. Testing: Lab mix characterization;

- **C24: Construction joint;**

a. Associated distress: Wheel Path Cracking, Longitudinal Cracking;
b. Testing: Consult As-builts or with district engineers;

- **C25: Excessive tangential stresses (slope, curvature);**

a. Associated distress: Corrugation and Shoving;
b. Testing: Visual assessments for areas of frequent breaking turns on curves;

- **C26: Thin wearing course;**

a. Associated distress: Alligator Cracking, Blowout, Peeling;
b. Testing: Visually assessed from cores;

- **C27: Poor compaction of the asphalt mix;**

a. Associated distress: Longitudinal Cracking, Rutting, Block Cracking, Potholes, Raveling, Bleeding;
b. Testing: Visual assessment on site and confirmed by construction notes of engineer.

4.5 Identification of the most likely causes of deterioration through Bayesian modeling

One of the major problems is developing countries is the lack of understanding and/or analysis into why pavements fail, which may be a result of a non-functional pavement asset management system, poor management, poor training/education, and/or poor engineering practice. Regardless of the reason, the first task of the donor agency engineer is to determine a feel for the roads based on visual observation, preferably made through the verification of the network prioritized sections (Chapter 3) to try and determine the main causes of deterioration prevalent in the country. Absent a functional PMS, the experience of the donor agency pavement engineer is substituted, which will result in a large degree of trial and error in testing requirements to determine the cause of deterioration. However, over time, these experiences in the specific region should become more precise in determining the cause of deterioration.

Over time, this learning can be captured and integrated into the PMS through the integration of Bayesian or Markovian probabilistic modeling. Specifically, as knowledge is gained over the entire network on certain families of roads on the causes of deterioration, a probability based model can be developed for each family of road to determine the most likely cause(s) (and testing required) to confirm the cause of the visible distress.

As the PMS learns over time, the probability of successful determination increases, which allows the road agency the knowledge and ability to make proper adjustments to the pavement design over time to avoid or minimize these issues in the future.

The Bayesian model allows the user the ability to determine the probability of a specific cause with more than one associated distress, much like a doctor would try and discern a specific cause for a patient's sickness from observed symptoms. The doctor, like the pavement asset manager, will begin by evaluating all the reported symptoms with the patients (or assets) history to identify the most probable causes behind the symptom(s) through a process of elimination. For example, a patient with specific ethnic heritage may have a higher probability of a specific disease or diseases relative to other ethnic backgrounds, which is why doctors always ask about family history. This is analogous to dividing the road network into specific families to help better identify similarities in symptoms through observable causes. Over time, these families begin to show more predictable behaviors that can be used to determine the most probable cause(s) behind each observed symptom.

The Bayesian model applied to the Cause (C) and Symptom (S) approach is shown in Equation 1 below:

$$p\left(\frac{Ci}{Sj} \cap \ldots \cap Sk\right) = \frac{p\left(\frac{Sj}{Ci}\right) \times \ldots \times p\left(\frac{Sk}{Ci}\right) \times p(Ci)}{\sum \; p\left(\frac{Sj}{Ci}\right) \times \ldots \times p\left(\frac{Sk}{Ci}\right) \times p(Ci)} \tag{4.1}$$

Where :

p = Probability of cause Ci

Ci = Cause (i)

Sj = Symptom (Observed distress) (j)

Sk =Symptom (Observed distress) (k)

The denominator sum is for all 27 causes, i.e. (i = 1, 2, … 27)

The application of this approach is shown in the abbreviated table 4.8 below for all 18 symptoms, or observed distresses.

Table 4.8 Basic Bayesian probabilities (p) matrix for 18 distresses (S) relative to the 27 causes (C)

	C1	**C2**	**C3 ….**	**C27**
S1	p(S1/C1)	p(S1/C2)	p(S1/C3) ….	p(S1/C27)
S2	p(S2/C1)	p(S2/C2)	p(S2/C3) ….	p(S2/C27)
S3	p(S3/C1)	p(S3/C2)	p(S3/C3) ….	p(S3/C27)
… S18	…… p(S18/C1)	…… p(S18/C2)	…… p(S18/C3) ….	…… p(S18/C27)

Each of the colored cells represents a potential relationship between the cause and the symptom that will be statistically populated and adjusted as the database is fed with new reliable data, with probabilities gathered over the road network for similar families; the non-colored cells are zero as there is no relationship between the two. A sample matrix with sample probabilities is provided in table 4.9 below.

Table 4.9 shows the 27 causes of deterioration in the columns with the 18 associated distresses in the rows. (See Annex II for more)These causes will vary on a country by country basis and are provided as an example based on previous work.

Table 4.9 Sample matrix of probabilities for 18 distresses and the 27 causes of deterioration for a sample road family

	PROBABILITY OF A CAUSE OF DETERIORATION	99.3%	0%	0%	0.4%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.3%	0%	0%	0%		
		Structural Deterioration			Materials Deterioration						Thermal Deterioration			Design/Construction Deficiencies																
DIGIT ENTRY OF DISTRESS OBSERVED		Fatigue Failure (C1)	Slope Failure (C2)	Shear Failure (C3)	Hydraulic Movement of the Cement Treated Base (C4)	Asphalt Oxidation and Aging (C5)	Sub material Reflective Cracking (C6)	Water Infiltration from edges (C7)	Water Infiltration from cracks (C8)	Weakening of Granular Materials due to seasonal changes (C9)	Asphalt Shrinkage (C10)	Differential frost penetration (C11)	Frost Heaving (C12)	Overheated Asphalt during Construction (C13)	Temperature sensitive bitumen (C14)	Vertical Movement or Poorly Compacted Materials (C15)	Water Suction into Pavement (C16)	Low Bitumen Content (C17)	Excessive Bitumen Content (C18)	Low Voids (C19)	Excessive voids (C20)	Chemical Compatibility with bitumen and aggregrate (C21)	Improper binding course (tack coat) (C22)	Rounded Aggregates (C23)	Construction Joint (C24)	Excessive tangential stresses (slope, curvature) (C25)	Thin wearing course (C26)	Poor compaction of the Asphalt mix (C27)		Probability of a Distress
1	Wheel Path Cracking (S1)	8.00%			0.50%																				0.20%					8.70%
0	Edge Cracking (S2)		0.50%	0.30%									0.50%			0.10%	0.10%													1.50%
0	Alligator Cracking (S3)	5.00%				11.00%								0.30%			1.00%										2.50%			19.80%
0	Settlement (S4)			1.20%				0.10%	2.00%							1.17%	8.00%													12.47%
0	Longitudinal Cracking (S5)						2.00%				1.00%														1.80%			0.10%		4.90%
0	Blowout (S6)	2.00%								2.30%						0.29%	1.90%										0.20%			6.69%
0	Transverse Cracking (S7)				0.50%	1.10%	0.30%				3.00%																			4.90%
0	Rutting (S8)									4.50%					0.60%	1.10%	3.00%		0.10%		0.90%			0.10%	0.00%			0.15%		10.45%
0	Polished Aggregate (S9)					0.10%																								0.10%
0	Block Cracking (S10)					0.20%												1.00%	0.20%			0.20%						0.10%		1.70%
0	Potholes (S11)															1.00%	0.23%											0.00%		1.23%
0	Corrugations and Shoving (S12)																0.20%		0.50%	0.10%				0.20%		0.30%				1.30%
0	Upheaval/Swell (S13)											1.20%	1.20%				1.00%													3.40%
0	Raveling (S14)																		0.90%			0.50%						0.20%		1.60%
0	Bleeding (S15)														0.20%	1.70%			10.00%	5.00%			0.90%					0.19%		17.99%
0	Slippage Cracking (S16)																			0.20%			0.80%							1.00%
0	Peeling (S17)																					0.59%					0.20%			0.79%
0	Loss of Aggregate on Surface Treatments (S18)																	0.90%				0.38%	0.20%							1.48%
	Probability of a Cause	15.00%	0.50%	1.50%	1.00%	12.40%	2.30%	0.10%	2.00%	6.80%	4.00%	1.20%	1.70%	0.30%	0.80%	5.36%	15.43%	1.90%	11.70%	5.30%	0.90%	1.67%	1.90%	0.30%	2.00%	0.30%	2.90%	0.74%	100.00%	100.00%

The system works as follows: when wheel path cracking is observed, there are three potential causes associated with this distress, each with its own probability of occurrence across the network. Wheel path cracking, as shown in table 4.9, has an 8.7 percent probability of occurring on the network, which is comprised of three potential causes, fatigue failure (C1) at 8.0 percent, hydraulic movement of the base course (C4) at 0.5 percent and construction joint (C24) at 0.20 percent. The probability of wheel path cracking being a result of fatigue failure

(C1) is 15.0 percent, hydraulic movement of the base course (C4) is 1.0 percent and construction joint (C24) at 2.0 percent on the entire selected network. The question is what is the probability that wheel path cracking is the result of fatigue failure (C1), hydraulic movement of the base course (C4) or a construction joint (C24)?

Using the Bayesian formula to determine wheel path cracking for fatigue failure, the numerator is determined by the product of 8.0 percent and 15.0 percent, with the denominator determined by the sum of the product of each of the 27 causes and its probability.

The formula is written as follows:
Probability of Fatigue Failure if wheel path cracking is observed = (8.0%*15.0%)/[(8.0%*15.0%)+ (0.5%*1.0%)+(0.2%*2.0%)] = 99.3%

And conversely,
Probability of hydraulic movement of the subbase if wheel path cracking is observed = (0.5%*1.0%))/[(8.0%*15.0%)+(0.5%*1.0%)+((0.2%*2.0%)] = 0.4%

And finally,
Probability of construction joint if wheel path cracking is observed = (0.2%*2.0%))/[(8.0%*15.0%)+(0.5%*1.0%)+((0.2%*2.0%)] = 0.3%

As a result of this analysis, the road agency will need to conduct testing to confirm the causes, which in this case would be deflection testing to evaluate the stiffness of the pavement to additional loading. Once the tests confirm the initial diagnosis, a corrective strategy can be designed and applied. In this particular case, the probability that future wheel path cracking is the result of fatigue failure will increase relative to the other two potential causes, however slightly, as well as the probability of wheel path cracking on the network, all things being equal. In addition, the probability of fatigue failure on the network will also increase, however slightly. Over many repetitions, the adjusted probabilities become more and more reliable, which allows the road agency to better identify maintenance and rehabilitation needs, but also identify potential areas of improvement in construction design and potentially the development of more robust fatigue curve models.

The improvements in construction design would come from the identification of potential solutions, either via improved technical specifications, QA/QC, mix design and or material selection. For the sections that have failed structurally, the road agency can determine the most likely traffic loading on each segment (with weigh stations data and traffic counts) and determine how the empirical results match the pavement design theoretical curve. Differences in either can be applied to future pavement designs to reach the desired outcomes.

In sum, the development of the itinerary diagrams by the donor agency will allow the donor agency the ability to properly demonstrate and justify all road investment decisions (accountability), but also assist the local road agency to truly begin the process of learning and adapting their pavement design and management techniques to their own local conditions through the identification of the cause(s) of deterioration. This approach identifies several ways in which the donor can properly asses the local road agency capacity to better tailor investment needs to build a more credible program. A suggested Bayesian model was developed to help these road agencies learn over time when properly applied to the PMS.

CHAPTER 5

VALIDATION OF THE ITINERARY DIAGRAMS CONCEPT IN DETERMINING THE CAUSE OF DETERIORATION

The previous chapter has made the case for the determination of the cause of deterioration and established the list of parameters that need to be considered and integrated in a general graphical framework referred to as the Itinerary Diagrams. The idea is to put together all the data that affect pavement deterioration on one platform, which essentially makes the case for the concept of itinerary diagrams to determine the cause of deterioration.

In order to validate the approach, two examples from recent projects in Sub Saharan Africa are provided below.

5.1 Use of the itinerary diagram to determine the cause of deterioration post construction

Within a year after the rehabilitation had been completed on a specific project, some rutting on the asphalt concrete wearing course for the first ten kilometers was observed. The production of the itinerary diagram (shown in figure 5.1 below) for the road shows the following results:

a. The thickness of the Asphalt Concrete was above the 5cm thickness requirement, which would suggest a lower deflection measurement compared to other sections that are not as thick, i.e. built to specification thickness (note the contract specification is between the green and purple lines in figure 5.1 below).

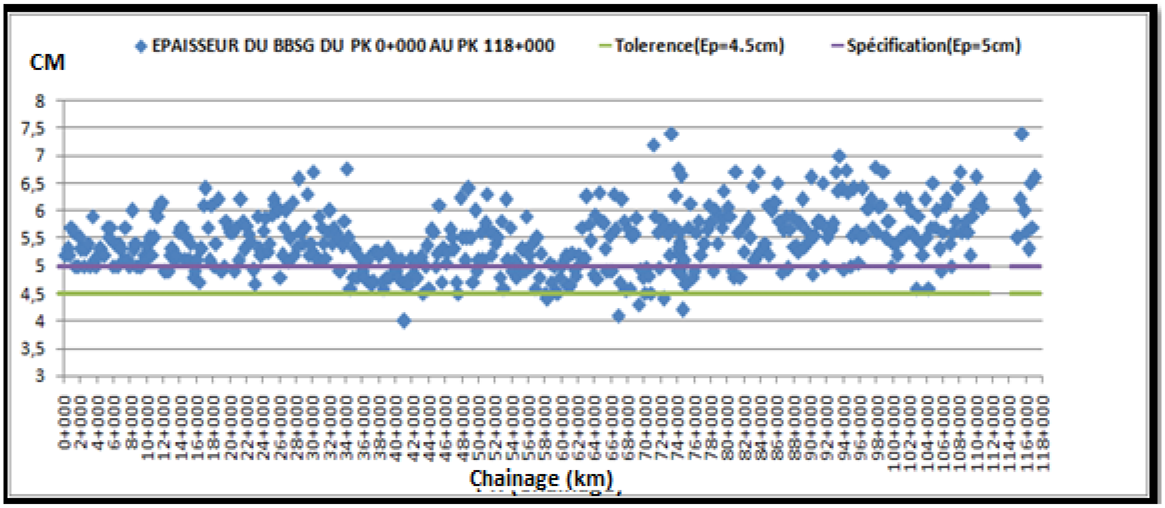


Figure 5.1 Thickness measurements for selected road project in SSA
Taken from SGS (2015a)

b. The characteristic deflection measurements however are higher than other subsequent sections such as between STA 30+000 and 58+000 as shown in figure 5.2 below, which have lower thickness measurements and are mostly within specification. The red line indicates the contract specification requirement. This suggests the rutting is not structurally related, i.e. not due to a rupture of the subgrade which logically could not have happened within one year, when the road was built to structurally withstand traffic levels projected for the next 20 years, unless the traffic was underestimated by a factor of 20 times.

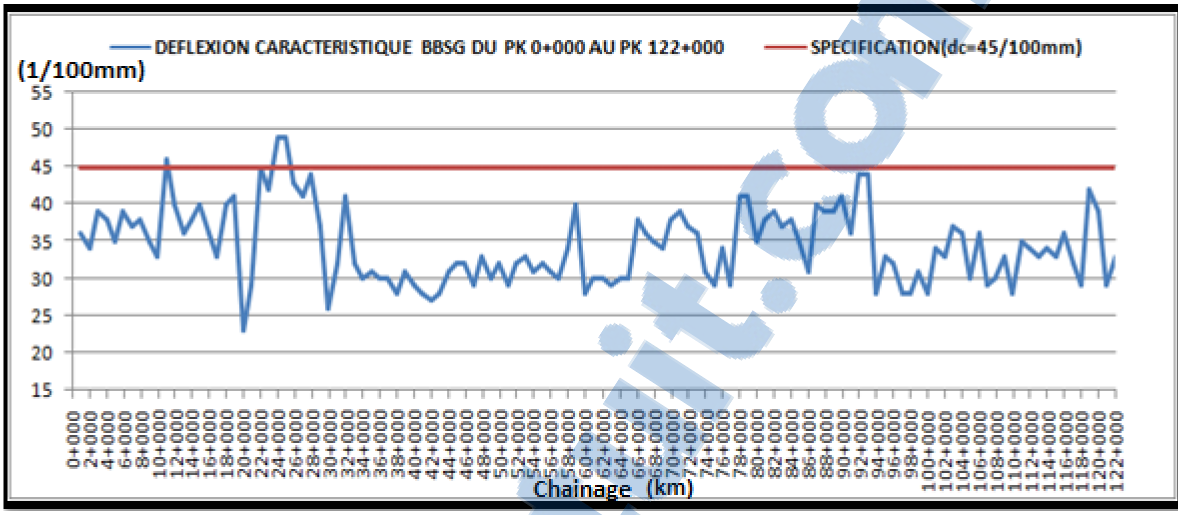


Figure 5.2 Deflection measurements for selected road project in SSA
Taken from SGS (2015a)

c. The creep test indicates that the mix is progressively moving lower over the course of the project chainage (as shown in the figure 5.3 below), which suggests the mix was initially more prone to rutting, but improving over the course of the project.

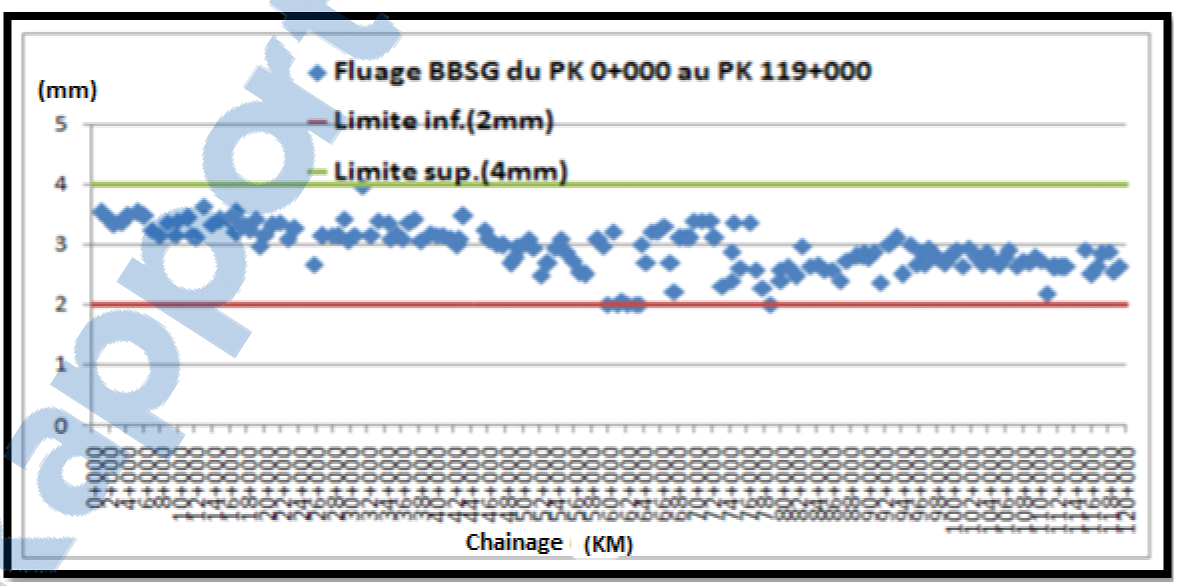


Figure 5.3 Creep tests for selected road project in SSA
Taken from SGS (2015a)

d. The Marshall Stability test begins at the specification lower limit (red line)and slowly increases over the chainage (x axis) and finally takes off toward the end of the project as shown in figure 5.4 below.

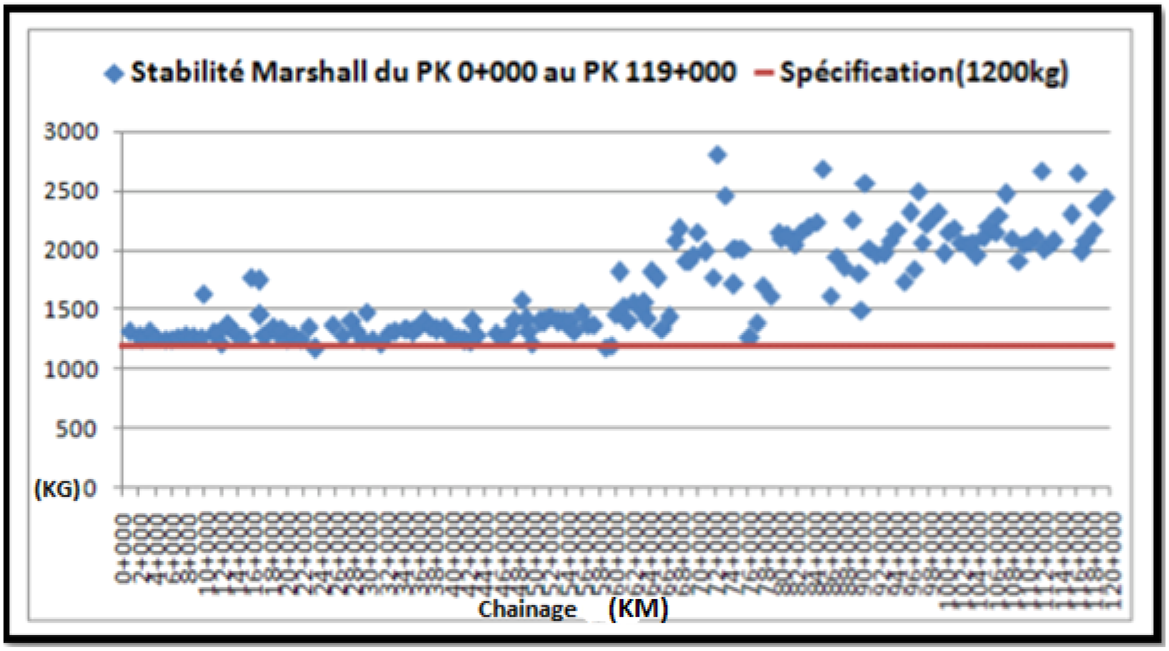


Figure 5.4 Marshall Stability tests results (kg) for selected road project in SSA by chainage, Taken from SGS (2015a)

As such, the most likely cause of rutting on the first ten kilometers was due to poor mix design. Rutting related to mix design is generally a result of too much binder.

e. Checking the binder dosage in the mix (shown in figure 5.5 below) shows a higher binder dosage for the first fifteen kilometers, which corresponds to the field-based findings and cause of deterioration.

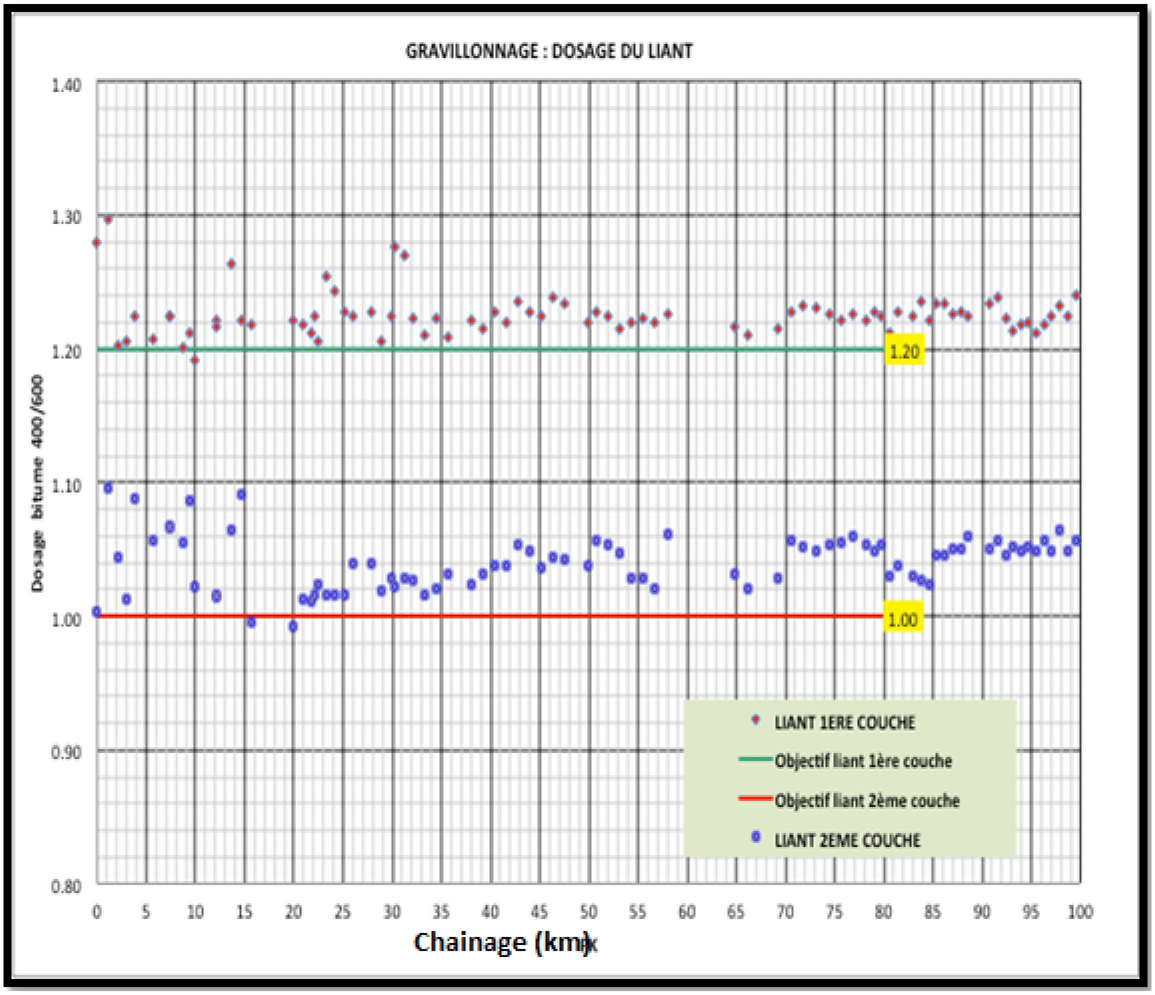


Figure 5.5 Binder dosage results for selected road project in SSA by chainage
Taken from SGS (2015a)

In conclusion, had the supervising engineer produced these itinerary diagrams charts from the beginning of the project and acted on them to investigate the causes of excess bitumen content and higher deflections, he would have been able to limit the extent of the rutting issue.

Also, had the post-evaluation procedure required the funding agency to investigate the causes of any distress observed, this finding would have probably figured in the *ex post* lessons learnt.

By integrating this system into a PMS database, the analysis can be performed as part of the management system, which will help the road agency develop better specifications and planning over time and hopefully improve the investment efficiency of donor financed projects.

For the post project evaluations, surveys can be carried out in much the same manner to monitor how well the investment fares over time with regards to roughness, condition assessments, maintenance work performed (or not), and traffic projections. The updated IRI measurements can be shown on the same itinerary diagram format over time, which will illustrate the projects true value over time relative to the HDM-4 projections.

5.2 Use of the itinerary diagram to determine the cause of deterioration during project assessment

On a current project in Sub Saharan Africa, the itinerary diagram approach is being used to perform preliminary project assessments. One of the major problems stated by the road agency for the failure of their roads is the persistent overloading of trucks. Analysis of recent weigh station data confirmed that truck overloading was a problem as shown in table 5.1 below.

Table 5.1 Average (8t) ESAL for each truck class in select SSA country
Adapted from WSP (2016)

ESAL/truck class	**Average ESAL (8t) for each truck class**
2 axles	8.74
3 axles	26.93
1 unit with 4 axles or more	28.71
2 units with 4 axles	15.65
5 axles	30.65
2 units, 6 axles or more	54.58

One of the early findings of this itinerary diagram approach is the ability to use Google Earth to show both the IRI and the Deflections on a map as shown in figure 5.6 below to compare the functional and structural assessments.

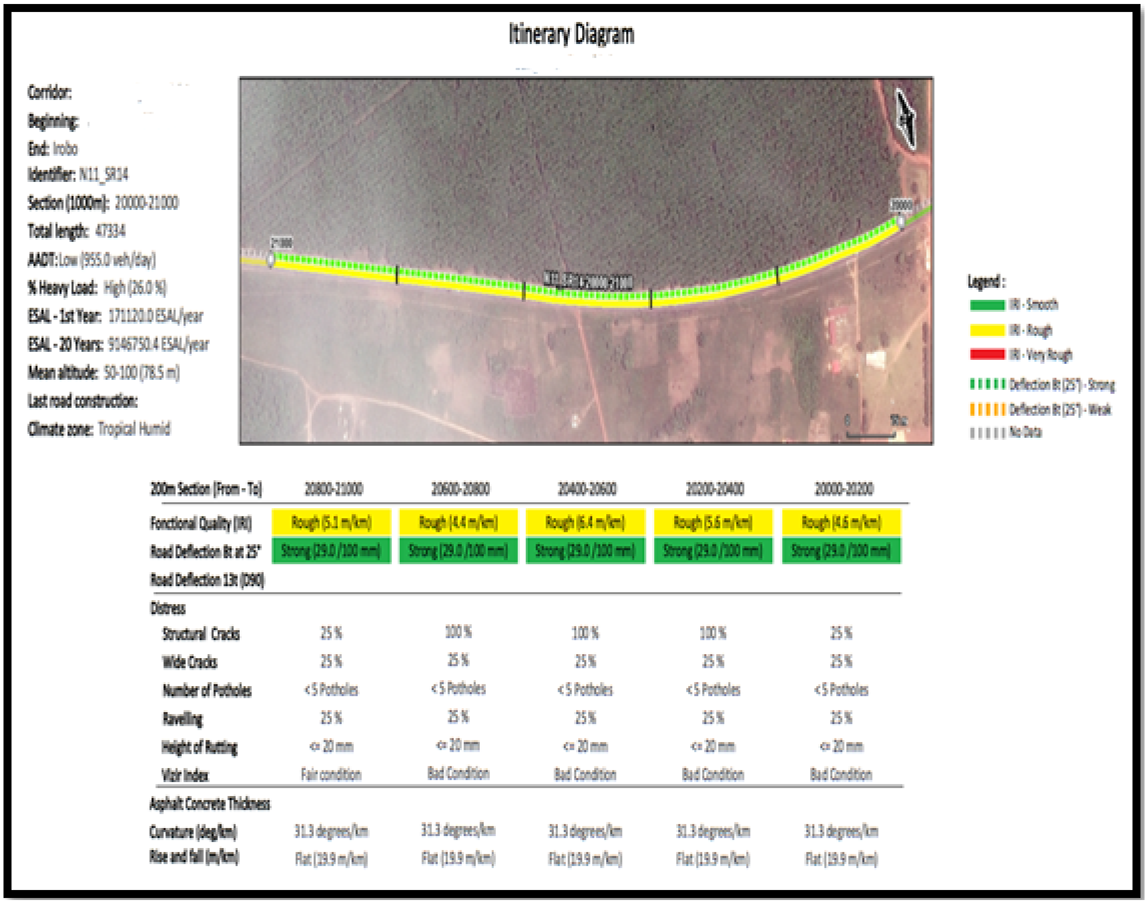


Figure 5.6 Itinerary Diagram along a selected road in SSA
Taken from WSP (2016)

The expectation was to find roads that had been structurally damaged as these roads are exceeding their 15 year design life by at least ten years. Upon examination of the data it appears that the roads are still structurally strong, but are showing rough (4-8m/km) functional characteristics. This observation has reduced the number of causes by three as structural deficiency is not the cause of deterioration. The most probable cause of deterioration is the asphalt aging due to oxidation, which has caused the structural cracking observed in the itinerary diagrams and subsequent potholes; the eventual weakening of the cement stabilized base course and a slow loss of structural support is expected to occur soon. The recommended intervention is to restore the pavement by repairing the potholes and to place an overlay on top.

The recommended approach to correct for this road condition in Cote d'Ivoire is to reconstruct at an approximate cost of $500-600,000 per km or more, while an estimate based on the cause of deterioration, would be half of this amount, which will provide additional economic justification for this road and additional funds for other projects in the SSA country.

CONCLUSIONS AND RECOMMENDATIONS

Infrastructure investment by donor agencies in developing countries offers many promising economic benefits; however, this investment needs to be done in a manner that takes into consideration the numerous challenges to deliver the expected economic returns to the developing country, but also to maintain a high degree of accountability and transparency for the donor agency benefactors (i.e. taxpayers) to continue funding these investments.

A road network prioritization method was provided that helps the donor agency quickly identify the more economically promising road investments in a country with which to invest. While this approach was determined to be 69 percent accurate for all selected roads, it did reach 90 percent accuracy for high return roads (above 30% ERR). Additional field verification is underway using the same approach (validation of the IRI and AADT); however, the engineer is using a fully calibrated (Level II) HDM-4 model to prioritize the investments. Part of the assessment will be to compare the results that the engineer finds and compare them to the approach described here to try and learn how to improve the accuracy of the proposed ERR model. As part of this task, VOC curves from all over the world and numerous agencies were collected and compared to help improve the overall accuracy of the prediction model. These have already come in handy for several transport economists in their review of HDM-4 models.

Depending on the availability of data, the comparison of the pre-selected 2,000km can be compared against a larger data set for the entire country to assess the validity of the originally selected 2,000km. There may be additional findings related to the pre-selection of the 2,000km from the larger network that need to be considered.

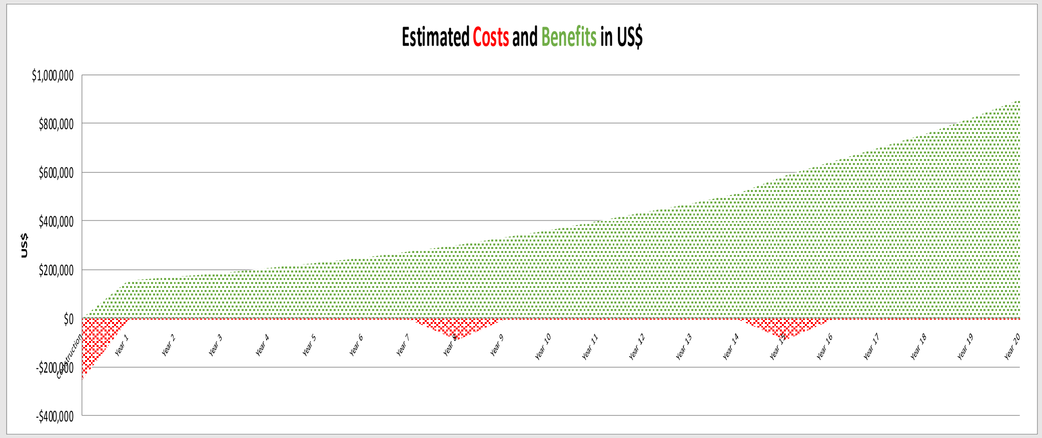
Once the road is selected, the adoption of the itinerary diagram approach coupled with the identification of the cause of deterioration is 1) proving to be quite beneficial in determining the economically efficient investments, 2) improving the evaluation of road agency capacity to manage its pavement assets through proper pavement asset management techniques, and 3) developing the engineering know how in developing countries to begin to improve pavement performance and lower lifecycle investment costs through the adaptation of modern pavement asset management techniques and practices. The application of the Bayesian approach to pavement asset management will improve the institutional knowledge at the road agency, while improving the overall pavement design field to reduce investment costs and improve overall performance for the road user. This complete approach is being adopted in several countries now and will be refined as it is implemented.

ANNEX I: MS EXCEL PROGRAM

Initial IRI	12
Final IRI	2
AADT	2879
% Trucks	12%
Annual Traffic Growth	7%
Cost/km	$ 257,246
Annual Routine Maintenance	$ 5,144.92
Periodic Maintenance	$ 90,000.00
ERR	59%
Annual IRI Deterioration Rate (m/km)	0.25

Automobile VOC for IRI		
No Project	Post	Savings
$ 0.35	$ 0.23	$ 0.12

Truck VOC for IRI		
No Project	Project	Savings
$ 1.00	$ 0.66	$ 0.34



Deterioration

			No Project IRI	Project IRI
		Construction		
	Year	1	12	2
	Year	2	12.25	2.5
	Year	3	12.5	2.75
	Year	4	12.75	3
	Year	5	13	3.25
Periodic Intervention IRI reduction	Year	6	13.25	3.5
	Year	7	13.5	3.75
1	Year	8	13.5	2.75
	Year	9	13.75	3
	Year	10	14	3.25
	Year	11	14.25	3.5
	Year	12	14.5	3.75
Periodic Intervention IRI reduction	Year	13	14.75	4
	Year	14	15	4.25
1	Year	15	15.25	3.25
	Year	16	15.5	3.5
	Year	17	15.75	3.75
	Year	18	16	4
	Year	19	16.25	4.25
	Year	20	16.5	4.5

Automobile

No Project VOC	After Project VOC	Savings per veh/km	Automobiles	Total VOC Savings/km	Total Annual VOC Savings/km
$ 0.35	$ 0.23	$ 0.12	2534	$ 304.91	$ 111,291.28
$ 0.35	$ 0.23	$ 0.12	2711	$ 336.92	$ 122,977.62
$ 0.36	$ 0.23	$ 0.13	2901	$ 372.42	$ 135,935.05
$ 0.36	$ 0.23	$ 0.13	3104	$ 410.77	$ 149,931.91
$ 0.37	$ 0.23	$ 0.14	3321	$ 452.16	$ 165,038.19
$ 0.37	$ 0.23	$ 0.14	3553	$ 496.79	$ 181,327.74
$ 0.38	$ 0.23	$ 0.14	3802	$ 544.87	$ 198,878.42
$ 0.38	$ 0.23	$ 0.15	4068	$ 601.42	$ 219,517.57
$ 0.38	$ 0.23	$ 0.15	4353	$ 661.05	$ 241,281.85
$ 0.39	$ 0.23	$ 0.16	4658	$ 725.30	$ 264,732.87
$ 0.39	$ 0.23	$ 0.16	4984	$ 794.47	$ 289,980.19
$ 0.39	$ 0.23	$ 0.16	5333	$ 868.87	$ 317,139.07
$ 0.40	$ 0.23	$ 0.17	5706	$ 948.85	$ 346,330.62
$ 0.40	$ 0.24	$ 0.17	6105	$ 1,034.74	$ 377,681.91
$ 0.41	$ 0.23	$ 0.18	6533	$ 1,177.42	$ 429,759.74
$ 0.41	$ 0.23	$ 0.18	6990	$ 1,285.39	$ 469,165.74
$ 0.42	$ 0.23	$ 0.19	7479	$ 1,401.29	$ 511,472.56
$ 0.42	$ 0.23	$ 0.19	8003	$ 1,525.64	$ 556,857.52
$ 0.43	$ 0.24	$ 0.19	8563	$ 1,658.92	$ 605,506.03
$ 0.43	$ 0.24	$ 0.20	9163	$ 1,801.68	$ 657,611.73
				$ 17,403.88	$ 6,352,417.61

Trucks

No Project VOC	After Project VOC	Savings per veh/km	Trucks	Total VOC Savings/km	Total Annual VOC Savings/km
$ 1.00	$ 0.66	$ 0.34	345	$ 117.19	$ 42,774.02
$ 1.01	$ 0.66	$ 0.35	370	$ 127.55	$ 46,557.50
$ 1.02	$ 0.67	$ 0.35	396	$ 139.87	$ 51,051.23
$ 1.03	$ 0.67	$ 0.36	423	$ 153.15	$ 55,901.06
$ 1.05	$ 0.68	$ 0.37	453	$ 167.48	$ 61,131.67
$ 1.06	$ 0.68	$ 0.38	485	$ 182.93	$ 66,769.24
$ 1.07	$ 0.69	$ 0.38	518	$ 199.57	$ 72,841.53
$ 1.07	$ 0.67	$ 0.40	555	$ 223.79	$ 81,683.04
$ 1.08	$ 0.67	$ 0.41	594	$ 244.48	$ 89,235.57
$ 1.10	$ 0.68	$ 0.42	635	$ 266.77	$ 97,370.92
$ 1.11	$ 0.68	$ 0.43	680	$ 290.76	$ 106,128.47
$ 1.12	$ 0.69	$ 0.44	727	$ 316.58	$ 115,549.91
$ 1.13	$ 0.69	$ 0.44	778	$ 344.33	$ 125,679.31
$ 1.15	$ 0.70	$ 0.45	833	$ 374.15	$ 136,563.26
$ 1.16	$ 0.68	$ 0.48	891	$ 430.48	$ 157,126.98
$ 1.17	$ 0.68	$ 0.49	953	$ 468.09	$ 170,854.56
$ 1.19	$ 0.69	$ 0.50	1020	$ 508.50	$ 185,600.93
$ 1.20	$ 0.69	$ 0.51	1091	$ 551.87	$ 201,432.10
$ 1.21	$ 0.70	$ 0.51	1168	$ 598.40	$ 218,417.74
$ 1.22	$ 0.70	$ 0.52	1249	$ 648.30	$ 236,631.22
				$ 6,354.25	$ 2,319,300.27

Net Benefits

	Total Benefits	Total Costs	Total Benefits
Construction		$257,246.00	-$ 257,246.00
Year 1	$ 154,065.30	$5,144.92	$ 148,920.38
Year 2	$ 169,535.12	$5,144.92	$ 164,390.20
Year 3	$ 186,986.28	$5,144.92	$ 181,841.36
Year 4	$ 205,832.97	$5,144.92	$ 200,688.05
Year 5	$ 226,169.86	$5,144.92	$ 221,024.94
Year 6	$ 248,096.98	$5,144.92	$ 242,952.06
Year 7	$ 271,719.95	$5,144.92	$ 266,575.03
Year 8	$ 301,200.61	$90,000.00	$ 211,200.61
Year 9	$ 330,517.42	$5,144.92	$ 325,372.50
Year 10	$ 362,103.78	$5,144.92	$ 356,958.86
Year 11	$ 396,108.66	$5,144.92	$ 390,963.74
Year 12	$ 432,688.98	$5,144.92	$ 427,544.06
Year 13	$ 472,009.93	$5,144.92	$ 466,865.01
Year 14	$ 514,245.17	$5,144.92	$ 509,100.25
Year 15	$ 586,886.72	$90,000.00	$ 496,886.72
Year 16	$ 640,020.30	$5,144.92	$ 634,875.38
Year 17	$ 697,073.49	$5,144.92	$ 691,928.57
Year 18	$ 758,289.62	$5,144.92	$ 753,144.70
Year 19	$ 823,923.78	$5,144.92	$ 818,778.86
Year 20	$ 894,242.95	$5,144.92	$ 889,098.03
	$ 8,671,717.88	$529,854.56	$ 9,201,572.44

ANNEX II : BAYESIAN MATIX

DIGIT ENTRY OF DISTRESS OBSERVED	PROBABILITY OF A CAUSE OF DETERIORATION	Fatigue Failure (C1)	Slope Failure (C2)	Shear Failure (C3)	Hydraulic Movement of the Cement Treated Base (C4)	Asphalt Oxidation and Aging (C5)	Sub material Reflective Cracking (C6)	Water Infiltration from edges (C7)	Water Infiltration from cracks (C8)	Weakning of Granular Materials due to seasonal changes (C9)	Asphalt Shrinkage (C10)	Differential frost penetration (C11)	Frost Heaving (C12)	Overheated Asphalt during Construction (C13)	Temperature sensitive bitumen (C14)	Vertical Movement or Poorly Compacted Materials (C15)	Water Suction into Pavement (C16)	Low Bitumen Content (C17)	Excessive Bitumen Content (C18)	Low Voids (C19)	Excessive voids (C20)	Chemical Compatibility with bitumen and aggregate (C21)	Improper binding course (tack coat) (C22)	Rounded Aggregates (C23)	Construction Joint (C24)	Excessive tangential stresses (slope, curvature) (C25)	Thin wearing course (C26)	Poor compaction of the Asphalt mix (C27)		Probability of a Distress
		Structural Deterioration			Materials Deterioration						Thermal Deterioration			Design/Construction Deficiencies																
		99.3%	0%	0%	0.4%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0.3%	0%	0%	0%		
1	Wheel Path Cracking (S1)	8.00%			0.50%																				0.20%					8.70%
0	Edge Cracking (S2)		0.50%	0.30%									0.50%			0.10%	0.10%													1.50%
0	Alligator Cracking (S3)	5.00%				11.00%								0.30%			1.00%										2.50%			19.80%
0	Settlement (S4)			1.20%				0.10%	2.00%							1.17%	8.00%													12.47%
0	Longitudinal Cracking (S5)						2.00%				1.00%														1.80%			0.10%		4.90%
0	Blowout (S6)	2.00%								2.30%						0.29%	1.90%										0.20%			6.69%
0	Transverse Cracking (S7)				0.50%	1.10%	0.30%				3.00%																			4.90%
0	Rutting (S8)									4.50%					0.60%	1.10%	3.00%		0.10%		0.90%			0.10%	0.00%			0.15%		10.45%
0	Polished Aggregate (S9)					0.10%																								0.10%
0	Block Cracking (S10)					0.20%												1.00%	0.20%			0.20%						0.10%		1.70%
0	Potholes (S11)															1.00%	0.23%											0.00%		1.23%
0	Corrugations and Shoving (S12)																0.20%		0.50%	0.10%				0.20%		0.30%				1.30%
0	Upheaval/Swell (S13)											1.20%	1.20%				1.00%													3.40%
0	Raveling (S14)																		0.90%			0.50%						0.20%		1.60%
0	Bleeding (S15)														0.20%	1.70%			10.00%	5.00%			0.90%					0.19%		17.99%
0	Slippage Cracking (S16)																			0.20%			0.80%							1.00%
0	Peeling (S17)																					0.59%					0.20%			0.79%
0	Loss of Aggregate on Surface Treatments (S18)																	0.90%				0.38%	0.20%							1.48%
	Probability of a Cause	15.00%	0.50%	1.50%	1.00%	12.40%	2.30%	0.10%	2.00%	6.80%	4.00%	1.20%	1.70%	0.30%	0.80%	5.36%	15.43%	1.90%	11.70%	5.30%	0.90%	1.67%	1.90%	0.30%	2.00%	0.30%	2.90%	0.74%	100.00%	100.00%

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