Development of a Sustainable Management System for Rural Road Networks in Developing Countries

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Marcela Alondra Chamorro G.

Abstract

Rural roads play a crucial role in the economic and social development of societies, linking rural communities to education, health services and markets. During the last decade, considerable efforts have been made to evaluate the benefits of rural road investment in developing countries. Although outputs of these studies have led to a global rethinking of traditional road appraisal methods, limited attempts have been made to integrate these findings to the rural road management process.

For the sustainable management of rural roads, social, institutional, technical, economic and environmental aspects should be considered under a long term perspective. The current practice in developing countries is that only some of these key sustainable aspects are being considered in the management process. In addition, rural roads maintenance management is commonly performed under a short term basis, not considering the life cycle costs and benefits in the economic analysis and project prioritization. Available management tools and studies have essentially focused their efforts on improving technical and economic aspects of low-volume roads. Whereas, the common practice observed in face of limited resources and lack of technical skills is that decisions are made under a political short term perspective.

This research is directed at the development of an applied and practical system for the sustainable management of rural road networks in developing countries. The approach considers the development of all components required by the proposed management system and their integration into a practical and easy-to-use computer tool.

To achieve this goal a sustainable framework for rural roads management was first developed, where system components and modules were defined. A network level condition evaluation methodology was selected and validated. Long term condition performance models were calibrated from the probabilistic analysis of field data. Optimal maintenance standards were developed under a cost-effectiveness approach. A long term prioritization procedure was developed to account for sustainable aspects of rural roads in the management process. A computer tool was finally developed to integrate the system components and display them in a friendly interface for potential users. The tool was programed in Visual Basic, considering Microsoft Excel interface. The computer tool considers the four system components: Input Data, System Modules, Network Analysis Interface and Output Data. System Modules include Condition Performance Module, Network Maintenance Module and Long Term Prioritization Module. For each of the system components and modules a separate worksheet has been included in the computer tool. The tool is centered on the Network Analysis Interface, which interacts with the other three system components. The user enters network data in the Input Data interface and may adjust information in System Modules considered if the network under study has differences to predefined conditions of. Adjustments to System Modules can be performed by the user, however it is advised that prior calibration is required for the successful analysis of the network.

The management system was applied and validated in two rural road networks in developing countries located in Chile and Paraguay. Sensitivity analysis was carried out to assess the impacts of input parameters in the performance of developed system. As a result of the research an adaptable and

adoptable sustainable management system for rural networks was developed to assist local road agencies in developing countries.

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Dedication

I would like to dedicate this work to my husband Alvaro and my daughter Marina, and to my parents Loly and Hernán. None of this would have been possible without your support.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AADT	Average Annual Daily Traffic
BCA	Benefit Cost Analysis
BAA	Basic Access Approach
CBR	California Bearing Ratio
CEA	Cost Effectiveness Analysis
DFID	Department for International Development
ERR	Economic or Internal Rate of Return
FPS	Ficha de Protección Social
GDP	Gross Domestic Product
HDM-III	Design and Maintenance Standards Model
HDM-4	Highway Development and Management Model
IDA	International Development Association
IRI	International Roughness Index
ISOHDM	International Study of Highway Development and Management Tools
LCCA	Life Cycle Cost Analysis
MOP	Ministry of Public Works of Chile
MOPC	Ministry of Public Works and Communications of Paraguay
RED	Roads Economic Decision Model
RONET	Road Network Evaluation Tools
RAI	Rural Access Index
SADC	Southern African Development Community
TRL	Transportation Research Laboratory
UPCI	UnPaved Road Condition Index
URCI	Unsealed Road Condition Index
VOC	Vehicle Operating Costs

Chapter 1
Introduction

1.1 Background

1.1.1 Definition of Rural Roads

Rural roads have been defined under various perspectives, depending on the level of development of a country and the specific technical and socio-economic aspects of the road. The International Labour Organization defines rural roads as all publicly owned roads whose primary purpose is to provide direct access for the rural villages and communities to economic and social services (ILO, 2010). This definition may be insufficient as it may be neglecting the importance of roads, tracks and paths owned by local governments and communities, commonly known as Rural Transport Infrastructure (Lebo, 2000). A broader perspective is considered by the International Development Association (IDA), the World Bank's fund for the world poorest countries, which defines rural roads as all other roads than main roads (IDA, 2007). This comprehensive definition may differ significantly between countries according to their socio-economic condition. In developed countries, rural roads are generally structurally designed low traffic facilities connecting towns with low populations with the primary and secondary network. Meanwhile, in developing countries rural roads are commonly unpaved low-volume roads designed to meet the social and economic needs of the rural population (Plessis-Fraissard, 2007). The rural network in developing countries commonly represents 80% of the total road network lengths, carries 20% of the total motorized traffic, but provides access to the majority of population to main roads and social networks (Raballand, 2010).

In this thesis, rural roads are considered as unbound gravel and earth roads, paths and tracks serving low volume traffic, less than 300 Average Annual Daily Traffic (AADT) and non-motorized traffic (including haulage carts, bicycles and pedestrians), designed to meet the social and economic needs of the rural population in a developing country. With this, production roads specially designed for exploitation of natural resources, such as forestry and mining roads, are excluded from the analysis.

Considering a three level hierarchy network, rural roads are usually secondary and tertiary/access roads in rural areas as illustrated in Figure 1.1 (SADC, 2003). Tertiary/access roads are tracks or very simple earth roads that begin at the farm/village level and connect the rural population to the secondary network. These are usually seasonal roads with low serviceability levels transited by non-motorized traffic and motorized traffic at low speeds. Secondary roads are earth or basic gravel roads which serve the needs of low-volume traffic of conventional vehicles and non-motorized vehicles. These roads are connected to the primary network, which are engineered all-season roads that present higher levels of heavy load motorized traffic and connect cities and towns (Tighe, 2007).

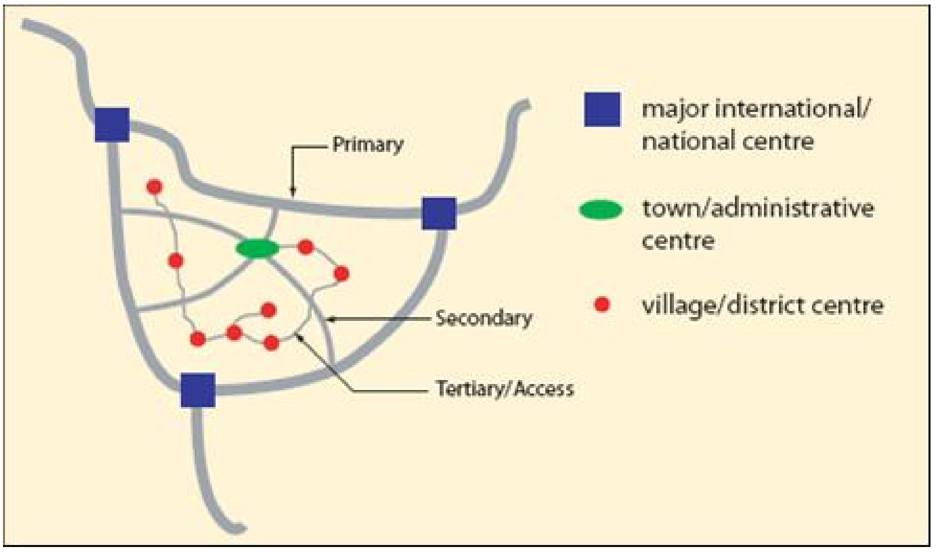


Figure 1.1 Road Hierarchy and Function (SADC, 2003)

The World Road Association Committee for Appropriate Development - PIARC C20, has defined accessibility as a measure of how easy a place is to get to (Tighe, 2000). A place is accessible when a person can get to it within an acceptable outlay of time, effort and resources, considering affordable means of transport. Mobility is a measure of the ease with which people can move through the road network. Places become more accessible when the population is more mobile. As illustrated in Figure 1.2, the hierarchy or category of a rural road is related to its role in providing access and mobility to the population it serves. Rural roads at the tertiary level serve as an access link in a road transport chain with one end in the agricultural fields or villages and the other in the town market. Primary roads serve as a mobility link in the road transport chain from the main highway network to the local market. At the secondary level, rural roads have a double function, providing access and mobility to population, goods and services (SADC, 2003).

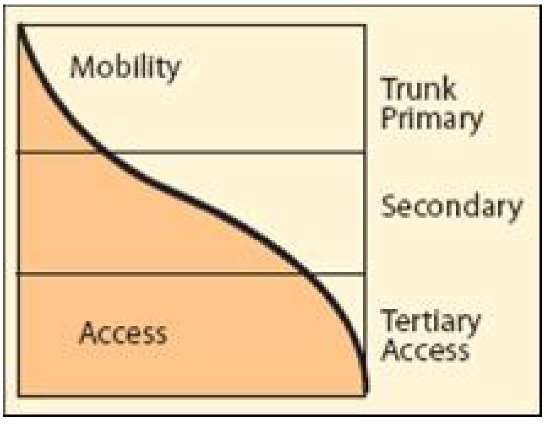


Figure 1.2 Multifunctional Nature of Roads (SADC, 2003).

1.1.2 Rural Roads and Development

Rural roads play a crucial role in the economic and social development of societies, linking rural communities to education, health services and markets. As presented in Figure 1.3, rural poverty alleviation in developing countries depends on the synergy and simultaneous improvement of rural infrastructure, productive sectors, social and economic services. All of these provided by an appropriate macroeconomic framework and good governance policies (Lebo, 2000).

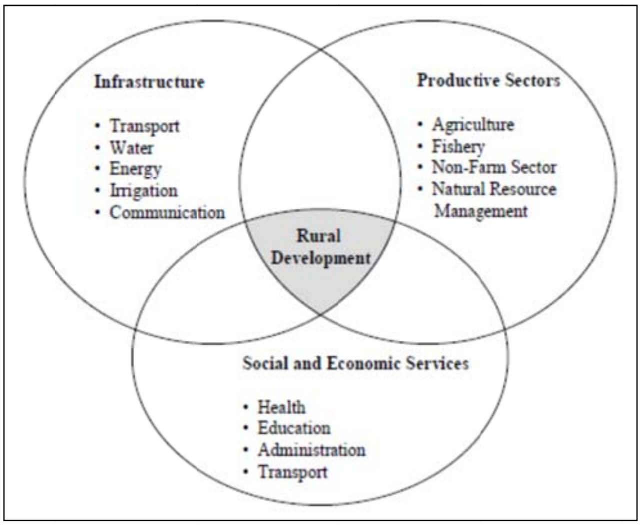


Figure 1.3 The Elements of Rural Development (Lebo, 2000)

Recent studies have evaluated the positive impact of rural roads investment and development of poor countries. In Asian and African countries, studies have demonstrated a close relationship between the extent of the road network and expenditure on roads with income growth. In India, a study found that expenditure on rural roads presented the highest impact in reducing rural poverty and increasing income. This impact was higher than that observed from crops irrigation, education, rural development or health (Fan, 1999)

Regarding education and health, studies held in Pakistan (Essakali, 2005) and Morocco (Levy, 2004) reveal that the presence of an all-season rural road in a village is associated with higher school enrolment rates, improvement in education quality, higher use of health services, higher immunization levels of the population and more births assisted by a skilled attendant. In particular, girls living in villages with all-season road access present school enrolment rate of 41% compared to 27% for those living in villages without all-season road access. This is explained by the fact that in poor accessibility conditions, girls have the daily duty of collecting firewood for cooking and heating. In the presence of all-season roads, butane gas is affordable and, therefore, firewood collection is no longer required (Plessis-Fraissard, 2007).

In the case of economic growth, it was demonstrated in China that every Yuan invested in rural roads resulted in an increase of 5.68 Yuan of rural non-farm gross domestic product (GDP) and 1.57

Yuan of agricultural GDP (Fan, 2004a). In Vietnam, a close relationship between the level of economic activity and the extent of the rural road network was observed. It was found that, for every Dong invested in roads, 3.01 Dong of agricultural production value would be produced (Fan, 2004b)

Regarding household consumption, Jalan and Ravallion (2002) found that kilometers of rural road per capita were one of the main explanations of household consumption growth in southern China. Similar conclusions were drawn in a study held in Ethiopia, where higher consumption growth was attributed to road quality improvement, especially concerning accessibility in the wet season (Dercon, 2005).

Negative impacts have also been observed in some cases due to poor design and/or management of rural road projects. These include involuntary resettlement, increased traffic accidents and environmental effects. It is therefore necessary that rural roads should be managed accordingly, supported by consistent public policies and suitable management systems.

1.1.3 Rural Roads Management in Developing Countries

Rural roads management can be defined as the process that covers all those activities involved in providing and maintaining rural roads at an adequate level of service. This considers the identification of optimum strategies at various management levels and the implementation of these strategies (Haas, 1994).

The management process is performed under three operational levels: project, network and strategic levels. At the project level, technical decisions are made towards the design, construction and maintenance of specific road projects. The main purpose of network management level is the development of a priority program and schedule of work to maintain a road network under available budgets. Finally, at the strategic level pavement performance and maintenance decisions are communicated to senior managers and the public.

As presented in Figure 1.4, rural road networks are commonly managed by communities, municipalities, local governments and, up to some extent, by provincial and central governments (Lebo, 2000). Although rural roads asset value is small compared to national and provincial road networks, the extent of rural networks represent the main proportion of a nation’s roads system. In the practice, agencies responsible of rural roads management in developing countries lack of enough budget and resources to manage the network properly. Technical skills of highway engineers are limited and practical decision-making tools for preparing road maintenance programs are not available. In addition, many roads are not classified, especially at the lower level of the networks, where a clear distinction between roads, tracks and paths may not be available (World Bank, 2007). Given this, agencies are unable to evaluate the overall condition of the road network, quantify the socio-economic effects associated to a poor network condition and, therefore, accounting to the government and the public the need for investing in rural roads maintenance (Mushule, 2004).

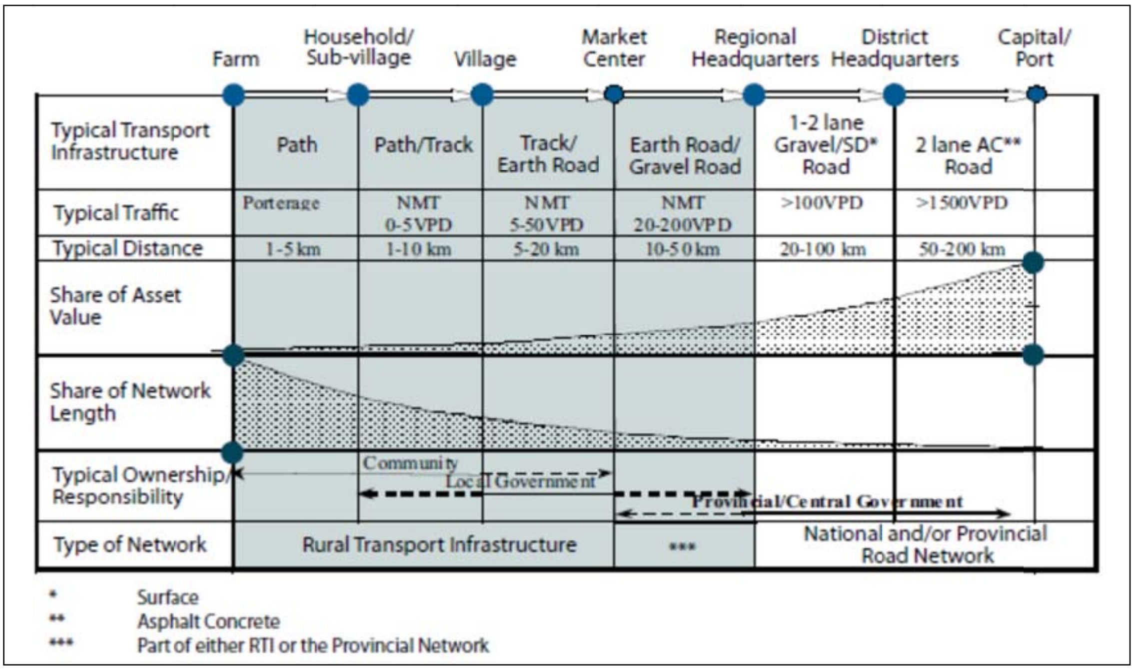


Figure 1.4 Features of Rural and National Roads (Lebo, 2000)

International organizations and research institutions have made important efforts in developing road management systems and decision-making tools for low income economies. During 1980's a major international study was carried out by The World Bank which resulted in the development of the Highway Design and Maintenance Standards Model, HDM-III (Watanatada, 1987). In the 1990's the ISOHDM study was developed to enhance and update HDM-III system. The study resulted in the development of the Highway Development and Management Model, HDM-4 (Kerali, 2000). HDM-4 considers three levels of analysis, namely project, programme and strategic analysis. The tool considers performance models for paved and unpaved roads. The economic analysis performed by the system is centered on the quantification of benefits and costs to road users caused by the level of service of a road or network. This approach is suitable for primary and secondary network management where traffic related economic decisions prevail; however, it can be insufficient in networks with very low traffic volumes.

Some attempts have been made to adjust HDM-4 and other management tools for their application to low-volume road networks. These have resulted in simplified tools suitable for agencies and managers with limited resources and technical skills. Examples of these are the Roads Economic Decision model (RED) (Archondo-Callao, 1999) and Road Network Evaluation Tools (RONET) (Archondo-Callao, 2007) developed by the Sub-Saharan Africa Transport Policy Program (SSATPP). The approach of these methodologies, however, has still centered the economic evaluation of maintenance projects under a vehicle operative cost perspective.

1.1.4 Sustainable Management of Rural Roads

The Southern African Development Community (SADC), in its Low-Volume Sealed Roads Guidelines, proposed that sustainable systems should include the seven dimensions presented in Figure 1.5. The approach considers political, social, institutional, technical, economic, financial and environmental aspects. The guidelines suggest that long term goals of sustained economic growth and poverty alleviation in the region have failed in the past because one or more of these seven key dimensions were missing or inadequate (SADC, 2003). Moreover, a sustainable management approach has to consider these key aspects throughout the whole life cycle of the rural road network.

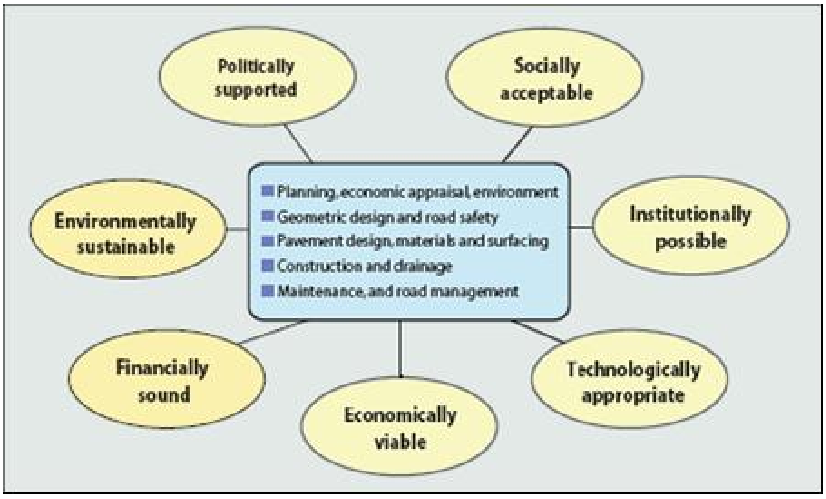


Figure 1.5 SADC Framework for Sustainable Provision of Low Volume Roads (SADC, 2003)

The problem that arises from the analysis of the current practice is that only some of these seven key sustainable aspects are being considered in the management process. In addition, rural roads maintenance management is commonly performed under a short term basis, not considering the life cycle costs and benefits in the economic analysis and project prioritization. Available management tools and studies have essentially focused their efforts on improving technical and economic aspects of low-volume roads. Whereas, the common practice observed in phase of limited resources and lack of technical skills is that decisions are made under a political short term perspective.

Regarding social aspects, considerable effort has been made during the last decade to evaluate and quantify the costs and benefits of rural road investments in developing countries. Several studies have applied and developed methods for the socioeconomic impact assessment and the selection of rural road investments (Grootaert, 2002; van de Walle, 2000; Asian Development Bank, 2002). The focus of these studies, however, has been centered on the quantification of socioeconomic direct and indirect effects rather than on the inclusion of social aspects in the management process of rural roads. In addition, the valuation process has primarily been applied on a per case basis. Although outputs of these studies have led to a global reassessment of traditional road appraisal methods, limited efforts have been made to integrate these findings to the rural road management process where they can effectively better quantify the overall impacts of investments at a network and strategic level. Outcomes from these case studies have been treated as local cases and analyzed from a specific sociological and economic point of view. In addition, the level of detail required for these case studies has been extensive and has resulted in huge expense and limited ability to apply them at the network level.

1.2 Problem Statement and Research Approach

The aforementioned discussion cites several limitations of the state-of-the-practice on rural roads management in developing countries. The main problems observed are:

- Available management tools commonly require detailed data of roads condition, structure and materials. Evaluations of road deterioration usually demand trained operators and automated equipment, not commonly available in developing countries. In addition, comprehensive field evaluations are required, which may not be affordable for network level application in developing countries. To overcome these limitations, several agencies have developed subjective rating methods for unpaved roads; however, their reliability is questioned especially when applied by personnel with low technical skills (Sayers, 1986; Archondo-Callao, 1999; Namur, 2009).
- Performance and economic models considered by available management tools need to be calibrated to local conditions. The calibration process in most cases is complex and requires comprehensive data collection. This can be expensive and technically challenging to implement for local agencies. However, if models are not suitably adapted to local conditions, important errors can be induced in the evaluation process.
- Most management tools perform economic analysis and prioritization of maintenance projects considering savings in vehicle operating costs (VOC) and road user travel time costs (TTC). This approach may be insufficient in rural roads having low volume traffic, where, socio-economic costs and opportunities for the rural population may be of more relevance. However, combining VOC and TTC with socio-economic benefits under a traditional cost-benefit analysis methodology may be unrealistic given the difficulties of quantifying social values in monetary terms. (Lebo, 2000).
- Limited systems are available that can be easily operated by local agencies in charge of rural roads management in developing countries. With limited resources and lack of technical tools, management decisions are often made from a political short term approach instead of a sustainable mid- to long- term perspective.

Given the state-of-the-art and state-of-the-practice of rural roads management in developing countries, it can be stated that there is no management system currently available that can overcome the four problems described above. Therefore, this research is directed at the development of an applied and practical system for the sustainable management of rural road networks in developing countries. The approach considers the development of all components required by the proposed management system and to integrate them in a practical and easy-to-use computer tool. The main components required to achieve this goal include: network level condition evaluation methodology, long term condition performance models, cost-effective maintenance standards, sustainable prioritization methodology and integrated rural roads management tool.

1.3 Research Hypotheses

The hypotheses proposed for this research program are as follows:

- Unpaved roads condition performance can be modeled from the probabilistic analysis of field evaluations.
- Maintenance standards for different climates, traffic levels and budgetary scenarios can be optimized for rural roads in developing countries using cost-effectiveness analysis.
- The management of rural road networks in developing countries can be improved by incorporating sustainable aspects in the prioritization process of maintenance projects.

1.4 Objectives and Scope

The main objective of the research is to develop a sustainable rural roads management system for agencies in developing countries, which considers practical and adaptable components applicable at the network management level.

The research is directed at improving the management process of unpaved road networks that serve rural populations in developing countries. Considering this, the scope is to define a system that can be used by agencies in charge of the network management, considering available resources and their technical skills. The system should be adaptable to different scenarios, in terms of climate, budget, traffic and road types, among other variables.

To accomplish the main objective, the following specific objectives involved include:

- Develop a sustainable framework for rural road networks management.
- Select and validate an unpaved roads condition evaluation methodology and indicator applicable at the network level.
- Calibrate and validate condition performance models for earth and gravel roads representative to different climates.
- Develop and validate optimal maintenance standards considering different climates, traffic and budgetary scenarios.
- Develop a sustainable prioritization methodology for rural road networks maintenance
- Integrate the developed system components in a simplified management tool.
- Validate the management system in two road networks located in Chile and the other in Paraguay.

1.5 Research Methodology

The research methodology considers twelve activities as presented in Figure 1.6. These activities are described in detail as follows.

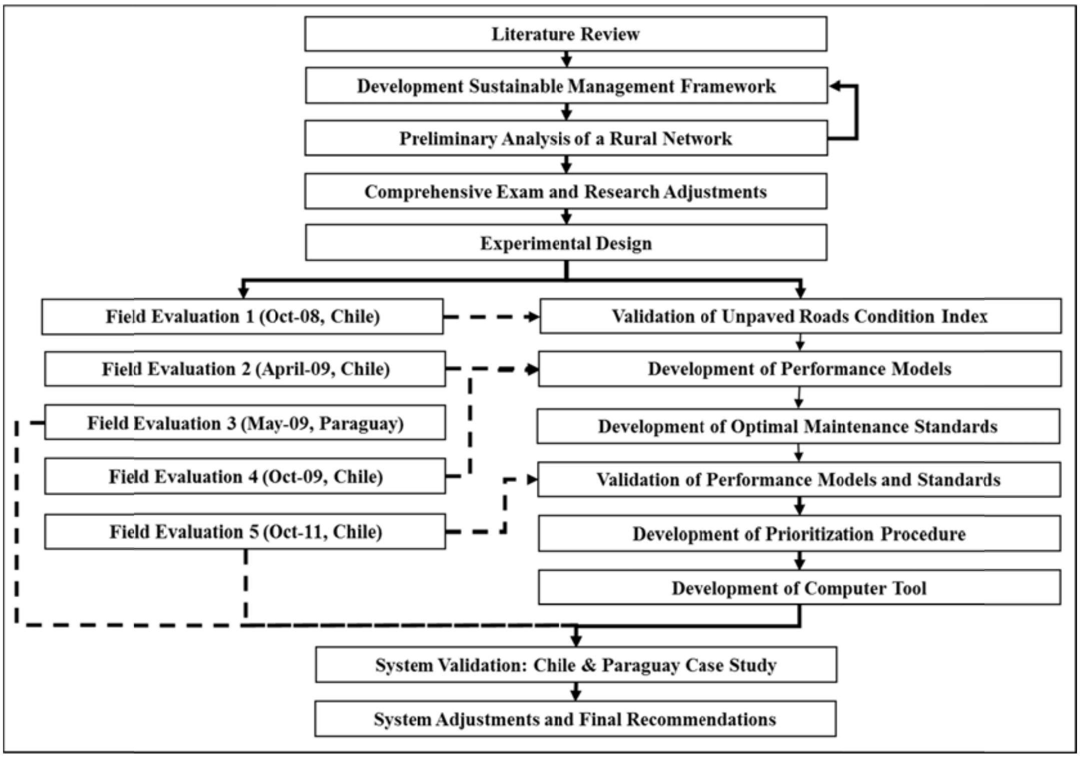


Figure 1.6 Research Methodology

1. Literature Review: Available literature was reviewed to identify the main deficiencies in existing management practices of rural road networks in developing countries. Sustainable aspects and the required system components were studied in detail and identified. This included the assessment of rural roads management practices in developing countries, unpaved roads condition evaluation and performance models, performance modelling techniques, socioeconomic impact analysis, accessibility and mobility valuation methods, available maintenance treatments and standards, optimization techniques and economic analysis methods, among others.
2. Development of a Sustainable Management Framework for Rural Roads in Developing Countries: A systematic and comprehensive framework considering the interaction between the strategic, network and project management levels was defined. The proposal then centered on the development of system components and the identification of sustainable aspects to be considered at the network level. This included a proposal on how system components had to be developed, how they should interact and how to consider sustainable aspects in the prioritization of roads maintenance. The final management system is a result of the integration and appropriate interaction of the components developed for network level application as proposed in the management framework.
3. Preliminary Analysis of a Rural Network in a Developing Country: The proposed framework was applied in a reduced rural road network in Chile. The analysis was carried out considering available accessibility and condition evaluation methodologies for rural roads under a current state analysis. From the analysis it was concluded that

condition performance models for network management had to be developed and were essential for the long term maintenance and budget planning. In addition, it was observed that the selected network evaluation methodology was technically appropriate and cost effective when applied in the field, however, it had to be validated.

4. Comprehensive Exam: The exam was held during the fourth term of the Ph.D. Program. Recommendations and feedback obtained from the committee were incorporated to the research, resulting in the improvement of the system components and proposed framework.

5. Experimental Design and Field Evaluations: A complete experiment was designed for the development and validation of management system components. Dependent and independent variables for each experiment were defined, as well as data collection and analysis methodologies. Five field evaluations were performed, four evaluations were held in Chile and one in Paraguay within thirty nine months.

6. Validation of Unpaved Roads Condition Index and Evaluation Methodology: The roads condition evaluation methodology was improved based on the findings obtained from field evaluations applied to different climates, road structures and countries. The index was successfully validated from statistical comparisons between visual condition evaluations and calculated values of Unpaved Roads Condition Index.

7. Development of Unpaved Roads Condition Performance Models: The models were developed considering a Markov probabilistic approach, unpaved roads condition data and Monte Carlo simulation. For the development of the models, field data was collected during three evaluation periods, spaced six to seven months in order to capture the seasonal variation of roads condition.

8. Development of Optimal Maintenance Standards for Network Management: Maintenance treatments for network management were defined for different climates, road structures, traffic volumes and budgetary levels. The effects of these maintenance treatments over roads condition was assessed from field evaluations. Finally, maintenance standards were defined per scenario taking in consideration suitable condition thresholds for routine maintenance, rehabilitation and reconstruction. After an extensive assessment of available economic evaluation techniques, it was concluded that the cost-effectiveness analysis method was the most suitable and practical methodology to compare and select optimal maintenance standards. Cost-effectiveness of each maintenance standard was performed considering a life cycle of ten years. From the analysis, most cost-effective standards per scenario were selected as optimum. In addition, maintenance standards presenting higher life cycle costs than those obtained from a higher budget level for the same scenario were identified and eliminated from the analysis.

9. Validation of Performance Models and Maintenance Standards: The unpaved roads condition performance models and maintenance standards were validated using data from a fourth field evaluation held 24 months after the previous field evaluation. The models were validated considering the statistical comparison of predicted condition and observed condition. Data from sections that were maintained during the 24 month period was used for the validation of maintenance standards. From the analysis models and standards were successfully validated.

10. Development of a Long term Prioritization Procedure: A sustainable prioritization method was defined considering cost-effectiveness of maintenance treatments and distribution of population in rural road networks. Road projects are ranked considering the sustainable priority per road. Available funding is defined by the system user, the budget level immediately below this fund is set as the do minimum option. The funding difference is used to maintain roads presenting higher priority levels. Roads are selected following the priority rank until the available fund is exhausted. The analysis is made for the long term and on an annual basis, giving the road manager the chance to modify available funding per year, if required.
11. Development of a Computer Tool for Rural Road Networks: The system components described previously were integrated in a simple and versatile computer tool. The management system was applied and validated in two different rural networks located in Chile and Paraguay. The networks presented different socio-economic characteristics, road surfaces, road conditions, climates and traffic levels. A sensitivity analysis was finally carried out, to evaluate the effects of fluctuations of input variables on network performance and maintenance costs.
12. System Adjustments and Final Recommendations: Limitations of the management system were identified from the case studies. Final adjustments to the system and software were made accordingly. Conclusions and recommendations were defined to assist agencies in developing countries in the application and calibration of the proposed system to their rural road networks.

1.6 Thesis Organization

In this introductory chapter the role of rural roads in the development of societies and poverty alleviation was first discussed. The need for developing a sustainable management system for rural road networks in developing countries arose from the analysis of the current state-of-the-practice. The research hypotheses, objectives, scopes and methodology were defined accordingly.

Chapter 2 presents the current state-of-the-art and state-of-the-practice of rural roads management. The concept of rural roads and technical aspects of unpaved roads are first presented. This includes the review of structural characteristics, typical deterioration, long term performance and maintenance practices. The discussion then centers on the economic evaluation of maintenance treatments and their prioritization, as well as currently available management systems applied to unpaved roads. The chapter finally analyses the limitations and opportunities for improving the current practice as a starting point for the research.

In Chapter 3, the basis proposed for a sustainable approach at all levels of management is first presented. The complete picture of the management process, considering the strategic, network and project management levels is then presented as an overall management framework. The proposed system components, modules and required developments are finally described in the chapter. Three System Modules are considered in the management system, including: Condition Performance Module, Network Maintenance Module and Long Term Prioritization Module.

Chapter 4 presents the experimental design and data collected for the development of System Modules. Seven experiments were defined, four required for the development of the Condition

Performance Module, one for the Network Maintenance Module, one for the Long Term Prioritization Module, and one for validating the overall management system. The development of these experiments and System Modules are presented in the subsequent chapters.

Chapter 5 centers on the developments required for the Condition Performance Module. These consider the validation of the UPCI methodology, development and validation of condition performance models for unpaved roads, and development and validation of maintenance effects over condition performance.

The development of the Network Maintenance Module is presented in Chapter 6. This includes the definition of maintenance activities and their costs, development of maintenance standards and trigger values per maintenance strategy. Optimal maintenance standards are developed from cost-effectiveness analysis considering different scenarios.

Chapter 7 presents the development of the Long Term Prioritization Module. A sustainable priority indicator is developed considering a combination of sustainable aspects required in the management process of rural roads.

The integration of the aforementioned modules in the management system is presented in Chapter 8. A computer tool is presented in the chapter, which integrates the three developed System Modules, network analysis interface, input data and output data. The system is applied and validated in two rural road networks. A sensitivity analysis was finally carried out, to evaluate the effects of fluctuations of input variables on network performance and maintenance costs.

Chapter 9 will finally present the conclusions of the study and recommendations for the application of the developed management system.

Chapter 2
Literature Review

2.1 Purpose of the Chapter

For a clear understanding of the management problem that currently affects rural roads in developing countries, it is essential to first identify and characterize them properly. This chapter defines the concept of rural roads and presents the various engineering aspects including structural characteristics, typical deterioration, long term performance and maintenance practices. The discussion then focuses on the economic evaluation of maintenance treatments and their prioritization. Examples of economic evaluation and prioritization methods applied to rural roads are presented. Special attention is provided to the application of methods to assess social aspects in the economic evaluation of rural roads. The chapter finally presents state-of-the-art and practice in management systems applied to unpaved roads. From the analysis, the current gaps in the research are identified followed by a discussion on how the research addresses these gaps.

2.2 Rural Roads Characteristics

Rural roads in developing countries are typically non-engineered unpaved roads, paths and tracks presenting low volume traffic and non-motorized traffic that serve the rural population. These are also referred to as unsurfaced, unpaved and unbound roads. Unpaved roads can be defined as all roads where vehicles travel directly upon a gravel or soil layer (Jones, 2003). The roads are classified as: earth tracks, earth roads and gravel roads. As defined by the Department of Transportation of South Africa the main characteristics of unpaved roads are (NITRR, 2009):

- Earth tracks generally consist of parallel ruts separated by vegetation, delineating a lightly trafficked rural access path. These tracks are not engineered and are often impassable during wet weather conditions. In most cases they carry less than five vehicles per day. They are not constructed or maintained by a road authority, instead they are managed by local communities and only sporadically by local road agencies. They are an important means of access by non-motorized traffic such as pedestrians, bicycles and animal-drawn carts.
- Earth roads, also referred in literature as dirt roads, are those where no imported gravel is used, but the in situ material is cleared of vegetation and lightly compacted. The roads may be shaped making use of the material which is removed from the side of the road during the construction of side-drains. In this way, a small embankment is formed and the road is raised slightly. These roads are usually constructed by a road authority or local agencies and are important for the economic or social advancement of the area. Unlike earth tracks, periodic maintenance should be applied to earth roads.
- Gravel roads, consist of a layer of imported selected natural soil or gravel material which is typically constructed to a specified standard and provides an acceptable all-weather surface. The vertical and horizontal alignment is generally upgraded to the desirable standards. Maintenance of gravel roads is carried out on a more regular and systematic

basis and a higher level of service is obtained although the road roughness varies considerably with time and depends significantly on the maintenance treatment.

Several countries have developed classification systems and geometric design manuals for unpaved roads in terms of surface types, road structures, topography, roads importance and traffic levels. Interesting recommendations have been drawn by researches and agencies in Canada (TAC, 1986; TAC, 1997; TAC, 2012; Dore,2009; MacLeod, 2008); South Africa (Jones, 2000; Visser, 1983; Paige-Green, 1992; NITRR, 2009), United States (FHWA, 2000; Keller, 2008), Australia (Austroads, 1989; Giumarra, 2003; Giummarra, 2000), New Zealand (MWH, 2005), United Kingdom (Keralli, 1991) and Chile (MOP, 2007). In general terms, rural roads in developing countries present traffic levels lower than 300 Annual Average Daily Traffic (AADT). Most literature recommends analyzing the economic feasibility of upgrading unpaved roads to a stabilized surface, surface treatment or pavement above this traffic level.

Structural characteristics of unpaved roads are defined in detail in design manuals. For gravel roads, detailed grading specification for aggregate base courses are suggested, while sufficiently cohesive fine aggregates to minimize loose materials, limit permeability and promote compaction are recommended for wearing courses (Jahren, 2001). The Unpaved Roads Manual developed in Australia recommends a gravel layer between 50 to 150 mm, with CBR at least 60%, PI limits less than 6 in humid climates, with annual precipitations above 600mm, and PI less than 10 for dry climates, presenting annual precipitations below 600mm (Giummarra, 2000). Technical recommendations for highways developed by the Department of Transportation of South Africa have recommended that a soaked CBR of 15% at 95% Proctor compaction is sufficient to provide a trafficable surface of an unpaved road, unless the surface drainage of the road is very poor and excessive ponding of water results (Paige-Green, 1992; NITRR, 2009; Netterberg, 1988). Given that earth roads present a non-structurally designed natural course, it is common to observe sections or entire roads having soaked CBR values below 15%. This explains the fact that most earth roads become impassable in wet weather.

2.3 Unpaved Roads Performance and Maintenance

Unpaved roads deteriorate over time due to the combined effects of traffic and environment. The deterioration rate and degree is higher than that observed in paved roads, while presenting structural and functional problems in earlier stages. The reason for early and rapid deterioration can be explained by the fact that unpaved roads suffer the direct effects of wheels over the road and are directly exposed to environmental conditions.

Traffic deterioration is basically caused by high shear stresses generated by vehicles. Stresses can increase with the mass and power of vehicles, as well as under acceleration, braking and maneuvering conditions. Findings from several researches held in South Africa evidenced that no significant differences in the modeling of gravel loss and riding quality deterioration of rural gravel roads were found by separating the traffic into light and heavy vehicles. Moreover, studies have demonstrated that unloaded heavy vehicles travelling at high speeds may cause a rapid deterioration of unpaved roads under dry conditions. (NITRR, 2009)

Environmental forces affecting unpaved roads include: moisture, heat, rain impact, snow and wind. The presence of these may accelerate deterioration problems caused by traffic, can affect the structural characteristics of support layers and can substantially reduce the presence and functionality of the wearing course. The application of good construction processes and prompt spot maintenance on affected areas can considerably minimize the negative effects of environment on unpaved roads.

2.3.1 Deterioration of Unpaved Roads

Deficiencies in the performance of unpaved roads can be classified as either structural or functional problems. In the case of gravel roads, structural problems relate to the inability of the pavement structure to support the traffic under the prevailing environmental conditions and occur within the wearing course or support layers. Functional problems are essentially surface defects arising from poor material selection, poor construction methods and traffic or weather conditions (NITRR, 2009). Regardless of the distinction between structural and functional defects, functional defects contribute on the appearance and progression of structural problems. In the case of earth roads, both problems are typically observed simultaneously as the wearing course is also the support layer.

The main structural problems observed in unpaved roads are impassability, potholes and rutting. Typical functional defects are: dustiness, stoniness, corrugations, cracking, ravelling, erosion, loss of shape/profile, slipperiness, loss of gravel and excessive loose material. Most important defects observed in unpaved roads are described as follows.

2.3.1.1 Structural defects

a) Impassability

Impassability of unpaved roads is not a specific type of failure but is produced by the combination of severe structural and functional problems. It is considered as the main cause of access problems to rural communities in wet weather. It can be defined as the failure of a vehicle to travel in the horizontal direction caused by a loss of traction at the surface (slipperiness) or at depth (shearing). The former may even relate to fairly flat grades but is usually related to steep grades, while the shearing of material at depth is the result of insufficient strength in the load-bearing material. Adequate wearing and course layers with high material strength, mostly presenting soaked CBR values above 15% at 95% Proctor compaction, provide a trafficable surface under all weather conditions (Netterberg, 1988).

b) Potholes:

Potholes are commonly produced by the low strength of the base course observed under humid conditions. Potholes directly affect the development of roughness causing substantial damage to vehicles, especially when they present diameters between 250 and 1 500 mm and a depth of more than 50 mm. They tend to progress and enlarge rapidly by the combined effects of traffic, poor drainage and water ponding in the depressions. Potholes are mostly observed at the bottom of vertical curves, on level road sections and near bridges and culverts. Due to difficult access they are not often repaired by the routine grader maintenance or by manual filling. The only way to successfully repair potholes is by enlarging and deepening the hole with vertical sides, filling it with moist gravel and then compacting it (NITRR, 2009).

c) Rutting

Rutting may be caused by ravelling of low-cohesive materials under traffic movement. It may also be caused by the deformation of highly cohesive wearing course materials under traffic during wet conditions. Ruts are parallel depressions of the surface in the wheel tracks. Rut depth has traditionally been a relevant criterion for failure of unpaved roads (Visser, 1981; Skorseth, 2005), however, its effects over roads transitability are minor compared to other deterioration, probably explained by the fact that ruts are parallel to the traveling direction and drivers may maneuver in face of severe rutting. Routine blading is the common maintenance method to repair ruts, however, an effective repair should consider moist compaction prior to blading.

2.3.1.2 Functional defects

a) Stoniness or Presence of Oversized Material

Stoniness is the relative percentage of material in the road which is larger than a recommended maximum size (usually 37.5 mm). Oversized materials can be observed as embedded or loose stones in gravel roads, and as natural rocks in earth roads. The former can be controlled by removing or reducing the size of wearing course gravel.

b) Dustiness or Presence of Fine Material

Dust can be defined as the fine material released from the road surface under the wheels of moving vehicles. Silt-sized particles (5 - 75 µm) are the predominant elements in dust. Dust generation is a function of aerodynamic shape and travel speed of vehicles, surfacing material properties and moist content. Dust produces several negative effects such as safety problems, health complications, air pollution, economic effects on farming and agriculture, discomfort and vehicle damage.

c) Corrugations

Corrugations consist of parallel crests forming right angles to the direction of travel. Crests may be of loose fine-sandy material (loose corrugations) or hard fine-sandy material (fixed corrugations). The wavelength of the corrugations is dependent on the modal vehicle speed, with longer wavelengths formed by faster traffic. Corrugations are one of the most disturbing defects of unpaved roads causing excessive roughness and poor vehicle directional stability. Their cause has been debated for decades but consensus seems to have been reached on the "forced oscillation theory" (Heath, 1980; Paige-Green, 1990). The theory is based on initiation of wheel bounce by some irregularity in the road resulting in kick-back of non-cohesive material, compression and redistribution of the wearing course as the wheel regains contact with the road. Loose corrugations are easily removed by blading, whereas fixed corrugations need cutting or light ripping with the grader before the material is spread again. (NITRR, 2009).

d) Ravelling and Gravel Loss

Ravelling and gravel loss is an inevitable problem observed in gravel roads with unbound wearing course. The rate of gravel loss is related to the traffic, precipitation and materials properties and material characteristics. The gravel loss rate can be reduced by selecting materials with high plastic factors, well-graded gravels and using high degree of compaction (Van Zyl, 2005; Van Zyl, 2007). Ravelling and gravel loss is lower in the wet season when more cohesion between granular aggregates is observed.

e) Erosion or Scour

Erosion or scour is the loss of surfacing material caused by the flow of water over the road. The ability of a material to avoid erosion depends on the shear strength in the condition at which the water flow occurs. Finer grained and poorly graded materials with minimal coarse aggregate are more susceptible to erosion. Run-off channels are a result of erosion causing extreme roughness, deep ruts and dangerous driving conditions. Gravel loss caused by erosion is mostly deposited in drains and culverts, requiring extensive manual maintenance. Erosion can be prevented by increasing the shear strength of the wearing course material or with an effective drainage system.

f) Poor Cross-Fall and Profile

Poor cross-fall shape accelerates the formation and progression of structural and functional problems. To avoid this problem timely routine maintenance should be performed, otherwise, excessive deterioration results in ineffective or costly restoration of desired crown shape.

2.3.2 Unpaved Roads Maintenance

Maintenance is essential to ensure the desired level of service of unpaved roads. Maintenance types can be classified into routine maintenance, rehabilitation and reconstruction or emergency maintenance. Given the accelerated rate of deterioration observed on unpaved roads, routine and periodic maintenance should be performed continuously and with a higher frequency than that observed in paved roads. Table 2.1 presents a summary of the maintenance activities commonly considered in these three general maintenance types.

Most of the maintenance activities described in Table 2.1, with the exception of blading, can be performed using labour intensive methods. This is important on very light traffic volume roads and tracks where large maintenance equipment cannot reach and where local communities are commonly in charge of the roads maintenance. In addition, it has the advantage of creating sustainable employment in rural areas. Studies have demonstrated that potholes repair, spot graveling and the loosening of fixed corrugations can be effectively done using labour (GDPTRW, 2008).

Table 2.1 Maintenance Categories and Activities

Maintenance Types	Maintenance Activities
Routine Maintenance	• Roadside maintenance • Drainage maintenance: considers maintenance of side and mitre drains. • Surface maintenance: Considers patching and blading. Blading can be performed as dry blading, wet blading, light blading and heavy blading/grading. Surface maintenance represents the major cost in a routine maintenance program.
Rehabilitation	• Reshaping: applied when defects are more than 50 mm in depth and only when sufficient material thickness of appropriate quality exists • Reworking: break down oversize material in an existing layer of adequate thickness, re-shaping and compaction • Forming or Simple Blading: shaping of the road-bed to ensure adequate road levels, proper side drainage, camber and cross fall. • Spot gravelling: gravelling of short sections on a road, typically only on curves, steep gradients, potholes or isolated rock outcrops. • Gravelling: addition of a suitable wearing course layer, typically 100 mm to 150 mm in thickness over the entire length.
Reconstruction, Corrective or Emergency Maintenance	• After unusually heavy precipitation or abnormal use of the road, excessive damage or wear is observed. Reconstruction or emergency maintenance is applied to ensure an acceptable condition for the prevailing traffic.

2.3.3 Unpaved Roads Condition Evaluation and Performance Indicators

The main purpose of condition evaluations is to identify functional and structural problems of unpaved roads for the programming of maintenance activities. Surveys are also intended to identify uniform sections requiring different treatments. Specific attention is given to rectify situations that impact on safety, accessibility, mobility, maintainability and material performance. Such as unsafe geometric situations, condition of the pavement structure, deterioration of the wearing course and condition of side and cross drainage

Several agencies have developed proprietary condition evaluation procedures and indicators, adjusted to commonly observed distresses and subject to available resources. Most procedures consider windshield visual surveys where the evaluator must rate under a qualitative scale the general condition and extent of defects observed in a kilometer. Performance indicators have been developed to identify the overall condition of roads and assist on the definition of network maintenance priorities. These may be a result from the combination of problems observed from windshield evaluations, serviceability values obtained from the ride comfort observed at certain survey speeds or the correlation of measured distresses. Most commonly used evaluation methods and indicators are described as follows.

2.3.3.1 Visual Evaluation Surveys and Indicators

Visual evaluations are the most common method to assess the condition of unpaved roads. These involve a subjective windshield visual survey to quantify the extent and severity of road problems observed in a sample unit, commonly 1 km of road. From these evaluations, the overall condition of surveyed sections is obtained by combining the different defects observed in the field into a performance indicator. Examples of these methods are: the MTO guidelines for unsealed roads used in Ontario, Canada (MTO, 1989); the PASER Manual developed by the University of Wisconsin-Madison and the Gravel Roads Maintenance and Design Manual developed by the South Dakota Local Transportation Assistance Program of the Federal Highway Administration, both used in the United States (FHWA, 2000); the TMH 12 Standard visual assessment manual for unsealed roads developed by the Department of Transportation of South Africa (Jones, 2000), the Unsealed Roads Manual: Guidelines to Good Practice developed by ARRB for application in Australia and New Zealand (Giummarra, 2000).

2.3.3.2 Serviceability and Roughness Measures

Maintenance requirements and costs depend on the desired level of service or serviceability expected for the prevailing traffic. Acceptable levels of service vary according to the importance, surface type, traffic volumes and typical use of a rural road. For example, secondary gravel roads should present higher service standards compared to local earth roads, given that they have the double function of providing mobility to the traffic and accessibility to villages, towns and primary network. Table 2.2 presents some guidelines for service levels recommended by South African authorities (NITRR, 2009; Jones, 2000).

Table 2.2 Guidelines for Levels of Serviceability (NITRR, 2009)

Level of Serviceability	Max Roughness (IRI in m/km)	Dustiness	Impassability
5	15	5	Frequently
4	11	3	< 5 days/yr.
3	9	3	Never
2	8	3	Never
1	6	1	Never

In most developing countries it is not possible to measure the International Roughness Index (IRI) given that measuring equipment is not available. In those cases subjective and correlation methods have been developed to relate travel speeds with roughness and roughness with other forms of deterioration (Sayers, 1986; Archondo-Callao, 1999). Table 2.3 presents correlations for traveling speeds recommended by South African authorities. The recommendations are a function of the type and condition of the vehicle used (NITRR, 2009).

Table 2.3 Estimation of IRI on the basis of comfortable travel speed (NITRR, 2009)

Roughness (IRI in m/km)	Approximate comfortable travel speed (km/h)
15	<35
12.5	45
10	60
7.5	80
5	>100

Equations 1 and 2 present correlations with typical distresses for gravel and earth roads recommended by the Ministry of Public Works of Chile (Namur, 2008).

Equation for gravel roads:

IRI = 6.97 + 0.60 Oversized Gravel (R^2=58%; S.E.=2.2) (1)

Equation for earth roads:

IRI = 4.14+6.60 Potholes+1.51 Corrugations Depth+0.92 Rut Depth (R^2=69%; S.E.=2.1) (2)

In both equations low multiple correlation coefficient (R^2) and high Standard Errors (S.E.), denote a poor goodness of fit of the proposed correlations.

2.3.3.3 The Unsurfaced Road Condition Index (URCI)

The Unsurfaced Road Condition Index (URCI) was developed by the Cold Regions Research Laboratory of the U.S Army Corps of Engineers (Eaton, 1987; Eaton, 1992). The method is similar to the pavement condition index (PCI) developed for paved areas. The URCI method identifies seven surface defects: improper cross section, inadequate roadside drainage, corrugations, dust, potholes, ruts, and loose aggregate. With the exception of dust, all other distresses are rated in terms of density, a measure of its length or area on the sample unit, and three severity levels (low, medium, or high).

The negative effect of each surface defect is evaluated separately through a set of six graphs, with three curves each, one per severity level. Density and severity are the entry variables to the curves, from which “deduct values” are obtained. A seventh graph is used by the method to compute the URCI for a sample unit. Entry data to this graph is the total deduct value, which is the sum of all deduct values obtained from the defects observed in a sample section, and the total number of deduct values (q). As an output, the URCI for the sample unit is obtained.

The main restriction of the method is that deduct value curves are representative to the location where they were developed. Studies to calibrate the curves to local conditions have been held in developing countries but trained evaluators are required and this can be expensive. A study held in Brazil indicated that there was no relationship between deduct values rated per sample unit and sections by a panel and the URCI deduct values obtained as a function of distress density (Soria, 2003)

2.3.3.4 The UnPaved Road Condition Index (UPCI)

In 2007, the Ministry of Public Works of Chile and a private consultant developed the UnPaved Road Condition Index (UPCI). The methodology evaluates the condition of unpaved roads based on objective measures of distress, drainage and profile characteristics (Chamorro, 2008; MOP, 2008). The advantage of the methodology is that it is applicable to any location, following a simple procedure and it is also cost-effective. The index was developed considering the Delphi calibration method (Fernando, 1983). Condition models were obtained from the application of a questionnaire to a professional panel. The panel rated the condition of earth and gravel roads under different scenarios combining several levels of distress, drainage conditions and profile characteristics.

From multiple linear regression analysis equations 3 and 4 were obtained, the former considering manual evaluations and the latter considering measuring equipment. UPCI represents the relative effect of each surface defect over the road condition, considering the following defects: Corrugations, Potholes, Erosion, Rutting or transverse deformations, presence of oversized aggregates and fines, Crown condition and International Roughness Index (IRI).

UPCI without considering roughness measures:

$$UPCI=10 - 1.16CR - 2.25PT - 1.47ER - 0.33RT - 1.56OA - 1.58CW \quad (3)$$

UPCI considering roughness measures:

$$UPCI = 11.64 - 0.41\ IRI - 1.60\ ER - 0.40\ RT - 1.79\ AG - 1.57\ CW \quad (4)$$

Where:

- CR: Corrugations measured in terms of depth in centimetres.
- PT: Potholes measured as the total square metres observed in a sample section.
- ER: Erosion, considered as 1 if either erosion depth is greater than 5 cm or width is greater than 10 cm.
- RT: Rutting measured in terms of rut depth in centimetres.
- OA: Exposed Oversized Aggregate is considered as 1 in presence of oversized aggregates with mean diameters greater or equal to 5 cm; otherwise it is equal to zero.
- CW: Crown condition, which is the average between drainage and transverse profile condition. Where drainage is evaluated in terms of the existence of adequate side drains and rated as 0 when observed in good condition, 0.5 in regular condition and 1 in poor condition. Transverse profile is rated as 0 when adequate side slope is observed, 0.5 for a regular profile and 0 for a flat or poor transverse profile.
- IRI: International Roughness Index measured in m/km with response type technology.

The method recommends condition limits for unbound gravel, stabilized gravel and earth roads, subject to three different climates (dry, Mediterranean and humid), as well as road conditions assigned to extreme surface defects.

2.3.4 Performance and Maintenance Models for Unpaved Roads

Several deterioration and maintenance models have been developed in the last 40 years to predict unpaved roads performance over time. Among these are the studies carried out by the World Bank during the 1980's for the Highway Design and Maintenance Standards Model (HDM-III), models developed in South Africa and Namibia, the Road Investment Model for Developing Countries (RTMI2) developed by the Transport and Road Research Laboratory (TRRL) and the ARRB models developed in Australia (Watanatada, 1987; Paige-Green, 1991; Parsley, 1982; Giummarra, 2007).

In general terms, deterioration performance models estimate the progression of one distress type subject to variations of independent variables affecting their performance over time. The independent variables are related to traffic characteristics, material properties, geometric design and climate. These variables require detailed data of the roads performance, limiting the application of the models to project level management. In addition, specialized knowledge is required for their application, thus, they are primarily used by agencies with high technical expertise.

Maintenance models have been developed to optimise routine maintenance and rehabilitation. These include blading and graveling frequency. These models may be very useful for estimating maintenance costs during the life cycle of unpaved roads or to estimate intervention thresholds. Several of these models, however, are representative to the conditions where they were developed and require detailed data of materials characteristics.

Some of the performance models available worldwide include:

- Performance Models Developed in South Africa and Namibia (TRH20): Between 1983 and 1989 an extensive project was carried out in South Africa to understand the performance of available materials and deterioration rates under different climates and traffic conditions. Models were developed from data collected on 110 sections. The models defined from the study are rate of gravel loss, roughness progression (measured in Quarter car Index or QI) and roughness after blading (Paige-Green, 1989; Paige-Green, 1991; NITRR, 2009).
- Maintenance and Design System Models (MDS): The MDS was originally developed by Visser (1981) using data collected during the World Bank Study in Brazil. The models considered are gravel-loss prediction, roughness progression (measured as natural logarithmic value of QI) and roughness after blading. The models were applied in South Africa for network level assessment in the province of Gazankulu, where recommendations were made to extend the scope of the models (Visser, 1987)
- Highway Design and Maintenance Standard Models (HDM III) and Highway Development and Management (HDM-4): The HDM-III models for gravel roads were developed with data collected in Brazil, and these models are also included in the HDM-4. The models considered by both systems are annual gravel-loss, rate of roughness progression and roughness after blading. The model for roughness progression corrected the tendency observed in other models, where roughness was overestimated at high roughness levels. For this the rate of roughness progression is decreased as roughness tends to a maximum level. The gravel loss model requires significant input data and may be especially cumbersome for developing countries, compared to other available models. (Paterson, 1991; Watanatada, 1987).

- Road Investment Model for Developing Countries (RTMI2) developed by the Transport and Road Research Laboratory (TRRL) from data collected in East and West Africa and the Caribbean. The study primarily focused on the effects of road geometry on vehicle operating costs (Parsley, 1982).
- Australian Models: deterioration models for unpaved roads were developed in Australia from a research project that started in 2001 that was headed by ARRB Group and counted with the support of some state road authorities. The study included 25 sites located in the state of Victoria, where roughness, gravel loss, and cross-fall (loss of shape) were assessed during a period of 12 months. The models have proved to be effective at the network level to estimate grading and graveling requirements. A major difficulty, however, has been to adapt the models to a wide variety of traffic, soil conditions, and climates
- Models developed by the Forest Engineering Research Institute in Canada (FERIC): A model for predicting road performance was developed by FERIC as part of a larger project aimed on improving forest road design methods. The model was developed for high traffic forest roads and presents a new concept where localized grading is recommended considering a flexible schedule (Provencher, 1995).

2.4 Economic Evaluation and Road Maintenance Prioritization

2.4.1 Economic Evaluation Methods

Several economic analysis methods can be applied to evaluate treatment maintenance strategies. All methods in pavement management should be able to consider the costs and benefit streams during the life cycle of roads. The most commonly used methods are briefly described on Table 2.4. (Haas, 1994; FHWA, 2003)

Table 2.4 Economic Evaluation Methods

Method	Description
Equivalent uniform annual cost	Initial capital costs and recurring future costs are averaged into equal annual costs over the analysis period. It is a simple and easily applied method. The disadvantage is that the analysis does not consider benefits.
Present worth	Can consider only costs, only benefits or the difference between costs and benefits. This last method is also known as the net present worth or net present value method. In all cases the method involves the discounting of all future sums to the present using an appropriate discount rate. The net present value method is one of the most commonly used to evaluate alternative maintenance strategies, however, it presents limitations when applied in cases where benefits cannot be estimated. The obtained outputs are not easily interpreted by some people. Some applications have required extensive studies to quantify benefits and costs considered by the method.
Rate-of-return	The method considers the discount rate at which the costs and benefits for a project are the same. It can also be applied as the rate in which equivalent uniform annual costs are equal to equivalent uniform annual benefits. The comparison is done between a basis project and alternatives. However, the comparison must be made by all possible cases. The results are well understood by the public, however, the use of costly maintenance alternatives may not be evidenced by the only use of this method.
Benefit-cost ratio	The method is the ratio of benefits divided by costs, where the present value of benefits is placed in the numerator of the ratio and the present value of the initial agency investment cost is placed in the denominator. The ratio is usually expressed as a quotient. Is often used to select among competing projects when an agency is operating under budget constraints. In particular, it can identify a collection of projects that yields the greatest multiple of benefits to costs, where the ability to incur costs is limited by available funds. However, care must be taken when relying on the method as the primary benefit-cost analysis measure, given the abstract nature of the ratio and the interpretation of negative values.
Cost-effectiveness	The method is recommended for the comparison of alternatives where significant non-monetary outputs are involved. It considers a subjective measure of benefits to be gained given the application of certain maintenance strategy. It requires the development of effectiveness measures or benefits, like a condition indicator. Expenditures are considered in terms of present worth of costs and the benefits or effectiveness as the value observed on a certain period of time. Alternatives are compared in terms of the ratio given by effectiveness divided by costs. The advantage of this method is that includes the effects of road condition or level of service in the economic analysis.

2.4.2 Priority Programming Methods

Several priority programming methods have been applied in roads management. They are often grouped in terms of management system generations or by method classes. In general terms the methods can be grouped as: ranking methods used by first generation systems; near optimization or heuristic methods, used second and third generation systems; and optimization methods considered in third generation systems. Methods and their characteristics are described in detail in Table 2.5 (Haas, 1994; Robinson, 1998).

Table 2.5 Priority Programming Methods

Method Class	Characteristics
Ranking Methods	Ranking can be made as a function of subjective ratings, present costs, roads condition or road hierarchy. Most methods are simple and easy to use, but may be subject to bias in cases where subjective ratings are considered. Most methods may recommend priorities far from optimal, unless an economic analysis is considered.
Heuristic and Near Optimization	Heuristic methods include marginal cost-effectiveness, multi-criteria analysis and economic boundary methods. All cases consider the comparison of different alternatives under economic analysis approach, considering net present value, costs and or effectiveness measures. The analysis also considers treatment life and analysis of deferment options. These methods are reasonably simple to apply, can be programmed and may give near optimal solutions.
Pure Optimization, and Programming	Formal optimization methods such as linear programming, total enumeration, dynamic programming, neural networks, genetic algorithms and fuzzy logic have been recently considered in the development of third generation systems. They can give optimal programs, but are complex to develop and could demand sophisticated software/hardware. They are more suitably applied to problems where costs and benefits can be quantified in monetary terms.

2.4.3 Economic Analysis and Prioritization of Rural Roads

While management of the primary network should focus on the economic optimization of road maintenance, given the high levels of traffic and significant asset value they present, rural roads management should also consider the socio-economic importance of roads in the prioritization process. These socio-economic aspects can be quantified in terms of the role of a road in ensuring access and mobility to the population or the importance of a road related to economic activities, such as farming, forestry or tourism

Inclusion of non-technical or economic impacts to the management process can be a huge challenge. One obvious problem that arises is the need to define a simple and versatile technique to account for socioeconomic impacts related to rural road investment. Traditional socio-economic impact valuation methods have demonstrated to be very expensive, time consuming and often not appropriate. An affordable and practical mechanism to introduce the social impact in the management process is to consider the role of access and mobility in reducing poverty as it relates to rural road investments. Examples of these are the Rural Access Index and the Basic Access Approach, both developed by the World Bank (Robertson, 2006; Lebo, 2000). Other studies have successfully incorporated sustainable aspects in the prioritization process by developing multi-criteria analysis. The methods mentioned are briefly described as follows.

2.4.3.1 Socio-economic Impact Valuation Methods

The socioeconomic impact of roads can be subdivided in direct or primary effects, and indirect or secondary effects. The objective of socioeconomic impact analysis is to assess the magnitude and distribution of both direct and indirect effects. Primary effects are those that can be directly measured such as reduced travel times and savings in vehicle operating costs (VOC). The indirect effects consist of increases in income and other dimensions of wellbeing, such as health, education, social interaction and political participation, caused by road improvements. These are related to social benefits, which are the way in which households and communities respond to changes in transport conditions. Special attention should be given to avoid double-counting when performing socioeconomic impact analysis (TRL, 2004).

The economic evaluation of rural roads is generally performed under a traditional approach considering a minimum threshold of economic or internal rate of return, Life Cycle Cost Analysis or Benefit Cost Analysis. Benefits accounted by these methods typically consider direct benefits to road users but do not account for indirect effects.

In developed countries, where the economy is less distorted and more competitive, it is expected that direct effects account for all consequences of road investment. However, in developing countries, and especially within their rural networks, rural road projects are difficult to justify and have historically been given lower priority. For example, a study held in 32 countries in Sub-Saharan Africa showed that on average 60 percent of their funds are spent in main roads, eighteen percent in rural roads and fifteen percent in urban roads. While all countries allocate funds to urban roads six of the 32 do not assign funds to rural roads (Benmaamar, 2006).

Several studies have been carried out in developing countries to assess the impact of rural road projects. For examples, projects have been carried out in Morocco, Peru, Brazil, Vietnam and Tanzania, in partnership with the World Bank, Asian Development Bank and other organizations. The findings, in many cases have been limited due to the lack of available baseline or control data. Overall, it has been difficult to identify the comprehensive benefits achieved from the specific projects. In essence they focus on just one aspect and they do not effectively integrate findings.

In 2002 The World Bank published the report “Socioeconomic Impact Assessment of Rural Roads: Methodology and Questionnaires” (Grootaert, 2002). The aim of the study was to develop a comprehensive framework to assist managers with data collection and analytic methods for impact assessment of rural road projects. The study distinguishes several quantitative methods for the evaluation of rural project impacts. Methods are grouped into two major types: Experimental or Randomized Control Designs and Non-Experimental or Quasi-Experimental Designs. All methods require a clear distinction of the area of analysis, which could be a community, a county or a district. Commonly two parallel groups or areas are analyzed, the treatment group which receives the road intervention and the comparison or control group which has similar characteristics to the treatment group but does not receive an intervention. (Baker, 2000; Ravallion, 2001)

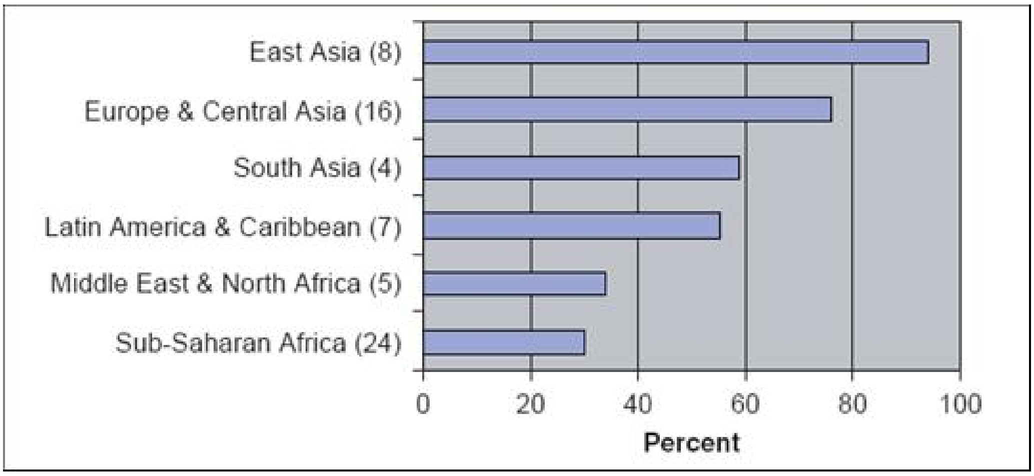
The principles and tools proposed by Grootaert were based on past experiences and good practices for the appraisal of socioeconomic impacts. Given the level of detail of the proposed methods, their application is more appropriate for project level management. Although the framework is very clear and flexible, the approach still considers major technical and financial efforts from agencies to pursue socioeconomic impact studies. In addition, even though the findings are helpful under an economic perspective no recommendations are made to enhance the management process of rural roads.

The Department for International Development (DFID) and the Transportation Research Laboratory (TRL) from the United Kingdom presented in 2004 “A Guide to Pro-poor Transport Appraisal: The Inclusion of Social Benefits in the Road Investment Appraisal”. The document includes a detailed analysis of the problem of socioeconomic impact assessment of rural roads in developing countries. It identifies the nature of social benefits, how they can be measured using indicators and how they can be included in the appraisal process. However, the recommended method likewise other socio-economic valuation methods, may require substantial efforts from agencies in developing countries for their implementation in rural roads management (TRL, 2004).

2.4.3.2 Rural Access Index

Isolation is one of the main limiting conditions for rural communities in developing countries, therefore, providing and maintaining a minimum level of access is fundamental for any rural development policy. At a strategic and network level of rural roads management, this should be one of the main goals. Technical and social information required at these levels does not require high level of detail, but needs to be objective to avoid biased decision making.

In 2005, The World Bank developed the Rural Access Index (RAI), which is a transport indicator that highlights the critical role of access and mobility in reducing poverty in poor countries (Roberts, 2006). The index measures the percentage of the rural population that lives within two km radius of an all-season road, which is equivalent to a walk of 20 to 25 minutes. This indicator is very helpful for the assessment of population accessibility at a network management level and for policy making. In fact, it was used as part of the results measurement system of the 14th round of International Development Association (IDA-14) for the 81 countries that receive IDA concessionary assistance. Current estimates of the Index show that 900 million rural residents from developing countries do not have adequate access to formal transport systems. As presented in Figure 2.1, the worse situation is observed for the region of Sub-Saharan Africa, where the average RAI is 30 percent (Plessis-Fressard, 2007).



Note: Numbers in parentheses indicate number of countries

Figure 2.1 Percentage of Rural Population with All-Season Access (Plessis-Fressard, 2007)

The World Bank Transport Paper "Rural Access Index: A Key Development Indicator" recommends to estimate RAI from household survey results (Robertson, 2006). The study presents a transport questionnaire module for new household surveys considering limited availability of resources to establish and update the measurement. Alternative methods of measurement and estimating RAI are also described in the study for cases where there is no chance to undertake a suitable household survey.

A study developed in 2010 provides some recommendations to improve the method, after observing that its application in some African countries has led to a bias in favor of investing in rural roads at the expense of secondary and main roads. From evaluations held in Burkina Faso, Cameroon and Uganda it was observed that the 2-kilometer criterion is not an economic threshold. The study recommends extending it to a buffer zone of 5 kilometers, stating that the last mile of public roads should be suitable for motorcycles or non-motorized vehicles rather than to small trucks. This is explained by the fact that most rural households are located fewer than 5 kilometers from a road and that road passability is not a major consideration for small farmers, with the exception of bridges or tunnels access (Raballand, 2010).

2.4.3.3 Basic Access Approach

The Basic Access Approach (BAA) for the cost-effective design and appraisal of rural transport infrastructure was presented by The World Bank in 2000 (Lebo, 2000). The method gives priority to the provision and maintenance of reliable, all-season access. Basic access interventions are defined by the study as the least-cost investments which provide a minimum level of all-season passability. In most of the cases, this means single-lane, spot-improved earth or gravel roads. In situations where motorized basic access is not affordable, the study proposes the improvement of existing path network and the construction of footbridges as an alternative.

The study proposes a two stage methodology. In a first stage, the method proposes to eliminate low-priority links of the network applying a screening method. A screening method helps decreasing the number of investment alternatives given budgetary constraints. For this, screening can look at targeting disadvantaged areas or communities based on poverty indexes, or eliminating investments into low-priority sections of the network selected based on agreed criteria. After screening methods have been applied to a given network, the second stage proposed by the method is to rank and prioritize road maintenance projects considering cost-effectiveness and cost-benefit analysis. Cost effectiveness analysis is recommended when traffic is less than 50 motorized four-wheeled vehicles per day. For this, a priority index is defined based on a cost-effectiveness indicator equal to the ratio of the total life-cycle cost necessary to ensure basic access, divided by the population served. For roads where more than a basic access standard is required, presenting traffic levels between 50 and 200 vehicles per day, the use of benefit cost analysis is recommended. For this, enhanced models for benefit cost analysis or the use of the World Bank RED software are recommended by the study.

2.4.3.4 Integrated Rural Accessibility Planning

Development of the Integrated Rural Accessibility Planning (IRAP) method started in the late 1980s, led by the International Labour Organization (ILO). It was developed as a response to the common practice observed in developing countries where most investment was placed in the primary road infrastructure, which was proved to be insufficient to address the issue of poverty alleviation. Research stimulated by initial findings continued during the 1990s. (Dingen, 2000)

The method can be described as “a multi-sectorial, integrated planning tool that addresses the major aspects of access needs of rural households for subsistence. The tool integrates the access and mobility needs of the rural population, the locations of basic social-economic services and the transport infrastructure in all sectors. The application of the method is participatory and pro-active involving communities in all stages of the planning and creating a platform for local level planners and beneficiaries to pro-actively plan for development. The method considers the improvement of the physical infrastructure as well as concepts such as “means of transport”, “location planning” and “quality improvement of services”. The method, however, is more likely to a planning tool rather than a prioritization method for network level management. (SSATP, 2008)

2.4.3.5 Multi-criteria Analysis and Ranking Methods

Multi-criteria analysis has been commonly used to rank rural roads investments. Criteria such as traffic level, proximity to health, access to educational facilities and agricultural assets receive weights or points relative to their perceived importance. Each road link is then allocated the number of points corresponding to the fulfillment of the particular criteria. The total points of each intervention can be the sum of points allocated per indicator, or in some cases, is estimated through the application of a more complex formula. The result of this process leads to a ranking of the investment options (Lebo, 2000).

The multi-criteria analysis method has the advantage of being able to consider non-monetary criteria in the prioritization method. The method, however, should be used with care as in most cases it implicitly reflects economic and subjective evaluations. If the weights and points are agreed upon in advance and allocated in a participatory way, the method has the potential to be an effective planning method based on implicit socioeconomic valuation. In several applications the outcome of the methodology has been non-transparent, especially when an important amount of factors are considered and a complicated formula is applied. Therefore, if adopted, this method has to be used with special care and kept simple, transparent, and participatory.

Some examples where multi-criteria analysis and ranking methods have been applied for rural roads management are:

- Prioritization method used in the project “Plan Vial Participativo de Caminos Vecinales”, which was held in Paraguay in 2008 and was developed by the Ministry of Public Works and Communications with a loan from the Inter-American Development Bank (MOPC, 2009).
- Prioritization method proposed by the Ministry of Public Works of Chile in the “Regional Maintenance Project” (MOP, 2008)
- Prioritization method recommended by the ROADEX III project funded by Northern Periphery nations and the European Regional Development Fund from the European Union (Johansson, 2006)
- Studies have been conducted at the University of Birmingham which compared existing multi-criteria analysis methods and their capability of being adopted in HDM-4 (Ortíz, 2004; Cafiso, 2003)

2.5 Management Systems and Tools Applied to Rural Roads

2.5.1 HDM-4

The Highway Development and Management model (HDM-4) has been adapted and adopted by many different countries for economic analysis and prioritization. It focuses on the technical and economic appraisal of road projects, the preparation of road investment programs as well as the analysis of road network strategies. It utilizes road network inventory, condition, traffic and economic data as input variables. (SSATP, 2008) The models contained in the system are:

- Road deterioration model, which predicts pavement deterioration for bituminous, concrete and unsealed roads. This is done by considering the consequence of impacts such as traffic loading, environmental weathering and inadequate drainage systems.
- Road works effects model, which simulates the impact of road works on pavement condition and determines the corresponding costs.
- Road user effects model (RUE), which calculates the cost of vehicle operation, road accidents and travel time cost.
- Socio-economic and environmental effects model (SEE), which determines the effects of vehicle emissions and energy consumption.

The system estimates on an annual basis, for each road section, the road condition and resources used for maintenance under each strategy. It also estimates the vehicle speeds and physical resources consumed by vehicle operation. After estimating the physical quantities involved in construction, road works and vehicle operation, user-specified prices and unit costs are applied to determine financial and economic costs. Relative benefits are then calculated for different alternatives, followed by present value and rate of return computations. Social costs are estimated through the Road Users Effects (RUE) model and the Social and Environmental Effects (SEE) model (Kerali, 2000). The model has recently incorporated in its last version the following improvements:

- Sensitivity Analysis to allow a user to investigate the impact of variations in key parameters on the analysis results.
- Budget Scenario Analysis to allow a user to compare the effects of different funding levels on the network being analyzed.
- Multi-Criteria Analysis, which provides a means of comparing projects using criteria that cannot easily be assigned an economic cost.
- Asset Valuation to provide a means to estimate the financial and economic value of road assets as a function of the level of investment.
- Unsealed Road Deterioration and Work Effects updated for better calibration.
- Road User Effects updated for improved results.

2.5.2 Roads Economic Decision Model

The Roads Economic Decision (RED) model is a tool developed by the Sub-Saharan Africa Transport Policy program in the late 1990s, to facilitate the economic analysis of low-volume roads in developing countries. The program is implemented in a series of Excel workbooks that collect all user inputs; present the results in a user-friendly manner; estimate vehicle operating costs and speeds; perform an economic comparison of investments and maintenance treatments; and perform sensitivity, switch-off values and stochastic risk analyses. The models considered by the program are:

- Main Economic Evaluation Module: Needed to perform the economic evaluation of one road.
- HDM-III Vehicle Operating Costs Module: To define the relationship between motorized vehicles operating costs and speeds to road roughness, for a particular country, using HDM-III relationships.
- HDM-4 Vehicle Operating Costs Module: To define the relationship between motorized and non-motorized vehicles operating costs and speeds to road roughness, for a particular country, using HDM-4 relationships.
- Risk Analysis Module: For performing risk analysis using triangular distributions for the main inputs.
- Program Evaluation Module: To perform the economic evaluation of a network of roads sections or road classes.

The model computes benefits accruing to normal, generated, and diverted traffic, as a function of a reduction in vehicle operating and time costs. It also computes safety benefits, and model users can add other benefits (or costs) to the analysis, such as those related to non-motorized traffic, social service delivery and environmental impacts. The program, however, does not estimate the annual deterioration of paved or unpaved roads over time. (Archondo-Callao, 1999; 2000; 2004)

2.5.3 Road Network Evaluation Tools

The Road Network Evaluation Tools (RONET) program was developed by the Sub-Saharan Africa Transport Policy program in the 2000s. RONET is structured with many configuration options for use on paved and unpaved roads in African and other developing countries (Archondo-Callao, 2009).

The program is directed at decision makers to appreciate the current state of the road network, its relative importance to the economy and to compute a set of monitoring indicators to assess the performance of the road network. For this, the program considers the evaluation of road roughness as the main condition performance indicator that can be obtained from subjective estimations. The condition of the road is related to maintenance requirements, which can be recurrent maintenance, periodic maintenance, and rehabilitation. Considering these basic assumptions, the program can estimate the minimum cost for sustaining the network in its current condition and the savings or the cost to the economy for maintaining the network at different levels of services. The optimal maintenance standard for each road class is selected as the option with the highest Net Present Value. Finally, the program can determine the funding gap that exists between current maintenance spending and required maintenance spending, by quantifying the effect of under spending on increased transport costs.

2.5.4 Road Network Investment System

The Road Network Investment System (RONIS) was developed at the University of Waterloo and was finalized in 1990. The system is a user-friendly microcomputer software which incorporates three modules, namely: Input Data and Candidate Analysis Module (ICAM), Economic Analysis Module (ECAM) and Heuristic Analysis Module (HAM). The software was developed for application in unpaved and paved roads (Turay, 1990; Turay, 1991).

The main performance models considered for unpaved roads are blading frequency and graveling operation, which are contained in the ICAM module. The relationship between blading frequency and average daily traffic was developed with data from available studies. In the case of the gravel operation model, the gravel loss model developed by Visser (1981) was considered as a basis. Four different maintenance treatments are considered for unpaved roads, one of these is upgrading to pavement. The economic analysis considered by the program is the net present value method considering benefits as the savings incurred by road users in terms of vehicle operating costs. The system finally uses a heuristic marginal analysis method to prioritize road maintenance projects in a network.

2.5.5 Maintenance and Design System

The Maintenance and Design System (MDS) was developed by Visser (1981) using data collected during the World Bank Study in Brazil. MDS was developed to determine the blading, gravelling and upgrading needs of unpaved roads according to economic criteria. The models contained are gravel-loss, roughness progression and roughness after blading. The analysis considered by the system follows three steps. First alternative blading strategies are ranked on individual uniform sections of road in terms of total cost. Secondly, the system optimizes the blading strategy for a network of unpaved roads subject to a budget constraint and passability requirement of some roads. Finally, economic warrants of paving specific roads in terms of traffic volumes. The optimum traffic for upgrading a road to pavement is that where Equivalent Uniform Annual Costs of paved standard are equal to unpaved standard.

The system was applied in South Africa in the province of Gazankulu, where some recommendations were made to extend the models to a wider range of materials, considering road roughness and vehicle operating costs in the economic analysis, and considering the effectiveness and efficiency of different blading techniques (Visser, 1983; Visser, 1987).

2.6 Limitations of Current State-of-the-Practice and Opportunities for Improvement

Several interesting initiatives and positive management experiences have been identified from the reviewed literature. The success of these practices, however, relies on their applicability in rural road networks in developing countries. The main limitations and opportunities that have been identified from the current practice are the following:

- Institutional and social considerations: An important aspect to consider when defining suitable condition evaluation and maintenance methods is the fact that rural roads in developing countries are managed by local agencies and even by communities. Most agencies do not have access to advanced evaluation and maintenance equipment. However, the labour force is commonly available especially between harvesting seasons. Roads management can be considered as an opportunity for both, managers and communities, where sustainable employment can be created for the evaluation and maintenance of the network.
- Network condition assessment: Several agencies have developed easy-to-use condition evaluation procedures based on subjective deterioration measures. Given that available labour in local agencies and communities have limited technical knowledge, objective rating methods should be more suitable in order to avoid possible bias induced by evaluators. Considering that evaluation equipment is commonly not available, it is recommended to implement manual evaluation methods that consider objective measures of surface deteriorations. Examples of these are the URCI and the UPCI methods. Both have the advantage that a condition indicator is estimated from field measures, which can be easily communicated to the public and could be a good parameter for network maintenance prioritization. In the case of URCI, the method was created in a developed country and there are scare chances to calibrate it to other conditions than the ones where it was designed. Meanwhile, the UPCI method can be applied to different climates, road structures and surface types, being an opportunity to consider it in the design of a rural road network management system for developing countries.
- Condition performance models: Several unpaved roads performance models have been developed to predict the progression of certain distresses over time or identify maintenance requirements. Most of them have been developed for gravel roads, especially to predict gravel loss, gravelling frequencies and roughness progression. The

common limitation is the complexity to collect required input data for the application and calibration of these models, as it may be challenging and expensive for some agencies in developing countries. Examples of these are the gravel loss models which involve detailed information on material properties, and roughness progression models, which require objective measures of surface profiles. An opportunity has been found in developing progression models of performance indicators that can be easily collected and calibrated, such as the UPCI or URCI. Given that the URCI is not suitable for all conditions, it is recommended to develop UPCI performance models which should be applicable to different climates, road structures and road surface types.

- Economic evaluation of rural roads maintenance: Most management systems consider benefit cost analysis as a basis for economic analysis, where benefits are estimated from savings to road users in terms of vehicle operating costs. Systems that apply this approach are the HDM-4 and RED. This method presents limitations in very low-volume roads, with traffic volumes below 200 vehicles per day, related to the small magnitude of user benefits and the stronger influence of the environment rather than traffic on infrastructure deterioration. In particular, the main benefits observed in roads presenting traffic levels below 50 vehicles per day relate to the provision of access. Cost-effectiveness analysis is a suitable economic analysis method of rural road networks in cases where social benefits are difficult to quantify in monetary terms. The BAA method has proposed the consideration of this method but in a short term project level basis, where improvement costs and population in the analysed roads are considered. The analysis procedure does not take in consideration the effects of different maintenance treatments over the condition of roads or their effects over different types of roads. The opportunity identified for the life cycle analysis of rural road networks, is to apply cost-effectiveness analysis, but considering effectiveness in terms of the overall condition of roads observed on a certain period of time above a minimum threshold level. The approach requires the development of performance models of a condition indicator considering the whole life cycle of roads. This can be done by considering the use of UPCI performance models. For this, the effects of different maintenance treatments over the roads condition should also be considered when developing the performance models.

- Prioritization of rural roads maintenance projects: When prioritizing maintenance projects at the network level, the unique consideration of cost-effectiveness as a priority method could be insufficient in cases where specific sustainable aspects require special attention. This is the case when priority wants to be given to roads presenting social services, main economic activities, certain poverty level or higher proportion of population served. Multi-criteria analysis has been used by some agencies to identify these sustainable aspects and suitably consider them in the prioritization process. Caution should be given, though, in the method considered to obtain priority ranks. A sustainable prioritization method should therefore account the outcomes of cost-effectiveness analysis as basis, and apply to them sustainable priority rank or indicator

- Available management systems and tools: In addition to the points discussed above, which apply to available management systems, a common limitation observed in most advanced software is the level of detail of required input data and operation sophistication. This is specially the case of applying HDM-4 and even RED in local agencies in developing countries. An opportunity is, therefore, to develop an easy-to-use tool that can be easily adapted and implemented by different agencies in developing countries.

Chapter 3

Development of a Sustainable Management Framework for Rural Road Networks in Developing Countries

3.1 Introduction

The analysis of the current state-of-the practice has evidenced the need for developing an effective system for the sustainable management of rural road networks. For the successful development of a network level management system it is paramount to analyse the entire management process, considering the strategic, network and project management levels. The basis proposed for a sustainable approach at all levels of management is first presented in this chapter. The overall problem, considering sustainable aspects, analysis methods and expected outputs for each management level is then presented. The interaction between management levels results in an integrated management framework for rural roads in developing countries. Having defined the overall rural roads management framework, the discussion then centres on the development of a sustainable system for network level management.

An overview of the proposed network management system is presented. The system considers four main components: Input Data, System Modules, Network Analysis Interface and Output Data. The proposed system is directed to assist agencies in charge of rural road networks in the development of optimal maintenance programs considering an expected condition or level of service and subject to budgetary restrictions. The recommended maintenance strategies and prioritization of maintenance projects are defined under a sustainable approach. For this, a long term cost-effectiveness analysis is considered for the selection of optimal maintenance standards at the network level, while the prioritization process for the definition of maintenance programs considers the application of a sustainable indicator.

3.2 Sustainable Approach

As described by the Brundtland Report (1987) and the NCHRP Report on Sustainable Pavement Maintenance Practices (Tighe, 2011), sustainability can be defined as ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’. To achieve this goal, rural roads should be managed under a sustainable long term perspective, considering social, institutional, technical, economic and environmental aspects, among others. The current practice in developing countries is focusing initially on construction techniques and design, where sustainable aspects during the life cycle of road infrastructure are mostly omitted. To avoid this continuum the following sustainable aspects are considered as a basis for the present research:

- Life cycle analysis: Management decisions should consider the whole life cycle of the infrastructure and their environment in order to be sustainable. With this, the condition of roads and their impact to society should be assessed considering short and long term needs. Accordingly, economic analysis and optimization of maintenance projects should consider current and future requirements.

- Integrated approach: All levels of management should consider within their scope the inclusion of social, technical, economic, political and environmental aspects in the evaluation of rural roads. This has to be suitably designed to include both the available and appropriate data for effective decision making.
- Social and policy aspects: It is proposed to consider social aspects in terms of a minimum access threshold at the strategic level of management. This can be related to a minimum condition standard which ensures all-weather access or a basic access level, such as the Rural Access Index (RAI). For network management it is proposed to consider a social indicator to prioritize road projects. In particular, it is recommended to use the proportion of population living in the vicinity of a road compared to the total rural population under evaluation as a basis. At the project level, it is important to evaluate the technical and economic feasibility of considering labour intensive maintenance techniques, which may create viable employment in rural areas.
- Technical aspects: Maintenance needs and network condition should be assessed periodically under affordable and efficient methodologies. It is proposed to evaluate road networks using the UnPaved Roads Condition Index (UPCI), which combines objective measures of roads condition. For the life cycle analysis of maintenance strategies and their impact on the society, performance models should be developed. These must consider all possible scenarios affecting rural roads condition, such as climate, roads structure and the effects of traffic on maintenance frequency.
- Economic aspects: Available funding levels should be defined at a strategic level of management. At the network level, however, decision-makers should be advised on the impacts of different budgets on the roads condition and consequently on the quality of life of the society. To account for social benefits and costs caused by the level of service of the road network, it is proposed to consider a long term cost-effectiveness analysis method. The method is used to select optimal maintenance standards for different budgetary levels.
- Institutional aspects: a critical issue when implementing technical tools is that they should be adaptable to different scenarios and adoptable by prospective users. A primary institutional aspect in developing countries is the limited technical preparation of rural road managers. A computer tool that integrates all components required for the management of rural roads is an output of the research. The tool should be easily implemented, updated, calibrated and operated by possible users.
- Environmental aspects: because of their nature, unpaved roads generate greater impacts on the environment than sealed roads. These are mostly produced during roads construction and maintenance. During roads operation, however, deteriorations can cause negative impacts to the environment especially when they are in an advanced progression stage. Examples of these are dust and erosion of surface materials which can cause important damages to the surrounding population and agriculture. Most environmentally related problems can be addressed and studied in detail at the project level, where initial environmental impact of road construction and the effects of using different construction material sources should be analysed. At the strategic and network level, the effects of environmentally negative deteriorations should be controlled and reported. The selected condition evaluation method should therefore consider presence

of fines and erosion. In addition, maintenance activities that demand reduced amounts of gravel, such as spot gravelling maintenance, should be included in the analysis.

3.3 Integrated Framework for the Sustainable Management of Rural Roads

When developing a roads management system the interaction between the three operational levels, strategic, network and project levels, must be considered. At a strategic level, the main targets for an agency in charge of the network management should be made clear, such as policy priorities and budgetary restrictions. Given the economic and technical capabilities, the agency should set network level priorities to satisfy medium to long term program objectives (i.e. performance levels, access conditions, network mobility, etc.). Finally, at the project level, management tools should assist in the selection of an appropriate design and appropriate construction, maintenance and rehabilitation techniques.

The present research is directed at the network level of management, where the current state-of-the-practice has several weaknesses. Notwithstanding, the role of each of the three levels of management and their interaction under an overall approach should be first discussed in detail. Figure 3.1 illustrates the proposed integrated framework for the sustainable management of rural roads in developing countries.

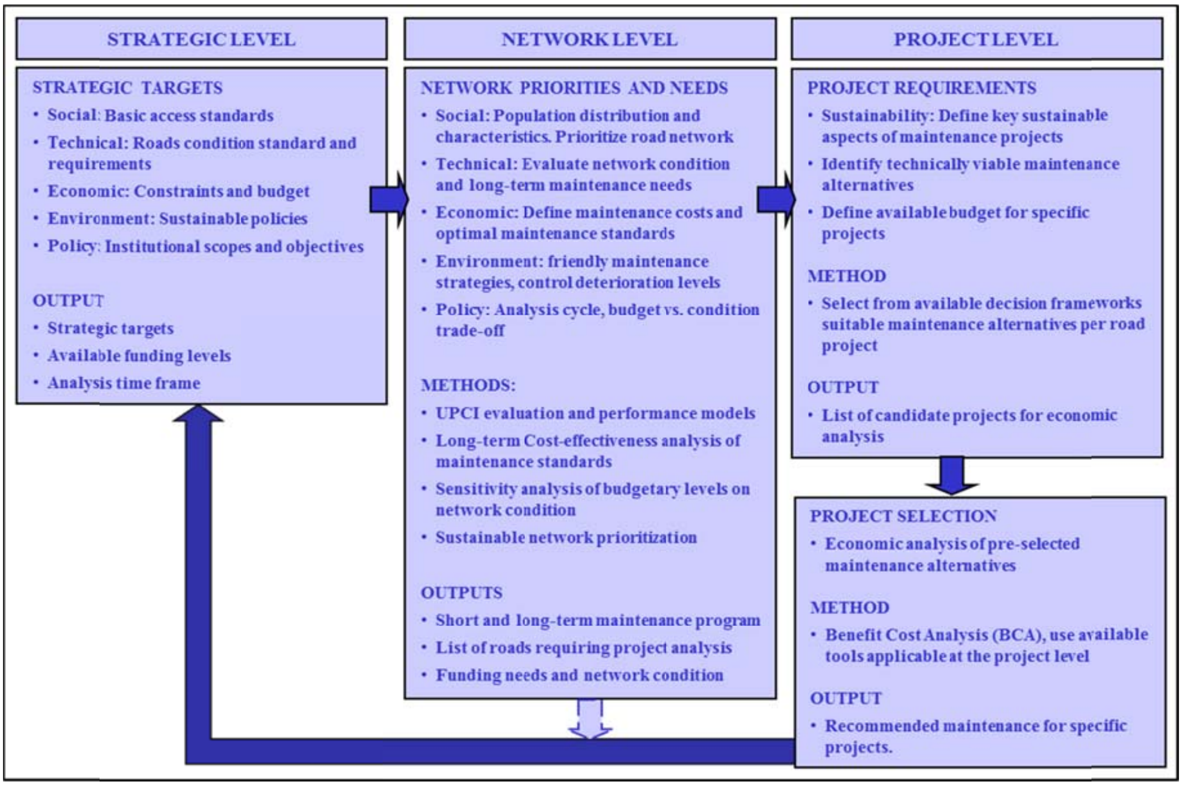


Figure 3.1 Integrated Management Framework

3.3.1 Strategic Level

Starting from a strategic level of management, the basic objective is to establish the agency short, medium and long term targets. For this, basic access standards should be defined to guarantee social and economic needs in rural areas. Basic access can be defined in terms of an accessibility measure, such as the RAI. Alternatively, access can be defined in terms of a minimum condition that ensures basic access to rural areas, which could be set in terms of the UPCI. Roads condition standards should be defined for the different road categories in terms of an objective measure, such as the UPCI.

Economic constraints and budgeting priorities for maintaining the rural road network should be defined at this level. The available budget should be consistent with access and condition standards. This should be checked at the network level, and if not sufficient, available funding should be increased or standards should be reviewed.

Agencies should define institutional scope and objectives at the strategic level, identifying responsibilities within their hierarchies and assign resources consistently to fulfill defined targets. Environmental policies should be set at this level, and should be enforced at the network and project levels.

The output of the strategic level includes sustainable strategic targets and associated available funding levels for the analysis time frame. This information is vital input data for the network level management system to ensure the continuity of the decision process and the inclusion of strategic policies.

3.3.2 Network Level

The second component involves network level management, where road maintenance needs and priorities are defined in the medium to long term time frame. This may involve the participation of federal agencies, local agencies, municipalities and communities, depending on the type of network being managed. The success and ease of application of this level depends on the quality and level of detail of available information. Household and roads inventory data is essential at this point.

Social characteristics of the population, such as household incomes, location of families within the network, location of social services, typical transportation means and transportation times should be identified. With this, accessibility and mobility needs of the rural population can be estimated in terms of the RAI and related to the roads condition in terms of the UPCI.

An objective indication of the overall condition of roads should be estimated and predicted over time. The use of the UPCI is recommended to evaluate the road network and development of performance models to predict roads condition in the long term. Having defined the roads condition, maintenance strategies and their effect over roads condition should be defined. Threshold levels for the application of the different maintenance strategies should be set in terms of the UPCI. Recommended maintenance strategies should also be environmentally sustainable and defined thresholds should procure minimum condition levels to avoid environmental impacts caused by severe deterioration.

Regarding economic inputs, typical maintenance costs related to different budgetary policies should be defined. The use of cost-effectiveness analysis is also recommended to identify optimal maintenance standards for different scenarios. The scenarios considered include: four budgetary levels (minimum, low, medium and high), three traffic volumes (low, moderate and high), two types of structures (weak and strong) and three climates (dry, Mediterranean and humid). In addition, environmental concerns and the road usage or importance (i.e. importance of transported goods and services) should be identified given that these could be additional constraints to social, technical and economic decisions.

As part of the policy analysis, agencies should look at the most suitable analysis period and funding time-frame. Given the accelerated deterioration of unpaved roads caused by traffic and climate, it has been recommended to consider for the short term a semi-annual analysis period (every six-months) and a ten year life cycle analysis period. Considering possible institutional and financial restrictions in some agencies, the analysis should be flexible to introduce modifications in the assigned budget and network policies at the short and long term. The sensitivity of the road condition subject to budgetary fluctuations should be visible to road managers, who will consider the risk associated to carrying out a treatment or not.

The prioritization of road projects should be a combination of all sustainable aspects included in the process. For this, the development of a sustainable indicator that combines cost-effectiveness of maintenance standards applied to specific roads has been recommended. This indicator is the result of multiplying the cost-effectiveness value defined for a specific road scenario (defined in terms of traffic volume, budgetary level, structure and climate) by the length, level of traffic and proportion of population living in the road under analysis. From the application of this sustainable priority indicator to all roads in a network, a priority rank is set. This is especially useful when deciding for better maintenance options or for upgrading the standard of priority roads to gravel or pavement.

As a result of the network level analysis, maintenance programs, funding requirements and the network condition for the short and long terms are defined. In addition, a priority rank is obtained and, from this, a list of candidate roads for project level analysis. These outputs also provide feedback for the strategic targets, where expected level of service and available funding levels are compared and changed if necessary.

3.3.3 Project Level

3.3.3.1 Project Requirements

Maintenance requirements for roads, such as a standard improvement to a gravel road, are defined during the project level analysis. The list of projects is selected in terms of their priority defined at the network level as well as other specific circumstances, such as needs for additional infrastructure to improve access and mobility (e.g. bridge construction). Suitable maintenance treatments on roads should be selected from available decision frameworks, taking into consideration the social, technical and environmental requirements defined as input. Ideally, these methodologies should be set as decision trees, flow diagrams or decision charts that combine several maintenance techniques subject to social, technical and environmental constraints. A recommended methodology to consider is presented in the report "Surfacing Alternatives for Unsealed Rural Roads", which was developed by the World Bank and is described in more detail in Appendix A (MWH, 2005).

The expected output of this step is the selection of recommended maintenance treatments for the improvement or standard upgrade of selected road projects. The most suitable treatment is determined from the economic analysis.

3.3.3.2 Economic Analysis and Project Selection

At a final stage, an economic evaluation is performed to all alternatives selected for each road project in the previous stage. For this, available economic analysis methods such as Benefit Cost Analysis (BCA) are recommended. In particular, roads requiring an upgrade to a paved or surfacing standard should present sufficient traffic to perform a BCA, where benefits can be estimated in terms of savings in vehicle operating costs and road user travel time costs. In some cases, where only one alternative is selected for a road, the economic analysis can be used to compare savings in terms of other competing projects. The use of available economic evaluation tools, such as the RED model (Archondo-Callao, 1999), is recommended at this final stage.

The output of this step is the definition of optimum maintenance and improvement projects for selected roads, considering available budget for the cases under study.

3.3.4 Importance of Developed Framework and Interface

The proposed methodology as described in the aforementioned begins with strategic management level and ends with project level evaluation. The distinct stages are interrelated. In short, project, network and strategic management levels are dependent to one another. This cycle, however, may be different case to case as it will need to adequately reflect differences in countries, regions, etc. Consequently an agency that has already defined their maintenance needs at the network level could be interested in the third and fourth steps only. Even, an agency can define at a network level which should be their minimum funding requirements, and later decide upon this output which should be the policy undertaken at a strategic level.

Because of the above, it is expected that all outcomes from subsequent steps could be an input of previous steps. This is defined as the synergy of the management framework, which is represented by the connecting arrows in Figure 3.1. An example of this is the fact that the network and project levels should be an input to strategic level, helping to improve policy making and budgetary decisions.

3.4 Development of a Sustainable Management Framework for Network Level Management

3.4.1 System Overview

The proposed system considers the interaction of four main components: Input Data, System Modules, Network Analysis Interface and Output Data. The system user primarily interacts to add input data and to perform the network analysis. However, because the system should be adaptable and flexible to future updates, the System Modules and Output Data can be accessed and modified by the user. Figure 3.2 presents an overview of the proposed system.

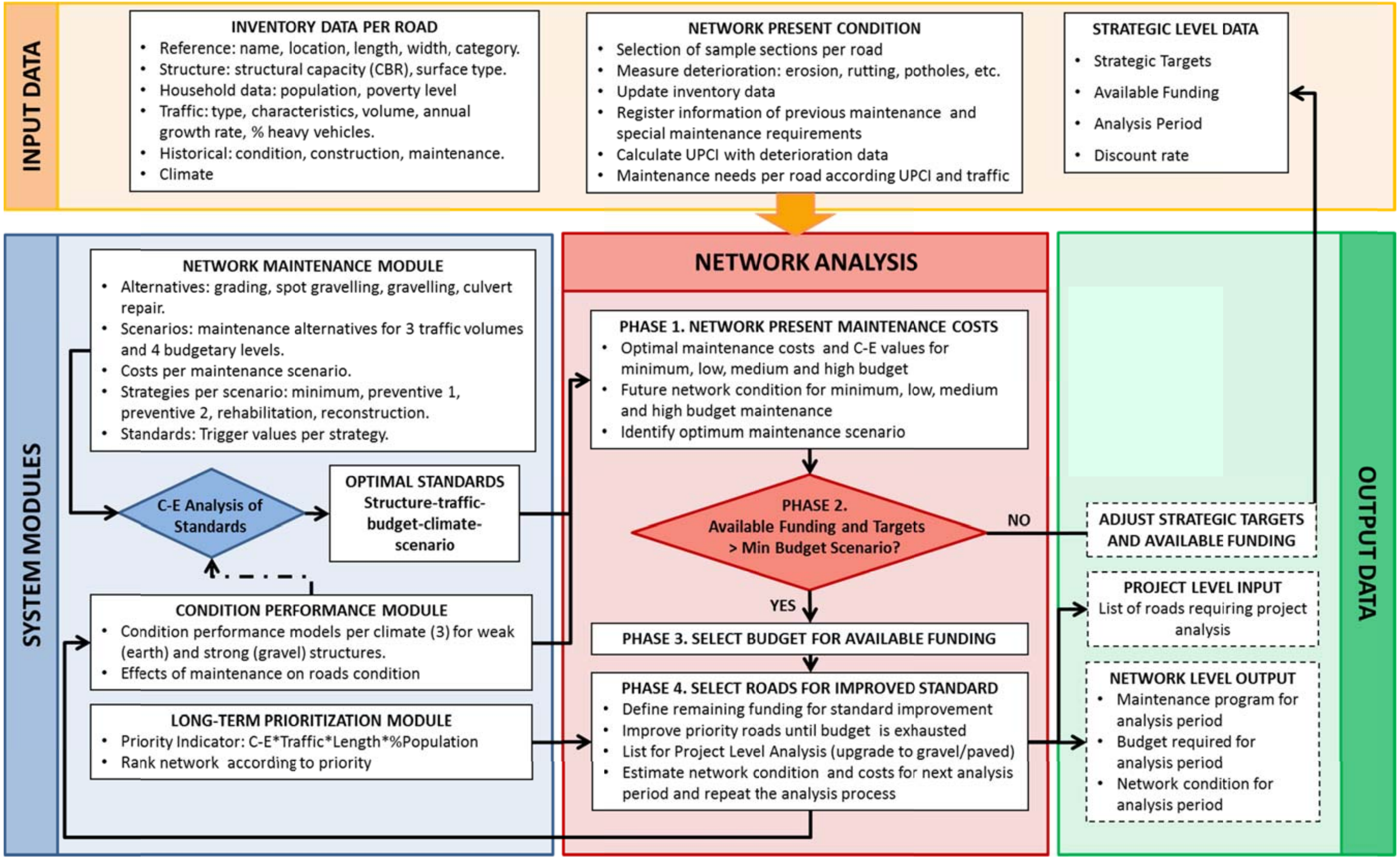


Figure 3.2 Proposed Network Management System

Input Data, Network Analysis Interface, System Modules and Output Data are described in detail as follows.

3.4.2 Input Data

To identify the current and future needs of a network, minimum input data is required as a starting point for the analysis. Three types of data are required for the network analysis: Inventory data per road, network present condition and strategic level data.

3.4.2.1 Inventory Data per Road

Inventory data required for network analysis includes:

- Roads Reference: name, code, location, length, width and category of each road.
- Roads Structure: roads surface type, either gravel or earth roads, are considered, and structural capacity which could be easily measured in terms of the California Bearing Ratio (CBR) with a dynamic cone penetrometer (DCP).
- Household data: population per road and poverty level of the rural population.
- Traffic data: traffic types and characteristics, traffic volumes per roads, traffic growth rate, and percentage of heavy vehicles.
- Historical data: previous roads condition, construction data and previous maintenance activities.
- Climate: characteristic climate to roads location, can be defined in terms of climate type (e.g. Dry, Mediterranean and Humid) or in terms of precipitation (e.g. mean monthly precipitation)

3.4.2.2 Network Present Condition

The network analysis requires updated condition data for proper application. The required roads information and condition data are:

- Selection of sample sections per road: Prior to the analysis the road agency needs to define the road sections to be analyzed in terms of available funds for roads evaluation. The UPCI methodology recommends 50m sample sections to assess roads deterioration. Two alternative sampling methods are recommended: selection of representative sections of a road or selection of systemized samples. To select representative sections, the agency has to perform visual evaluations to identify homogeneous sections of a road. One sample section is selected for each homogeneous section. In most cases where rural roads are short, only one sample section representative to the complete road condition is selected. The alternative method is to select 50m sample sections at the beginning of every 1 or 2 km of a road.
- Measure deterioration: Surface deterioration should be measured following the UPCI evaluation methodology which considers objective measures of seven surface defects. Deterioration is collected manually in each 50m sample section. Deteriorations considered by the methodology are: corrugations, rutting, potholes, erosion, oversized and fine aggregates, drainage condition and transverse profile condition.

- From field evaluations inventory data should be checked and updated. This includes roads length, width, surface type, among others.
- Previous maintenance activities applied to the roads and special maintenance requirements should be reported and identified during field evaluations.
- From field evaluations the condition of each road can be calculated following the UPCI method.
- Maintenance needs per road can be identified considering UPCI values, characteristic road traffic and any additional information registered during field evaluations.

3.4.2.3 Strategic Level Data

Data obtained from the strategic analysis is an essential input for network level management. These data include:

- Strategic Targets: Basic access standards, roads condition standard and requirements, economic constraints, environmental policies, institutional scopes and objectives.
- Available funding level for the rural network or per road category.
- Analysis period: life cycle analysis timeframe and short term analysis (e.g. to fit strategic funding program).
- Discount rate for long term economic analysis

3.4.3 Management System Modules

The three System Modules that were developed are: Condition Performance Module, Network Maintenance Module and Long Term Prioritization Module. A brief description of these is presented as follows. Information regarding their development and application is detailed in the following chapters.

3.4.3.1 Condition Performance Module

Condition performance models in terms of UPCI progression over time were developed and incorporated to the system. Three climate scenarios were considered and defined in terms of precipitation and duration of dry season, these are namely: dry, Mediterranean and humid climates. Performance curves were developed for two types of structures, weak and strong structures. Roads presenting a CBR below 15% are weak structures, typically earth roads. Roads presenting CBR equal or above 15% are strong structures most commonly observed as gravel roads.

The module also considers the effects of maintenance on roads condition, which were developed and validated from field data.

3.4.3.2 Network Maintenance Module

Maintenance activities and their costs under various application conditions were considered. Maintenance activities include: grading, spot gravelling, gravelling, culvert repair, standard upgrade to gravel and pavement.

Different maintenance scenarios include three levels of traffic per road type and four budgetary levels. Traffic volumes for weak roads, mostly earth roads, are: less than 50, between 50 and100, and more than 100 AADT. Traffic for strong roads or gravel roads are: less than 100, between 100 and 200, and more than 200 AADT. Budgetary levels consider minimum maintenance, low, medium and high budgets.

Maintenance strategies were defined per scenario, considering the most suitable combination of road activities per strategy, which includes: minimum maintenance strategy, routine strategy 1 (local gravel and minimum grading), routine 2 (routine grading), rehabilitation and reconstruction. Trigger values were defined for the application of each strategy, which combined resulted in maintenance standards per scenario.

Optimal standards were obtained from the cost-effectiveness analysis of applying each strategy to the whole life cycle of roads. The analysis required the consideration of the performance models and the effects of the various maintenance strategies to the roads condition (illustrated as a dotted connector in Figure 3.2). This was done considering all structure, traffic, climate and budget scenarios.

3.4.3.3 Long Term Prioritization Module

A sustainable priority indicator (SPI) was developed, which considers the cost-effectiveness of optimal standards, traffic volumes, roads length and percentage of population living in each road of the network. The analysis is made in a short and long term basis. For each analysis period the road network is ranked in terms of roads priority considering the SPI. The user defines available funding, which should be above a minimum budget level required to warranty basic access. A basis budget level is defined, considering the optimal standard that could be afforded with available funding. If funding is available after applying optimal maintenance for the basis level, the user can improve high priority roads to a higher standard. Once available funding is exhausted, the system calculates the network condition after maintenance and maintenance costs for the analysis period. For the life cycle analysis, the system iterates the previous stages for the whole life cycle of the network.

3.4.4 Network analysis interface

The network analysis considers four phases. First, present maintenance costs and network condition are estimated considering the four possible budgetary scenarios. For this, optimal maintenance standards are considered, which were obtained from the Network Maintenance and Condition Performance Modules.

Secondly, a comparison should be made between available funding defined at the strategic level and minimum budget scenario. Similarly, expected network condition at the strategic level should be contrasted to the network condition for a minimum budget. If none of these are fulfilled strategic targets and available funding should be reviewed. If these are fulfilled, the third phase considers selection of optimal maintenance standards for available funding. If the optimum maintenance standard is feasible, the user is recommended to select this funding level.

The final stage is to prioritize the network considering the Long Term Prioritization Module.

3.4.5 Output Data

During the network analysis, one of the outputs could be a recommendation to adjust strategic targets and available funding as described previously. This is the case when a minimum condition or funding criteria is not met.

A second output from the analysis, is a list of roads requiring project level analysis. These are the particular case of roads requiring standard upgrade to gravel, seal or pavement. The criteria are set in terms of traffic volumes, where roads presenting traffic volumes above 200 AADT are recommended for analysis. Other user specified criteria can be incorporated in the analysis to detect candidate roads for project analysis, which should be mostly detected from field evaluations.

The network level output data are: maintenance program, required budget and network condition for analysis period. This is displayed for each analysis cycle (or year) and for the long term life cycle (e.g. ten year analysis period)

3.5 Summary of the Chapter Findings

The success of a rural roads network management system relies on three main principles: consider a sustainable approach, include interaction with other management levels and develop an easy-to-use tool which is adaptable to diverse scenarios.

These four principles have been considered in the proposed management system as follows:

- Sustainable approach: The basis for a sustainable perspective is to understand the management problem as a long term process where different levels of decision interact. Having this set, all sustainable aspects involved in the decision process have been suitably considered at all management levels, including when possible: social, technical, economic, environmental, institutional and policy aspects.
- Interaction with other management levels: For a clear understanding of the decision process the overall management framework has been defined. This includes sustainable aspects, analysis methods and expected outputs at the strategic, network and project levels of management. A clear understanding of the framework interface and the synergy between management levels is vital for the successful implementation of the overall system. Output data of the strategic level is identified, which serves as input data for the network level decisions. Outputs of the network analysis serve as feedback to improve strategic policies and as input data for the project level analysis.
- Easy to adopt and adapt network management tool: A common aspect observed in agencies in charge of rural roads is the limited technical preparation of rural road managers and potential system users. A management system that can be easily operated and implemented has been proposed in this chapter. The system considers four components: Input Data, System Modules, Network Analysis Interface and Output Data.

The system has been defined for different scenarios, making it adaptable to different climates, budget levels, road structures and traffic volumes. A simple computer tool that contains these four system components was developed. The tool user primarily interacts with the software to introduce input data and to perform the network analysis. However, the tool is open for future update and calibration of system components and output data.

The proposed network management system and tool required the development of three System Modules: Condition Performance Module, Network Maintenance Module and Long Term Prioritization Module. The subsequent chapters present the developments required for each of these modules. Chapter 4 presents the experimental design data collection for the development of System Modules. Chapter 5 presents the basis to define the Condition Performance Module, including UPCI validation, development of condition performance models, effects of maintenance on condition performance and the validation of proposed models. Chapter 6 presents the development of optimal maintenance standards considered in the Network Maintenance Module. Chapter 7 presents the development of a sustainable priority planning procedure required for the Long Term Prioritization Module. Chapter 8 finally presents the development of the computer tool that integrates all system components and the application of the management system to two case studies.

Chapter 4
Experimental Design and Data Collection

4.1 Introduction

The applicability of the proposed network management system depends on the design of consistent experiments for the reliable development of System Modules. Seven experiments were defined in the present research for the development of System Modules. The following four experiments were considered for developing the Condition Performance Module: Validation of UnPaved Roads Condition Index (UPCI) methodology, development of unpaved roads condition performance models, definition of maintenance effects on roads condition and validation of unpaved roads condition performance models and effects of maintenance on roads condition. For the development of the Network Maintenance Module, an experiment was carried out to define the optimal maintenance standards. For the Long Term Prioritization Module, an experiment was designed to develop an engineering based sustainable priority procedure. Finally, the management system with all these modules and components were integrated into a computer tool. It was further calibrated and validated for two road networks in developing countries.

Inventory and strategic level data were collected and obtained from local agencies. Network condition data was collected in the field considering the UPCI methodology. A summary of the collected data is presented in the chapter. Detailed analysis of each experiment and their integration into the respective Network System Modules are presented in the subsequent chapters.

Findings from the developed experiments were published in three refereed journals, including: the proposed management system framework, the development and validation of the UnPaved Roads Condition Index (UPCI) methodology, and the development and validation of condition performance curves (Chamorro, 2009a; Chamorro, 2009b; Chamorro, 2011).

4.2 Experimental Design

4.2.1 Experiment Objectives

For the development of the three modules contained in the management system and the development of the computer tool, seven specific objectives were defined:

1. Validate UnPaved Roads Condition Index (UPCI) methodology.
2. Develop unpaved roads condition performance models.
3. Define effects of maintenance on roads condition.
4. Validate unpaved roads condition performance models and effects of maintenance on roads condition.
5. Develop optimal maintenance standards.
6. Develop a sustainable priority procedure.

7. Apply and validate the network management system.

Objectives one to four were required for the successful development of the Condition Performance Module. Objective five resulted in the development of the Network Maintenance Module. Objective six was necessary for the development of the Long Term Prioritization Module while objective seven resulted in the integration of the overall system including the computer tool validation.

4.2.2 Experiment Definition

A specific experiment was developed for the fulfillment of each of the objective. Two rural road networks were selected and evaluated for this, one located in Chile and other located in Paraguay. Data collected in the Chilean network served as a basis for the development of the seven experiments. Data collected in Paraguay was only used in the seventh experiment, for the application and validation of the Network Management System. The proposed experiments are summarized as follows.

4.2.2.1 UPCI Validation

The validation process considered the assessment of a network under the UPCI methodology. The dependent variable was the UPCI value which was calculated from seven deteriorations (independent variables) measured in the field. The sources of deterioration included: corrugations, rutting, potholes, erosion, oversized and fine aggregates, drainage condition and transverse profile condition. In parallel, the same network was evaluated using the windshield visual inspection technique. From the visual inspection, the UPCI observed values were obtained. The UPCI observed and calculated values were statistically compared for the validation of the UPCI methodology. From the analysis some adjustments were recommended to the data collection methodology and the UPCI equations were successfully validated.

4.2.2.2 Development of Unpaved Roads Condition Performance Models

The selected road network was assessed under the UPCI methodology three times within a 15 month period. The dependent variable was the calculated UPCI value and the independent variables included road deterioration. Evaluations were held every six to seven months to capture the effects of climate and seasons. For the development of performance models, only roads that were not maintained between evaluations were considered in the analysis.

Structural evaluations with the dynamic cone penetrometer (DCP) were performed to classify the road network in terms of roads structural strength. Six scenarios were included in the analysis considering two types of structure (weak and strong) and three climates (dry, Mediterranean and humid). It must be noted that traffic volume were not considered in the analysis at this stage, given that the developed models are applicable to very low volume roads, with traffic less than 200 AADT. Literature has discussed and evaluated the causes of unpaved roads deterioration (Paterson, 1991; NITRR, 2009; Lebo, 2000), noting the primary sources of deterioration for very low traffic volumes are the presence of humidity and structural problems. The effects of traffic volume, however, are considered in the development of maintenance standards, where they play a crucial role on the definition of maintenance frequency and costs.

Several modelling techniques were analysed in detail for the development of performance models. The finally selected method was Markov chain models, which combined with Monte Carlo simulation, were able to capture the stochastic nature of unpaved roads deterioration. As a result, condition performance curves for the six scenarios were obtained for a 10 year analysis period.

4.2.2.3 Effects of Maintenance on Roads Condition

Data collected for calibration of the condition performance models was also used to identify the effects of maintenance on the roads condition. Additional transportation data was collected, including traffic volumes, traffic distribution (heavy motorized, light motorized and non-motorized), roads with bus service, school bus route and roads requiring ambulance access. Maintenance activities between evaluations were obtained from reports of the local agency. Sections that were maintained between evaluations were considered in the analysis. The collected data was statistically analysed from which effects on UPCI for each maintenance strategy were recommended.

4.2.2.4 Validation of Condition Performance Models and Effects of Maintenance on Roads Condition

A fourth evaluation held 24 months after the third field evaluation was conducted for the validation process. The analysis considered the assessment of deterioration with the UPCI methodology. Additionally, maintenance activities held between evaluations were obtained from the local agency. For the validation process, performance curves were used to calculate the expected condition (calculated UPCI) of roads after a 24 month period and considering the maintenance activities performed per road. The expected condition was statistically compared to the observed condition obtained from field evaluations (observed UPCI). From the analysis, models and the effects of maintenance on roads condition were then validated.

4.2.2.5 Development of Optimal Maintenance Standards

The experiment first considered the development of maintenance strategies, defined as a set of maintenance activities related to minimum maintenance, routine maintenance, rehabilitation and reconstruction. Typical maintenance strategies available from literature were compared to strategies observed in the networks under study. For the development of maintenance standards, trigger or threshold values for each maintenance strategy are defined. Trigger values were defined considering experience from field evaluations and deterioration trends observed from performance models.

For the development of optimal maintenance standards, two dependent variables were defined: UPCI values and maintenance costs. UPCI values for life cycle analysis were obtained from condition performance curves. Costs for maintenance activities were obtained from available literature and agencies costs. Both variables were required for the cost-effectiveness analysis of recommended maintenance standards. The method estimates the long term life cycle costs of applying a certain maintenance strategy and the associated long term condition exceeding a minimum threshold value. From the analysis, optimal maintenance standards for all experiment scenarios were developed. These included the combination of two structure types, three traffic volumes, four budget levels and three climates.

4.2.2.6 Development of a Sustainable Priority Procedure

Additional data was collected from the analysed network. This included: household data, such as persons per family, poverty level and main economic activity; and social information of the network, such as location of social services and distribution of rural population in the road network. This information was the basis to define a sustainable priority indicator considered in the Long Term Prioritization Module.

4.2.2.7 Application and Validation of the Network Management System

Data was collected in two different networks located in Chile and Paraguay. The networks presented different climates, traffic volumes, road structures and socio-economic development. The developed management tool was validated with this data. A sensitivity analysis was finally carried out to complement the validation process, where the effects of modifying system variables were analyzed in detail.

4.2.3 Analysis Scenarios

The following analysis scenarios were considered in the experiments, which included different road types and structures, climates, traffic and budgetary levels.

4.2.3.1 Road Types and Structures

Road types and structural capacity are closely related in unpaved roads. Available literature recommends for gravel roads the consideration of granular layers with a soaked CBR of 60% (Giummarra, 2000). Conversely, earth roads present a non-structural designed natural subgrade course which rarely exceeds a soaked CBR above 15%. In South Africa, authorities and experts have recommended that a soaked CBR of 15% at 95% Proctor compaction is sufficient to provide a trafficable surface of an unpaved road in presence of a good drainage (Paige-Green, 1992; NITRR, 2009; Netterberg, 1988).

Field evaluations were carried out in the field. Data was collected with a dynamic cone penetrometer (DCP) after a rainy day. Earth roads presented a CBR that ranged between 13 and 6%. In addition, most of these roads presented access problems during the rainy season when not maintained. Meanwhile, gravel roads presented a CBR above 30% and almost no access problem. Details of roads structural data collected in the field are presented in Appendix B.

Given the literature recommendations and field evaluations, the research considered two types of structures, weak and strong. If equipment is not available these can be classified in terms of road surface types as earth and gravel, respectively. The characteristics of recommended classes are:

- Weak Structures: They have a soaked CBR of less than 15% at 95% proctor compaction. These are generally earth roads on clay and silt natural soils, or earth roads with poor drainage.
- Strong Structures: They have a soaked CBR equal or greater than 15% at 95% proctor compaction. These are generally gravel roads with an unbound granular base and wearing course.

4.2.3.2 Climate

Three types of climates were defined for the analysis: dry, Mediterranean and humid climates. The climates are defined in terms of mean monthly precipitation, and duration of dry and humid seasons. These were consistent with the climate proposed by the UPCI methodology where a detailed analysis of including a fourth climate, humid with presence of ice and snow, was considered. From the study, it was concluded that the effects of precipitation on roads condition for this fourth climate type were statistically similar to those observed in a humid climate, for a network level application (MOP, 2008).

The characteristics of the proposed climate types are:

- Dry Climate: Characterized by an extended dry season, of more than 8 months, with almost no precipitation. A short humid season is observed, where precipitation does not exceed 50mm per month. On average during a year the mean monthly precipitations is less than 20 mm.
- Mediterranean Climate: Characterized by 4-5 months of dry season with almost no precipitation during summer and a rainy season of 7-8 months where more than 1000 mm of precipitation are accumulated yearly. During the most humid months, monthly precipitations of up to 400 mm can be observed. On average during a year the mean monthly precipitation ranges between 20 and 200 mm.
- Humid Climate: These can be tropical humid climates or cold climates with the presence of rain, ice and/or snow. The climate presents an extended humid season, of more than 8 months followed by a short dry season. During the rainy season, precipitation may exceed a monthly precipitation of 1000 mm. On average during a year the mean monthly precipitations is above 200 mm.

4.2.3.3 Traffic

Traffic levels were defined after reviewing several recommendations available from literature. Traffic volumes were used for the development of maintenance standards given that the effectiveness and performance of a maintenance treatment is directly related to number of vehicle passes (Paterson, 1991). In addition, studies have demonstrated that most of the deterioration caused by traffic is related to the traffic volume and vehicle speeds rather than the traffic load distribution (NITRR, 2009).

The World Bank defines rural road infrastructure as earth roads and tracks with less than 50 vehicles per day as presented earlier in Figure 1.4. These are also defined as basic access roads (Lebo, 2000). Given their structural capacity, earth roads should not be presenting traffic volumes higher than 200 vehicles per day, where an upgrade to gravel or sealed standard is recommended.

Regarding gravel roads, these commonly present traffic volumes above 50 vehicles per day. Low volume traffic gravel roads commonly present less than 100 vehicles per day (Archondo, 2004). In addition, several authors have recommended a detailed analysis for upgrading to sealed or paved standard for traffic volumes higher than 200-300 vehicles per day (MWH, 2004; Kerali, 1991).

Recommended traffic volume levels considered in the study are presented in Table 4.1. These are based on literature recommendations and deterioration trends observed in the field.

Table 4.1 Traffic Levels

	Low Traffic	Moderate Traffic	High Traffic
Weak Structures (Earth)	< 50 AADT	50-100 AADT	> 100 AADT
Strong Structures (Gravel)	< 100 AADT	100-200 AADT	> 200 AADT

4.2.3.4 Budget Levels

Four budget levels were defined in terms of the effectiveness and quality of maintenance activities considered per strategy. These are related to low cost, medium cost and high cost maintenance policies. A fourth Minimum Budget was defined as the basis funding where a minimum maintenance is considered to ensure network preservation. The frequency and maintenance activities considered per strategy vary depending on the level of damage and traffic of a road, rather than on the budget level. A detailed description of maintenance activities and costs considered per budget level are presented in Appendix C.

The defined budgetary levels are presented as follows:

- Minimum Budget: The minimum budget level was defined as the minimum acceptable maintenance policy that ensures a basic access in rural areas. This is considered to be a light blading performed once, twice or five times per year for low, moderate and high traffic volumes, respectively.
- Low Budget: The low budget considers low cost maintenance activities including light blading, reduced spot graveling, minimum graveling and reduced funding for culvert replacement.
- Medium Budget: The medium budget considers medium cost maintenance activities including heavy blading with partial compaction, spot graveling, partial graveling, and medium funding for culvert replacement.
- High Budget: The high budget considers high cost maintenance activities including heavy blading with compaction, spot graveling, extensive graveling and replacement of culverts.

4.2.4 Experiment Factorial

From the combination of the analysis scenarios, two experiment factorials were defined. One factorial including road structures and climates was designed for the development of the Condition Performance Module, which included the validation of UPCI methodology, and the development and validation of performance models and effects of maintenance on roads condition. In this case the dependent variable under study was the UPCI value estimated from roads deterioration data collected in the field during three evaluation periods referred to as $UPCI_1$, $UPCI_2$ and $UPCI_3$.

The second factorial was designed for the Network Maintenance Module, which required the development of optimal maintenance standards. The dependent variables in this case were UPCI values and maintenance costs, both needed for the cost-effectiveness analysis. The scenarios considered in the experiment combined road types and structures, climates, traffic and budgetary levels.

Data collected in both factorials was complemented with additional data obtained from household data and social information of the network for the development of the Long Term Prioritization Module.

The proposed factorials for developing the Condition Performance Module and Network Maintenance Module are presented in Table 4.2 and Table 4.3, respectively. As presented in the first case, six scenarios were defined from the combination of two road structures and three climates. The second factorial considered eighteen scenarios (two road structures, three climates and three traffic levels) for each of the four budget levels, totalling in 72 cases.

Table 4.2 Factorial for the development of the Condition Performance Module

		Climates		
		Dry	Mediterranean	Humid
Roads Structure	Weak (earth)	$UPCI_{1,2,3}$	$UPCI_{1,2,3}$	$UPCI_{1,2,3}$
	Strong (gravel)	$UPCI_{1,2,3}$	$UPCI_{1,2,3}$	$UPCI_{1,2,3}$

Table 4.3 Factorial for the development the Network Maintenance Module

			High Budget			
		Medium Budget				
	Low Budget					
Minimum Budget				**Climates**		
				Dry	Mediterranean	Humid
Traffic Volume	Low	**Structure**	Weak (earth)	*UPCI, Costs*	*UPCI, Costs*	*UPCI, Costs*
			Strong (gravel)	*UPCI, Costs*	*UPCI, Costs*	*UPCI, Costs*
	Moderate	**Structure**	Weak (earth)	*UPCI, Costs*	*UPCI, Costs*	*UPCI, Costs*
			Strong (gravel)	*UPCI, Costs*	*UPCI, Costs*	*UPCI, Costs*
	High	**Structure**	Weak (earth)	*UPCI, Costs*	*UPCI, Costs*	*UPCI, Costs*
			Strong (gravel)	*UPCI, Costs*	*UPCI, Costs*	*UPCI, Costs*

4.3 Selection of Rural Road Networks

4.3.1 Network Selection

Two rural road networks were selected for the application of the proposed experiments, located in Chile and in Paraguay. The networks were selected considering available reports and data (MOPC, 2008). The selection criteria considered climate, level of development, types of structures and soils, types of roads, volume and types of traffic volumes, different economic activities, and previous information available. Data collected in the Chilean network served as a basis for the development of the seven experiments, while data collected in Paraguay was only used for the application and validation of the Network Management System.

4.3.1.1 Description of Selected Road Network in Chile

A rural network of 38 unpaved roads and 181 km of extension was selected for the study. The selected roads comprise the entire unpaved network of the Municipality of Portezuelo. As presented in Figure 4.1, the network is located in the VIII Region of Chile and 430 km southeast of Santiago, the capital city of Chile.

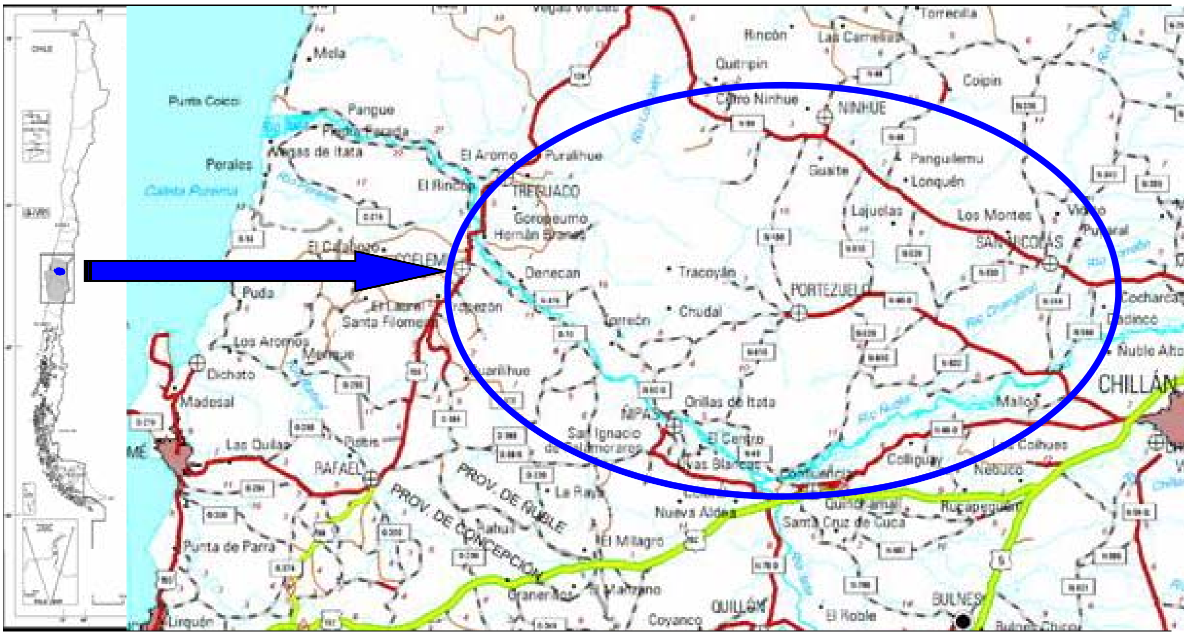


Figure 4.1 Location of the Selected Road Network in Chile

Portezuelo is currently the seventh poorest Municipality of the country, presenting an average monthly income per capita of US$ 300. The average length of time at school of its population is 5.5 years. In rural areas the main economic activity is farming and agriculture for subsistence, while there is also some limited wine industry and forestry.

The network presents secondary and tertiary roads according to the national roads classification. From these, 16 roads present gravel surface and 22 are earth roads, totalling in 135.7 km and 45.3 km, respectively. Gravel roads are secondary roads with suitable geometric design and good granular surface material. In terms of the USCS classification method these roads present gravel and sandy natural soil, with some presence of silt. In general terms, gravel roads have a CBR above 15%. Earth roads are tertiary roads and tracks with no engineered design. These are generally located in undulated to mountainous terrain providing access to rural population, forestry and agricultural zones. Earth roads predominantly present fine-grained soils such as clay and silts, with some presence of sand. Earth roads present a CBR below 15%. Details of roads structural data are presented in Appendix B.

Approximately 115 km of the secondary network are managed by the Ministry of Public Works of Chile (MOP), and more than 50 km of tertiary roads and tracks are maintained by the Municipality or informally by local rural communities. In practice, although the MOP is responsible for defining maintenance needs for the secondary network, maintenance priorities are specified by the Municipality. The reason for this is that the condition of roads is unofficially tracked by the Municipality, by their drivers or by public claims.

The network presents seasonal climatic conditions. The predominant climate is Mediterranean, presenting 5 months of dry climate with almost no precipitation during summer and a rainy season of 7 months where more than 1000 mm of precipitation are accumulated yearly. During the most humid months, July and August, monthly precipitations of up to 400 mm can be observed.

Traffic volume and type slightly vary during harvest and forest exploitation. Traffic volumes, however, are low in secondary roads ranging from 50 to 200 AADT. Tertiary roads present very low traffic, below 50 AADT.

4.3.1.2 Description of Selected Road Network in Paraguay

A rural network of 23 unpaved roads and 141.6 km of extension was selected for the study. The selected roads comprise the entire unpaved network of the Municipality of Yguazu. As presented in Figure 4.2, the network is located in the department of Alto Parana, located 200 km east of Asuncion, the capital city of Paraguay. The department is located at the east end of the country, being of primary importance as it has boundaries with the neighbour country, Brazil.

The municipality of Yguazu has a population of 8,748 habitants and a surface of 762 square kilometers. It is primarily a rural district, having a basic economic activity of farming and agriculture. Since the late 90's the primary economic activity has centered on soy bean production. Some agriculture is also focused on corn, cotton and wheat production.

The region where the network is located presents a sub-tropical climate with a total precipitation of 2,000 mm a year. The dry season is two months long. The rainy season lasts more than 6 months, between October and March, presenting mean monthly precipitations over 300 mm and high temperatures ranging between 32°C and 38°C.

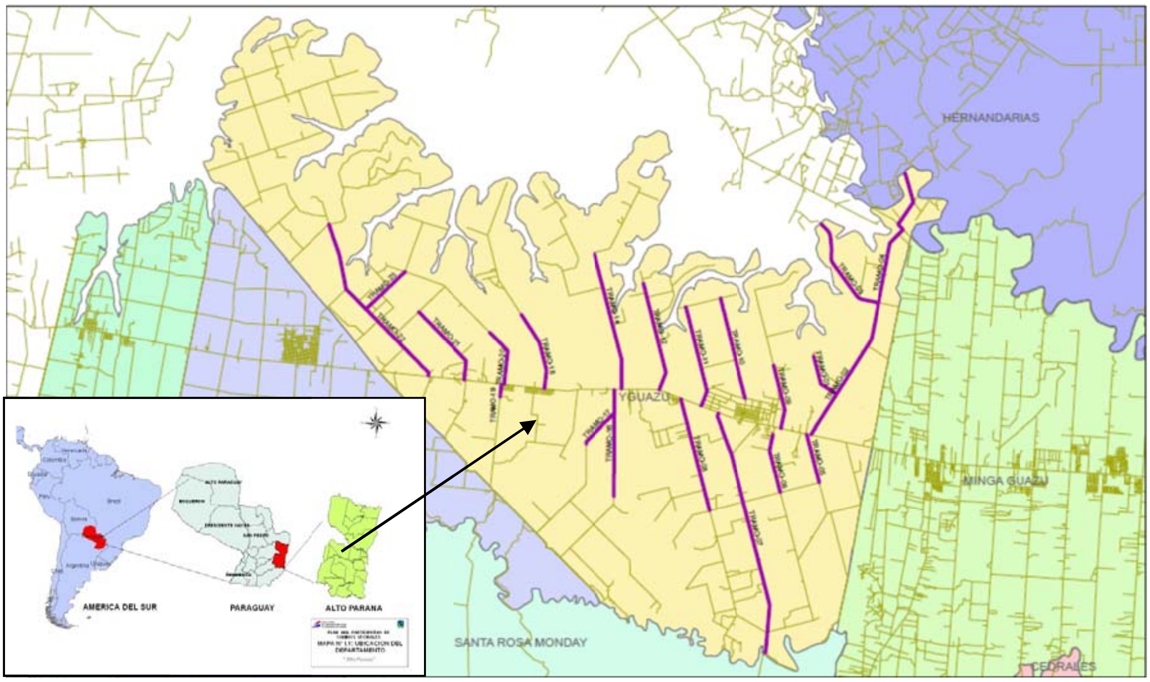


Figure 4.2 Selected Road Network in Paraguay

The network presents secondary and tertiary roads. Secondary roads and some tertiary roads are maintained by the Ministry of Public Works and Communications (MOPC). The rest of the local network is commonly maintained in case of emergencies, either by the local government, communities and the MOPC. From the total network, 4 roads present gravel surface and 19 are earth roads and tracks, extending 29.1 km and 112.56 km respectively. Gravel roads are secondary roads with basic geometric design and a thin granular surface course. In terms of the USCS classification method these roads present gravel and a high presence of clay in the natural core course. In general terms gravel roads present a CBR slightly above 15%. Earth roads are tertiary roads and tracks with no engineered design. These are generally located in flat terrain, providing access to rural population. Earth roads present very fine-grained soils predominantly of clay. Earth roads present a very low CBR, mostly below 8%.

Traffic volume and characteristics slightly vary during harvest and forest exploitation. Traffic in secondary roads is moderate to high, ranging from 100 to 250 AADT. Tertiary roads present low to moderate volume traffic, between 50and 100 AADT.

4.3.2 Selection of Sample Sections

Before applying the UPCI method in the field, sample sections were selected and marked per road. The sampling method considered in the research was the selection of representative sections per road. Given that in both case studies the roads were short and presented homogenous deterioration throughout their extent, in most cases only one sample section was required. To select representative sections, roads were travelled in both directions to appreciate their overall condition. For each round a windshield visual inspection of roads was made, considering the distresses included in the UPCI methodology. In addition, the road distress types and severities of representative sections were measured considering the UPCI methodology. Finally, 50 m sample sections representative to the mean condition of each road were selected. Selected sections were referenced and marked in the field for future evaluations.

4.4 Data Collection

From preliminary field visits, it was observed that both networks presented important seasonal variations due to climate. It was also observed that the condition of roads was slightly affected by seasonal fluctuations of traffic volumes.

The Chilean road network was evaluated four times in a 39 month period. Three evaluations were performed spaced every 6 to 7 months following seasonal patterns. Evaluations were made immediately after the dry and humid seasons to capture the effects of climate over the roads conditions. These evaluations were performed within a 14 month period during early September 2008, mid April 2009 and late October 2009. The first evaluation was considered for the validation of the UPCI methodology and the three of them were included in the development of condition performance models and maintenance standards. Two years after the last evaluation, in October 2011, a fourth evaluation was made to validate the condition performance models, maintenance standards and management system.

The Paraguay network was evaluated in May 2009; the collected data was used for the application and validation of the Network Management System.

4.4.1 Inventory Data Collection

Availability of inventory data was defined after meeting professionals from the maintenance department of the MOP in Chile and the MOPC in Paraguay.

In the Chile case study additional information was obtained from the roads, social and transportation departments of the Municipality of Portezuelo. Given that available information on the network extent and condition was limited, a first field visit was coordinated with the roads department of the Municipality to identify the main characteristics of the network. Roads extent, surface type and category were defined and illustrated in a map. Population nearby each road was also quantified with the help of the 2002 National Census (INE, 2002) and with the help of people from the social department of the Municipality. The social characteristics of the rural population were also provided by the social department of the Municipality. This additional data is collected on an annual basis under the national social household survey, “Ficha de Protección Social”.

In the Paraguay case study, updated data from the network was available from a recent study developed by the MOPC with a loan from the Inter-American Development Bank. Inventory data was obtained from this report and was reviewed and updated after field evaluations (MOPC, 2009).

4.4.2 Network Condition Evaluations

The Unpaved Roads Condition Index methodology was considered for the evaluation of the network. The method is simple, objective, cost-effective and flexible. It is simple given that no special equipment and advanced technical skills are required. It is objective, as road deterioration dimensions are objectively measured in the field. It is cost-effective, as the evaluation process is quickly applied, does not consume important resources and is effective for assessing the network condition. Cost-effective evaluation method to assess the overall condition of unpaved roads is required. Finally, it is flexible and easily adapted to diverse scenarios as it considers different road types and climates. The method has been successfully used in Chile since 2008, for different climates and types of roads (MOP, 2008; Chamorro, 2009)

The method considers the manual evaluation of seven types of deterioration, performed by one rater, when measuring equipment is not available: corrugations, potholes, erosion, rutting or transverse deformations, presence of oversized aggregates and fines, condition of drainage and transverse profile. The evaluation sheet presented in Appendix D was used for the field evaluations. When roughness measuring equipment is available, the International Roughness Index (IRI) is also considered in the analysis. UPCI represents the relative effect of each surface deterioration over the road condition, and is calculated considering equations 3 and 4, which were also presented in Chapter 2 (Chamorro, 2009; MOP, 2008)

UPCI without considering roughness measures:

$$UPCI=10 - 1.16CR - 2.25PT - 1.47ER - 0.33RT - 1.56OA - 1.58CW \quad (3)$$

UPCI considering roughness measures:

$$UPCI = 11.64 - 0.41\,IRI - 1.60\,ER - 0.40\,RT - 1.79\,OA - 1.57\,CW \quad (4)$$

Where:

- CR: Corrugations evaluated as the mean vertical distance between the highest and lowest point of the deformation obtained from three consecutive measures observed in a section and measured in centimetres.
- PT: Potholes measured as the total square metres observed in a sample section, calculated as the product of the mean diameter in metres, typical depth in metres and number of potholes in a sample section.
- ER: Erosion, caused mainly by weather and drainage problems, is a dummy variable considered as 1 if either erosion depth is greater than 5 cm or width is greater than 10 cm.
- RT: Rutting or transverse deformations caused by loose aggregate, evaluated as the mean vertical distance between the highest and lowest point of a rut, obtained from three measures per wheel path and measured in centimetres.
- OA: Exposed Oversized Aggregate is a dummy variable, considered as 1 when oversized aggregates with mean diameters greater or equal to 5 cm are observed as a generalized phenomenon within the sample section
- CW: Crown condition is the average between drainage and transverse profile condition. Both defects are rated as 0 when observed in good condition, 0.5 in fair condition and 1 in poor condition. The transverse profile is assessed in terms of the shape of the crown and drainage in terms of the condition of side ditches.

- IRI: International Roughness Index measured in m/km with response type technology..

The method recommends condition limits for unbound gravel, stabilized gravel and earth roads, subject to three different climates (dry, Mediterranean and humid), as well as road conditions assigned to extreme surface defects. These are presented in Tables 4.4 to 4.7.

Table 4.4 Condition Limits for Unbound Gravel Roads

	UPCI Values per Climate		
Condition	**Dry**	**Mediterranean**	**Humid**
Very Good	10 to 8.0	10 to 8.0	10 to 8.0
Good	7.9 to 5.0	7.9 to 5.5	7.9 to 7.0
Regular	4.9 to 4.0	5.4 to 4.5	6.9 to 5.0
Poor	3.9 to 2.0	4.4 to 2.5	4.9 to 3.5
Very Poor	1.9 to 1.0	2.4 to 1.0	3.4 to 1.0

Table 4.5 Condition Limits for Stabilized Gravel Roads

	UPCI Values per Climate		
Condition	**Dry**	**Mediterranean**	**Humid**
Very Good	10 to 8.5	10 to 8.5	10 to 8.5
Good	8.4 to 5.5	8.4 to 6.0	8.4 to 7.5
Regular	5.4 to 4.5	5.9 to 5.0	7.4 to 5.5
Poor	4.4 to 2.5	4.9 to 3.0	5.4 to 4.0
Very Poor	2.4 to 1.0	2.9 to 1.0	3.9 to 1.0

Table 4.6 Condition Limits for Earth Roads

	UPCI Values per Climate		
Condition	**Dry**	**Mediterranean**	**Humid**
Very Good	10 to 7.5	10 to 8.0	10 to 8.0
Good	7.4 to 4.5	7.9 to 5.5	7.9 to 6.5
Regular	4.4 to 3.0	5.4 to 4.0	6.4 to 4.5
Poor	2.9 to 2.0	3.9 to 2.0	4.4 to 3.0
Very Poor	1.9 to 1.0	1.9 to 1.0	2.9 to 1.0

Table 4.7 Conditions Assigned to Maximum and Minimum Defect Values

Defect	**Value**	**Condition**
IRI (m/km)	≥ 12 m/km	Very Poor
IRI (m/km)	≤ 4 m/km	Very Good
Corrugation (cm)	≥ 3 cm	Very Poor
Pothole (m*m per sample section)	≥ 2 m^2	Very Poor
Rutting (cm)	≥ 4 cm	Very Poor
Erosion in the wheel path (cm)	Width ≥ 5 cm	Very Poor

4.4.3 Definition of Strategic Data

Given the socio-economic characteristics of each case study, interviews with local authorities, available studies, existing policies and observed condition of the network, the following strategic data was defined for each network.

4.4.3.1 Chile Case Study Data

- Social Targets: Basic access of 100% of the network was defined as a primary social target. This has been defined as a national policy given the socio-economic condition of the country, which is applicable to roads with no alternative. This is the case of the network under study, where most rural households do not count with alternative access.
- Technical Targets: The minimum condition standard required for basic access is defined for tertiary local roads. In the case of secondary roads, a minimum mobility standard has been defined, where roads should not present a condition below 5, measured in a scale from 1 to 10.
- Environmental Goals: Companies developing maintenance activities extract gravel from authorized quarries, following the environmental impact National Standards of Chile. Maintenance activities should prioritize use of spot gravelling for local problems and be reactive when important erosion and dust is produced.
- Available Funding Level: MOP has a fixed annual budget of CAD$ 240,000 to maintain the sub-network under study. This accounts for direct costs such as materials and occasional replacement of equipment parts. Labour and fuel, however, are managed under a separate budget. The available budget has been defined in terms of a fixed policy, considering the maintenance activities performed in the past years. However, if minimum access and mobility standards are not met, the available fund can be adjusted..
- Analysis Period: Given the seasonal effects of climate in the network deterioration, a six-month short term analysis frame has been defined. For the life cycle analysis of the network a 10 year analysis horizon has been defined.

4.4.3.2 Paraguay Case Study Data

- Social Targets: Basic access of 80% of the network was defined as a primary social target. This has been defined in terms of the socio-economic condition of the country and recent policies defined by the MOPC (MOPC, 2009). The network under study presents several alternatives connecting rural population in cases where households do not count with alternative access.
- Technical Targets: The minimum condition standard required for basic access is defined for tertiary local roads. In the case of secondary roads, a minimum mobility standard has been defined, where roads should not present a condition below 5, measured in a scale from 1 to 10.

- Environmental Goals: National parks are close to the road network. A minimum impact policy has been defined by the MOPC to avoid gravel extraction close to parks and restrict traffic in the parks.
- Available Funding Level: MOPC has a fixed annual budget of CAD$ 180,000 to maintain the sub-network under study. This accounts for direct costs such as materials and occasional replacement of equipment parts. Labour and fuel, however, are managed under a separate budget. The available budget is flexible if minimum access policy is not met.
- Analysis Period: Given the seasonal effects of climate in the network deterioration, a six-month short term analysis frame has been defined. For the life cycle analysis of the network a 10 year analysis horizon has been defined.

4.5 Data Summary

4.5.1 Chile Case Study Data

Tables 4.8 and 4.9 present a summary of the condition of gravel and earth roads, respectively, collected in the four field evaluations. The UPCI values presented in the tables were calculated from deteriorations evaluated in the field and the use of Equation 3. Sections that were not evaluated in a specific season are denoted as N.E. Detailed data collected in the Chilean network is presented in Appendix E. Typical distresses observed in the network are presented in Appendix E.1, inventory data in Appendix E.2 and detailed condition and maintenance data in Appendix E.3.

During the 39 months of evaluations, the network presented a mean UPCI condition of 6.16, where gravel roads presented a mean condition of 6.9 and earth roads a mean condition of 5.7.

Table 4.8 Summary of Gravel Road Condition: Chile Case Study

Road Characteristics			UPCI Values (1 to 10)			
Section Code	Road Name	Road Length (km)	sep-08	April-09	oct-09	oct-11
2	N620	13.900	7.1	8.1	6.2	8.3
3	N496_R	2.000	3.5	8.4	2.8	6.1
8	N600	9.700	6.8	9.0	5.7	9.5
14	N490	4.000	6.3	7.4	6.2	7.7
15	N480	7.700	6.5	4.8	6.5	7.1
16	N462	3.300	3.9	2.4	4.2	3.4
19	N616	3.200	8.3	8.3	9.0	8.3
20	N486	5.800	4.7	5.5	7.6	7.7
21	N466	11.700	9.4	6.3	5.5	9.5
26	N482	11.200	7.2	8.0	6.5	8.4
28	N478	5.300	N.E	8.0	5.8	7.0
34	N610	10.200	10.0	7.7	6.5	5.0
36	N510	4.900	5.9	5.4	6.5	9.2
37	N60-R_1	15.900	N.E	10.0	5.5	6.2
38	N60-R_2	15.900	N.E	8.3	N.E	5.9
39	N68	11.000	N.E	10.0	8.8	6.3

	UPCI Mean Condition			
Total Length	sep-08	April-09	oct-09	oct-11
135.700	6.6	7.4	6.2	7.2

Table 4.9 Summary of Earth Road Condition: Chile Case Study

Road Characteristics			UPCI Values (1 to 10)			
Section Code	Road Name	Road Length (km)	sep-08	April-09	oct-09	oct-11
1	V_LLA	0.550	5.8	7.4	7.7	4.9
4	N496_T	2.800	3.1	5.4	6.3	7.1
5	V_QTA	1.400	4.6	6.0	2.0	2.1
6	V_CU1	4.00	7.7	4.3	6.8	7.6
7	V_CU2	5.00	4.9	7.8	6.5	6.7
9	N498	2.000	2.8	9.2	7.3	7.7
10	V_BQH	0.850	4.7	5.6	4.0	4.4
11	N474	5.000	2.3	6.4	4.0	5.4
12	V_BA1	1.500	3.7	3.6	N.E	4.0
13	V_BA2	1.800	3.7	N.E	4.3	N.E
17	V_BAB	1.100	7.0	6.6	6.2	5.6
18	V_CAB	1.700	3.3	7.3	3.7	5.8
22	N492	6.800	6.2	8.4	7.2	7.1
24	V_HLB	1.700	5.0	3.1	N.E	N.E
25	V_LNJ	1.200	5.4	7.1	3.8	7.6
27	N500	3.000	3.4	6.7	6.4	8.9
29	V_PSA	1.300	4.9	5.4	5.8	N.E
30	V_CHU	3.000	6.2	5.3	5.0	9.2
31	V_AMI	2.000	5.4	6.5	4.1	6.3
32	N494	5.400	8.2	6.7	3.3	6.2
33	V_LPL	1.600	5.8	5.5	6.4	6.7
35	V_RCM	2.000	3.2	4.8	N.E	N.E

	UPCI Mean Condition			
Total Length	sep-08	April-09	oct-09	oct-11
45.300	4.9	6.2	5.3	6.3

4.5.2 Paraguay Case Study Data

Table 4.10 presents a summary of the condition of earth and gravel roads in the network. The UPCI values presented in the table were calculated from deteriorations evaluated in the field and the use of Equation 3. The network presented a mean UPCI condition of 3.82, where gravel roads presented a mean condition of 4.16 and earth roads a mean condition of 3.74. Typical distresses observed in the network are presented in Appendix E.4.

Table 4.10 Summary of Paraguay Network Condition

Section Code	Road Name	Surface Type	Road Length (Km)	Traffic AADT	Population	% Population	Road Width	UPCI
1	V_1	Earth	2.700	100	95	0.9%	7	3.9
2.1	R 212_1	Gravel	2.733	212	771	7.6%	6.6	3.1
2.2	R 212_2	Gravel	5.467	212	1542	15.2%	7	7.0
3	R 212_3	Gravel	6.300	150	1157	11.4%	6.2	3.0
4	R 4000	Earth	8.600	286	1000	9.9%	5.4	7.4
5	R 2816	Earth	4.600	100	180	1.8%	5.2	1.0
6	R 2815	Earth	11.260	150	265	2.6%	8.5	6.2
7	R 208	Gravel	14.600	252	1385	13.7%	5.7	3.6
8	R 2813	Earth	14.700	250	430	4.2%	7.1	6.4
9	V_9	Earth	3.800	150	65	0.6%	10.5	4.5
10	V_10	Earth	6.100	75	75	0.7%	7.1	5.4
11	R 2814	Earth	6.100	50	90	0.9%	4.2	3.6
12	R 2812	Earth	6.500	90	225	2.2%	5	3.1
14	R 2811	Earth	8.200	50	565	5.6%	8.5	1.7
16	R 2811	Earth	6.300	50	565	5.6%	5.6	1.3
17	V_17	Earth	2.600	30	100	1.0%	5.6	1.0
18	R 2810	Earth	5.300	50	155	1.5%	6	1.4
19	V_19	Earth	0.800	40	85	0.8%	6.9	1.6
20.1	V_20_1	Earth	3.600	20	45	0.4%	5	2.9
20.2	V_20_2	Earth	3.600	50	55	0.5%	4.7	6.5
21	2809	Earth	3.700	70	410	4.1%	4.8	3.7
22	2808	Earth	11.000	83	760	7.5%	7.5	4.3
23	V_23	Earth	3.100	60	100	1.0%	7	5.6

Total Length Km	Mean Traffic AADT	Total Population	UPCI Mean Condition
141.66	112	10,120	3.8

Chapter 5
Development of the Condition Performance Module

5.1 Introduction

Four experiments were designed for the development of the Condition Performance Module. These were: validation of the UnPaved Roads Condition Index (UPCI) methodology, development of unpaved roads condition performance models, definition of maintenance effects on roads condition and validation of unpaved roads condition performance models and effects of maintenance on roads condition. The experimental design, factorials and data considered for the analysis were presented in detail in Chapter 4. The present chapter presents the data analysis process and findings obtained for each experiment. As a result, a validated data collection methodology, condition performance models and maintenance recommendations were obtained. These are the core elements forming the Condition Performance Module.

5.2 Validation of UPCI Methodology

To verify the suitability of applying the UPCI methodology in the selected networks, a preliminary validation of the methodology was performed. The validation process consisted in applying the evaluation methodology to the Chilean network. In addition, a subjective condition rate which ranged between 1 and 10 was defined per section, namely a UPCI observed value.

From the field evaluation the following two modifications to the evaluation methodology were suggested:

- It was recommended to include the presence of fine aggregates as part of the Exposed Oversized Aggregate (OA) dummy variable in Equation 3. With this the variable was renamed as presence of "Oversized or Fine Aggregates" (OFA) and the equation was corrected as follows:

  UPCI without considering roughness measures:

  $$UPCI=10 - 1.16CR - 2.25PT - 1.47ER - 0.33RT - 1.56OFA - 1.58CW \qquad (5)$$

  OFA is a dummy variable representing the presence of oversized aggregates or prevalence of fine aggregates as a generalized phenomenon within the sample section. The variable is considered as 1 when oversized aggregates present mean diameters greater or equal to 10 cm, or when areas with fine aggregates present high levels of dust during the dry season and loose mud during the humid season. The other variables where unchanged, maintaining their definition as described in Chapter 4.

- Condition limits assigned to extreme defect values were adjusted. Erosion, corrugations and rutting effects on passability were over estimated by the methodology. The adjusted values are presented in Table 5.1.

Table 5.1 Corrected Conditions to Maximum and Minimum Defect Values

Defect	Value	Condition
IRI (m/km)	≥ 12 m/km	Very Poor
IRI (m/km)	≤ 4 m/km	Very Good
Corrugation (cm)	> 5 cm	Very Poor
Pothole (m*m per sample section)	> 2 m^2/sample	Very Poor
Rutting (cm)	> 6 cm	Very Poor
Erosion (cm)	Depth > 10 cm	Very Poor

Taking in consideration the recommended modifications, UPCI values were calculated per section using Equation 5. Calculated and observed UPCI values are presented in Figure 5.1. Both samples were statistically compared with a 95% confidence following the t test for difference in means. From the analysis the UPCI methodology was validated successfully and, therefore, its application is suitable for the network under study. The statistic test and data considered in the analysis is presented in Appendix F.1

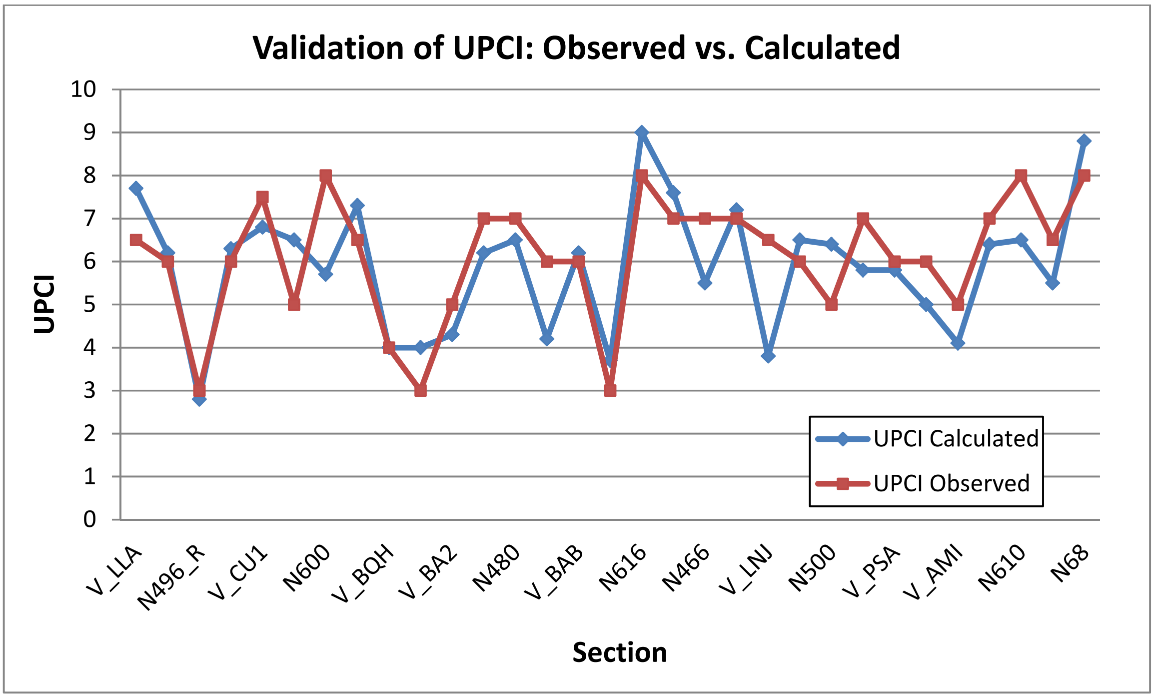


Figure 5.1 Validation of UPCI Methodology

5.3 Development of Condition Performance Models

5.3.1 Selection of a Modelling Method

The performance of roads over time can be predicted and modelled following deterministic or probabilistic techniques. Deterministic models predict precise condition values based on historical data and observed behaviours. Meanwhile, probabilistic models predict the probability of a future condition subject to the current state and the effects of independent variables affecting roads performance (Karan, 1977). Three different probabilistic approaches have been used in pavement engineering for this purpose: econometric models, Markov Chain models and reliability analysis. Among these, the most widely used technique are the Markov Chains, as they can be easily calibrated, do not require historical databases, can capture non-linear behaviours and are flexible to be adapted when new data is available (Tack, 2005). Markov chains can be used to determine probability transition matrices which reflect the future condition of a road subject to an initial condition state. These matrices can be developed from expert opinion, existing condition data or from evaluations performed in the field during representative time periods.

Markov chain models were selected in this study to define condition performance models for unpaved roads.

5.3.2 Development of Probability Transition Matrices

Probability transition matrices derived from field evaluations were identified as the most suitable method for this purpose, given the stochastic nature of unpaved roads deterioration and the seasonal variations observed in the field. Data collected in the Chilean road network in three field evaluations were considered. Data was separated in terms of structure strength in two ranges, weak and strong structures. Weak roads presented CBR less than 15%, while strong roads presented CBR equal or greater than 15%. Given the characteristics of the network, all weak roads were earth roads and tracks, while strong roads were gravel roads.

To derive probability transition matrices the following steps were considered:

- Definition of UPCI ranges: Nine states of one UPCI value were defined for the analysis, ranging from 1-1.9 UPCI to 9-10 UPCI.
- Development of a condition summary table: This table presents the total length of roads, in kilometres, changing from an initial condition i to a future condition j during a 6 month period. With this, the condition variations observed per road during two time intervals were captured in the analysis. As presented in Tables 5.2 and 5.3, rows represent the current state i and columns represent the future condition j of the road after a six month period. Only sections that were not rehabilitated during the analysis period were considered for this purpose.
- Definition of Probability Transition Matrices (PTM): Condition summary tables were transformed to probability matrices by estimating the proportion of roads changing from a state i to a state j, given the total road lengths observed per state i. In other words, each tile of Table 5.2 was divided by the total road lengths observed per row.
- Cumulative Probability Transition Matrices: For simulation purposes, cumulative PTM's were defined by summing the cumulative probabilities j per row in each PTM. Two

cumulative PTM's were finally defined, for gravel and earth roads, as presented in Tables 5.4 and 5.5 respectively.

Table 5.2 Gravel Condition Summary Table

		Future Condition j (after six months)									
	Range	10-9	8.9-8	7.9-7	6.9-6	5.9-5	4.9-4	3.9-3	2.9-2	1.9-1	Total m
Current Condition i	10-9	0	11000	10200	11700	25600	0	0	0	0	58500
	8.9-8	0	3200	0	25100	5300	0	0	2000	0	35600
	7.9-7	0	0	0	14200	0	0	0	0	0	14200
	6.9-6	0	0	0	0	11700	0	0	0	0	11700
	5.9-5	0	0	0	0	4900	0	0	0	0	4900
	4.9-4	0	0	0	0	0	0	0	0	0	0
	3.9-3	0	0	0	0	0	0	0	3300	0	3300
	2.9-2	0	0	0	0	0	0	0	0	0	0
	1.9-1	0	0	0	0	0	0	0	0	0	0

Table 5.3 Earth Condition Summary Table

		Future Condition j (after six months)									
	Range	10-9	8.9-8	7.9-7	6.9-6	5.9-5	4.9-4	3.9-3	2.9-2	1.9-1	Total m
Current Condition i	10-9	0	0	2000	0	0	0	0	0	0	2000
	8.9-8	0	0	6800	5400	0	0	0	0	0	12200
	7.9-7	0	0	550	1600	0	400	2900	0	0	5450
	6.9-6	0	0	0	1100	3000	7000	5400	1400	0	17900
	5.9-5	0	0	0	3000	5900	850	1700	0	0	11450
	4.9-4	0	0	0	0	0	0	0	0	0	0
	3.9-3	0	0	0	0	0	0	1500	0	0	1500
	2.9-2	0	0	0	0	0	0	0	0	0	0
	1.9-1	0	0	0	0	0	0	0	0	0	0

Table 5.4 Gravel Cumulative Probability Transition Matrix

		Future Condition j (after six months)								
	Range	10-9	8.9-8	7.9-7	6.9-6	5.9-5	4.9-4	3.9-3	2.9-2	1.9-1
Current Condition i	10-9	0.00	0.19	0.36	0.56	1.00	0.00	0.00	0.00	0.00
	8.9-8	0.00	0.09	0.09	0.79	0.94	0.94	0.94	1.00	0.00
	7.9-7	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
	6.9-6	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
	5.9-5	0.00	0.00	0.00	0.00	0.67	1.00	0.00	0.00	0.00
	4.9-4	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
	3.9-3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
	2.9-2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
	1.9-1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Table 5.5 Earth Cumulative Probability Transition Matrix

		Future Condition j (after six months)								
	Range	8.9-7	8.9-8	7.9-7	6.9-6	5.9-5	4.9-4	3.9-3	2.9-2	1.9-1
Current Condition i	10-sep	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
	8.9-8	0.00	0.00	0.56	1.00	0.00	0.00	0.00	0.00	0.00
	7.9-7	0.00	0.00	0.10	0.39	0.39	0.47	1.00	0.00	0.00
	6.9-6	0.00	0.00	0.00	0.06	0.23	0.62	0.92	1.00	0.00
	5.9-5	0.00	0.00	0.00	0.26	0.78	0.85	1.00	0.00	0.00
	4.9-4	0.00	0.00	0.00	0.00	0.00	0.26	0.78	0.85	1.00
	3.9-3	0.00	0.00	0.00	0.00	0.00	0.00	0.91	1.00	0.00
	2.9-2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.91	1.00
	1.9-1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

5.3.3 Effects of Climate on Unpaved Roads Performance

Given that the regions are located in a Mediterranean climate, weather variations observed between seasons can be related to the expected performance for different climates. To capture the effects of climate on roads performance, a separate analysis was made considering data collected after winter and summer, rainy and dry seasons respectively. From the analysis it was observed that roads evaluated after the winter (evaluations performed during September) presented an accelerated deterioration trend compared to those evaluated after summer (evaluations performed in April). From collected data, the mean condition of roads after winter was 18% less than the condition observed after summer. In gravel roads a mean condition of 6.4 was observed after winter and a mean condition of 7.3 after summer. While in earth roads a mean condition of 5.0 was observed after winter and a mean condition of 6.2 after summer. A higher difference between seasons is observed in earth roads with respect to gravel roads (25% higher). This evidences that earth roads are more vulnerable to environmental conditions. The slopes of both deterioration trends were estimated and compared to the overall behaviour observed from the complete dataset, representative of a Mediterranean climate.

From the analysis it was concluded that the deterioration trend observed after the summer is representative to a 75% percentile of the modeled dataset. Given that the season presents mean monthly precipitations less than 20 mm, the deterioration trend can be associated with a dry climate. In the case of evaluations performed after winter, it was observed that the trend is representative to a 25% percentile of the dataset. The region presents mean monthly precipitations above 200 mm, which can be associated to a humid climate. For the overall dataset, a 50% percentile represents the Mediterranean climate of the region, with mean monthly precipitations between 20 and 200 mm.

5.3.4 Simulation of Deterioration Trends

Final deterioration curves were developed using a Monte Carlo simulation. The simulation was performed separately for gravel and earth roads using the cumulative PTM's presented in Tables 5.4 and 5.5. The simulation was performed considering 10,000 trials, where one trial was defined as a set of 20 random numbers between 0% and 100%. Each random number represents the cumulative probability that a road will be in condition i at a certain point in its lifetime. The simulation starts with a new road presenting a UPCI condition of 10. The condition of that road after a six month period is determined from the first random number in a trial. The number is checked from left to right in the condition range of 10-9 (first row) of the cumulative PTM. The condition of the road after six months of service is the first cumulative percentage which the random number exceeds. The second random number is then checked from left to right in the row representative of the condition obtained from the previous step. This checking is performed for all 20 random numbers until a 10 year analysis period is simulated in a trial.

After the 10,000 trials were simulated, the conditions per trial were linearized per condition range. For example, in the cases where the road condition after four consecutive analysis periods presented the same condition range, the UPCI value trend or slope was considered to be 0.20.

5.3.5 Unpaved Roads Condition Performance Curves

The final unpaved road condition performance curves obtained from the simulation process for strong structure roads (or gravel) and weak structure roads (or earth) are presented in Figures 5.2 and 5.3. Each graph includes three curves, representing the performance observed under dry, Mediterranean and humid climates. It must be noted that the models were defined considering that no maintenance was performed during the service life of the roads. The developed curves represent the long term behaviour of unpaved roads, being the basis required for a life cycle cost analysis to compare different maintenance strategies. The effects of different maintenance treatments over the roads condition and the application of the models for economic analysis are discussed in subsequent sections.

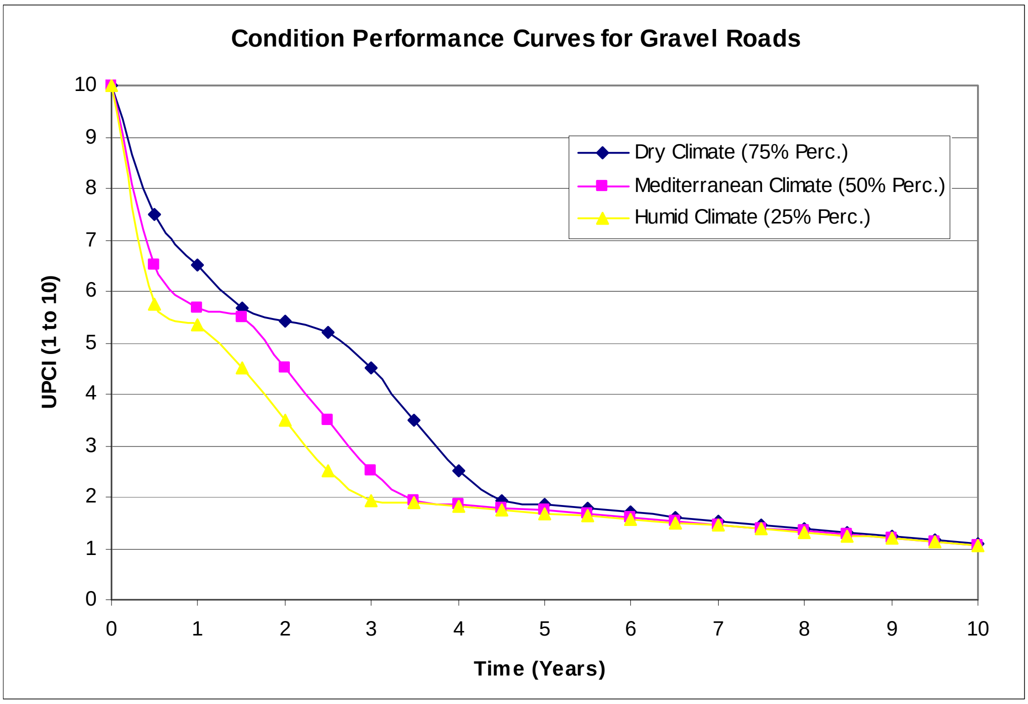


Figure 5.2 Condition Performance Curves for Strong Structure Roads or Gravel Roads

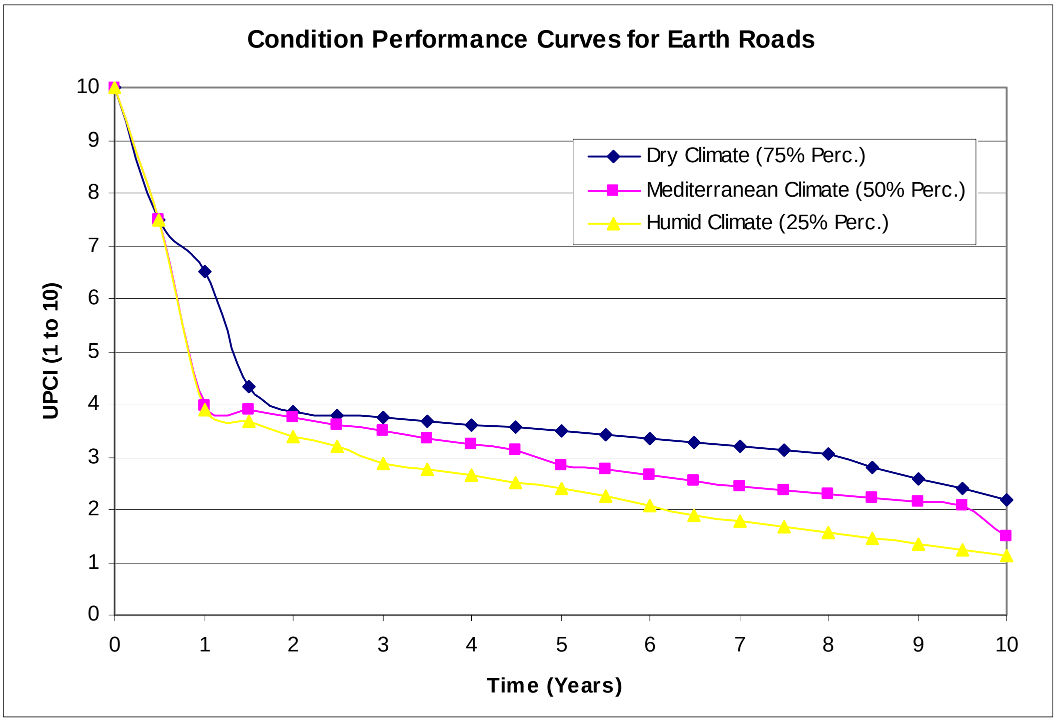


Figure 5.3 Condition Performance Curves for Weak Structure Roads or Earth Roads

5.3.6 Analysis of Developed Condition Performance Models

Both graphs clearly represent the performance observed in the field during the thirteen-month analysis period. As expected for gravel roads, the UPCI value drops significantly during the first year of service due to the appearance of specific distresses caused by traffic and environmental effects. During this phase, functional distresses start to appear, such as corrugations, gravel loss and ravelling. Structural problems may be in an incipient stage, such as slight rutting and pothole formation. This phenomenon coincides with the initial phase of distresses affecting the roads serviceability observed from literature. Then, a stable phase of one to three years is observed while structural and drainage related distresses start to develop. After this stable phase a second accelerated deterioration phase is observed, which characterizes the end of service life of the road. During this phase distresses critically affecting transitability, such as potholes, erosion, drainage problems and significant rutting, are prevalent. These distresses commonly represent the combined effect of structural problems and tend to be collinear. This trend represents the final phase of performance curves observed from literature. In the last five to three years of service, a road presents severe access problems and is in very poor condition, resulting in UPCI values less than 2.

The main difference observed between both graphs is that the condition drops significantly during the first years in the case of earth roads. This is explained by the poor structural capacity of earth roads and absence of a granular wearing course that protects the structure, which tend to deteriorate fast in the presence of traffic and rain. Given this accelerated deterioration, the steady phase is practically reduced to one year, after which a monotonous decreasing trend is observed.

5.4 Maintenance Effects on Roads Condition

The analysis process for the development of performance curves only considered road sections that were not maintained between two evaluation periods. For sections where maintenance was performed the effects of maintenance on roads condition was analysed. For this, additional data was collected per road including: traffic volumes, type of traffic (considering motorized and non-motorized), traffic distribution (light and heavy), roads with bus service, school bus route and roads requiring ambulance access. Maintenance activities between evaluations were obtained from reports of the local agency. The collected data is summarized in the tables presented in Appendix E.

For the analysis, performance curves were used to estimate the condition of roads on the date they received maintenance. The analysis was done within the six month cycle between maintenance. For the analysis, back calculation of roads condition considering the last evaluation and forward calculation considering the previous evaluation were considered. This was performed for the Mediterranean climate curve as a basis and the climate curve corresponding to the season between evaluations. Table 5.6 is presented as an example to describe the procedure.

The three roads presented in the example were evaluated on September 2008 and April 2009. Between both evaluations the dry season, or summer, prevailed. Between evaluations the dates and types of maintenance were registered, as presented in Table 5.6.

Table 5.6 Calculation of Maintenance Effects

Road Code	Structure	Traffic	UPCI	Pre Maintenance Dry	Pre Maintenance Mediterranean	Maintenance	Post Maintenance Dry	Post Maintenance Med	UPCI
27	Earth- Weak	20	3.4	3.3	3.3	Local grading Feb, March/09	7.1	7.8	6.7
35	Earth- Weak	10	3.2	3.1	3.0	Grading March/09	5.2	5.4	4.8
15	Gravel- Strong	100	6.5	6.4	6.4	Grading Oct, Nov/08	5.4	5.6	4.8

Using the performance curves for strong and weak structures, presented in Figures 5.2 and 5.3, the expected UPCI value immediately before the date of the first maintenance was estimated starting with the UPCI value obtained in the first evaluation (September 2008). This value is presented in the "Pre Maint" columns of Table 5.6 for each section. Similarly the expected UPCI value immediately after the maintenance was estimated from UPCI values of the second evaluation (April 2009). For both cases the analysis was done considering the Mediterranean climate and dry climate curves, in order to capture possible fluctuation for different climates. The expected effect or "jump" in the condition caused by a specific maintenance strategy or treatment per climate was calculated as the difference between both UPCI values, pre and post maintenance. In the case where a section was maintained more than once between evaluations, the overall effect was estimated and the date of the first maintenance treatment was considered as a basis.

The analysis was made for all sections that were maintained and considering the effects of the corresponding climates. The results were grouped per maintenance type and climates. The effects were analysed in absolute values and in terms of relative condition improvement, as a percentage of the condition of the road. Descriptive statistics were applied to the results, where sample means, standard deviations, maximum and minimum values were obtained. Results from the analysis are presented in Appendix F.2.

Data statistics were analysed in detail, and Tables 5.7 and 5.8 summarize the final recommendations obtained from the analysis.

Table 5.7 Maintenance Strategies and UPCI effects Recommended for Gravel Roads

Maintenance Type	UPCI Increase	Application Range Min	Application Range Max	Recommendations
2 or more Grading (application subject to traffic level)	3.2	4.0	5.5	Routine Maintenance
Local gravel + Grading	2.7	4.0	8.5	Routine Maintenance
Culvert/Bridge Repair + Local Grading	1.5		5.5	Rehabilitation
Local Gravel	2.1	4.0	9.0	Routine Maintenance

Table 5.8 Maintenance Strategies and UPCI effects Recommended for Earth Roads

Maintenance	UPCI Increase	Application Range		Recommendations
		Min	Max	
Local Gravel/ Pothole Patching	2.0	5.5	10	Routine Maintenance
One Grading	2.0	5.5	10	Routine Maintenance, L Traffic
Two Gradings	3.0	5.5	10	Routine Maintenance, M traffic
Culvert Repair + One Grading	3.5	4.0	5.5	Rehabilitation L traffic
Local gravel + One Grading	4.0	4.0	5.5	Rehabilitation L traffic

The following findings were obtained from the analysis:

- Four types of maintenance strategies were applied to gravel roads and five types of maintenance strategies to earth roads. Based on the effects on roads condition and literature, recommendations were made for their classification and development of maintenance standards.
- A variability of 30% in average was observed on the standard deviation of calculated UPCI increases. This trend was observed in gravel and earth roads.
- Most variable observations were obtained for one grading in earth roads, where variability of the standard deviation was more than 50%. This is explained by the fact that the effectiveness of one grading is very sensitive to the condition of the road prior application, especially when a light blading is considered. Given its variable effectiveness and reduced contribution to increase UPCI after application, simple light grading is recommended as a minimum strategy for low and medium volume traffics in earth roads and for low traffic volumes on gravel roads.
- Strategies that combined more than one maintenance treatment or considered more than one application of a specific maintenance treatment within the analysed period, presented higher effectiveness and low variability. For example, the application of two grading in earth roads presented a variability of 15% in terms of its standard deviation. This value is considerably less than the 50% or more observed for one grading application.
- Ranges of UPCI were obtained from the analysis of maximum and minimum values for each strategy. This resulted in recommendations of trigger values for the design of maintenance standards for routine maintenance, rehabilitation and reconstruction.
- The effectiveness of strategies was highly dependent on traffic volumes. It was therefore essential to consider maintenance policies for different traffic volumes. Different application frequencies should be defined in terms of vehicles per day. In this sense, the analysed data was consistent with literature recommendations.
- A relationship between maintenance effectiveness and climate was not apparent from the analysis. This could be explained by the fact the calculation of UPCI considered the developed condition models, which already capture the effects of climate. Considering this, the effects of climates should be accounted for as a long term performance effect and not as a maintenance strategy effect, to avoid double counting.

5.5 Validation of Unpaved Roads Condition Performance Models and Maintenance Recommendations

The validation of performance models and maintenance effects considered data collected in the third and fourth field evaluations of the Chilean road network. The analysis consisted on the comparison of UPCI values from the fourth field evaluation contrasted to predicted UPCI values considering the third field evaluation. For this, performance curves were used to calculate the expected condition (calculated UPCI) of roads after a 24 month period and considering the maintenance activities performed per road during that period. The expected condition (calculated UPCI) was plotted and compared to the observed condition obtained from field evaluations (observed UPCI). Calculated and observed UPCI values for earth and gravel roads are presented in Figure 5.4 and 5.5. Both samples were statistically compared with a 95% confidence following the t test for difference in means. From the analysis performance models for earth and gravel roads and the effects of maintenance on roads condition were successfully validated. A trend is observed in both graphs where observed data tend to be higher than calculated values when UPCI is more than 6. This is explained by the fact that maximum UPCI values were established for each maintenance strategy, given that in the practice a lower effectiveness is observed for routine maintenance and rehabilitation for roads in good condition. With this, calculated UPCI is conservative when compared to the performance observed in the field for higher UPCI values. The statistic test and data considered in the analysis is presented in Appendix F.3.

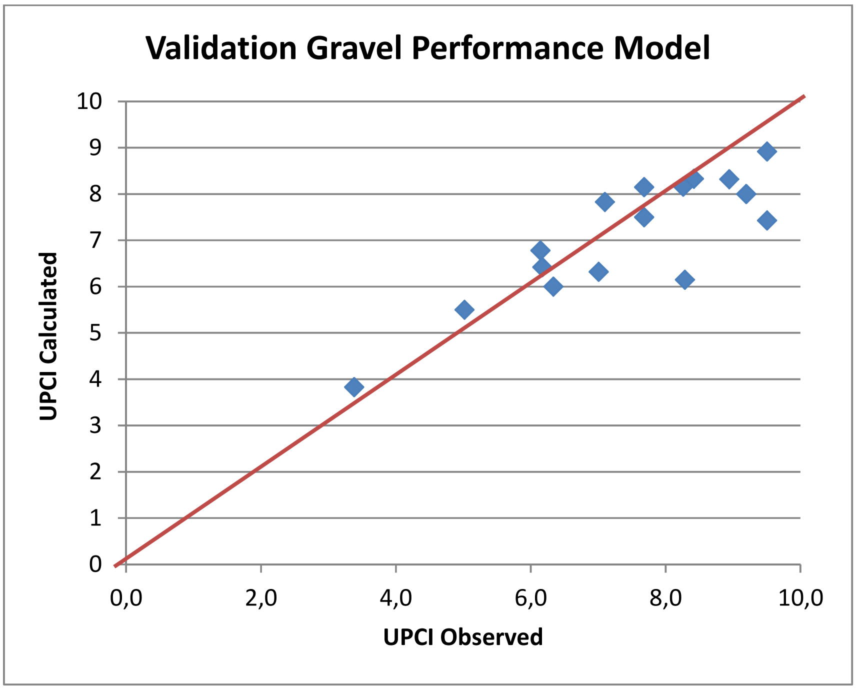


Figure 5.4 Validation of Gravel Curves: UPCI observed vs. calculated

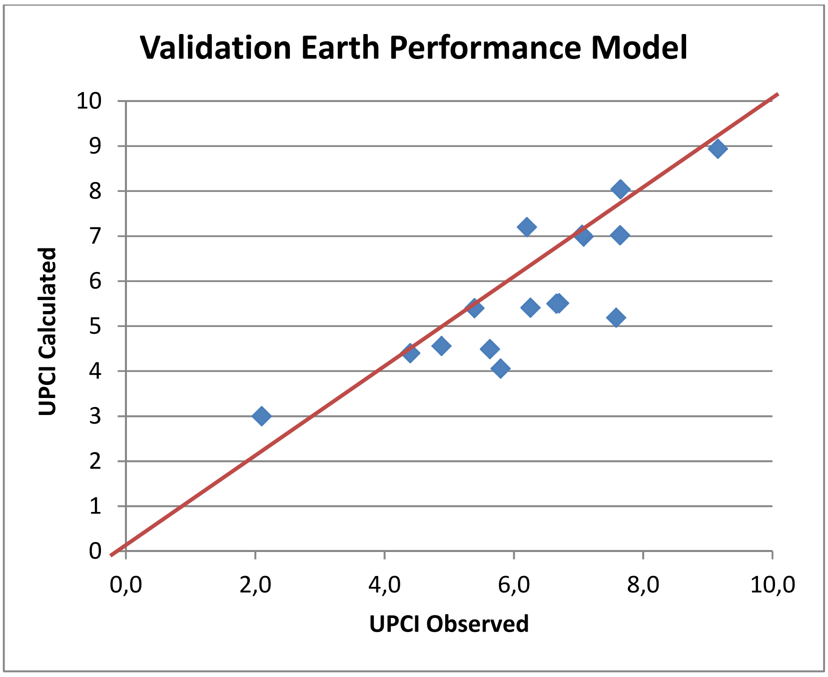


Figure 5.5 Validation of Earth Curves: UPCI observed vs. calculated

5.6 Summary of the Chapter

The basis for condition performance analysis and prediction in the long term considered in the proposed management system is presented in detail in the present chapter. The network evaluation methodology recommended, the UnPaved Roads Condition Index (UPCI), was successfully validated. With this, the unpaved roads condition performance models were developed based on a reliable evaluation method.

Performance models were obtained from the statistical analysis of the road deterioration observed in a thirteen month period. The modelling technique selected was Markov chain models, which can reliably predict the stochastic nature and non-linear performance of unpaved roads over time. Performance curves for strong structures or gravel roads and weak structures or earth roads were finally obtained from Monte Carlo simulation. Data that was not considered in the development of performance curves was analysed in detail to define maintenance recommendations. Maintenance effects on roads condition were obtained from the analysis; in addition, trigger values for different maintenance strategies were defined.

The unpaved roads condition performance models and effect of maintenance on roads condition were validated. For this, data was collected in October 2011 and compared to data collected 24 months before but projected to the same timeframe with the use of performance models. From the analysis, condition performance models and maintenance recommendations were successfully validated. The four elements developed and validated in the present Chapter, UPCI methodology, performance curves and maintenance recommendations are the core elements forming the Condition Performance Module.

Chapter 6
Development of the Network Maintenance Module

6.1 Introduction

After analysing the current condition of a road network, the next step in the management process is to decide how to maintain roads in order to achieve a desired network standard. For this, the proposed management system considers the development of the Network Maintenance Module, which includes all required elements for short and long- term maintenance decisions.

To decide upon the most suitable maintenance strategy for a specific road, rational comparisons about long term performance and related maintenance costs should be considered. The cost-effectiveness analysis method was considered for this purpose, as it objectively estimates the effects of roads condition and maintenance during the whole life cycle of a road.

Optimal maintenance standards were developed considering eighteen scenarios at four different budget levels. Scenarios considered two types of road structure, three climate zones and three traffic levels. For each scenario, two maintenance standards were defined, considering two different routine maintenance policies. From the cost-effectiveness analysis, optimal standards were recommended and the optimum budget level was defined for each scenario.

6.2 Development of Maintenance Strategies

6.2.1 Definitions

Maintenance treatments refer to the application of a specific maintenance treatment to the road surface. The effectiveness of treatments vary depending on the level of deterioration prior application, material properties, traffic and the activities considered in the treatment (such as prior compaction, reshaping, forming, etc.). Most common maintenance treatments for unpaved roads were described in detail in Chapter 2. These could be summarized in four main treatment categories:

- Drainage Maintenance and Improvement (D): including maintenance of subdrains and drains, ditch improvement and culvert replacement.
- Blading or Grading (B): which could be performed as dry blading, wet blading, light blading and heavy blading/grading. In addition the effectiveness of the blading can be improved in the presence of certain defects when considering reshaping reworking and forming.
- Local or Spot Gravelling (R): gravelling of short sections on a road, typically only on curves, steep gradients, potholes or isolated rock outcrops.
- Gravelling (G): defined as the addition of a suitable wearing course layer of unbound gravel, typically 100 mm to 150 mm in thickness over the entire length of the improved section.

Some maintenance treatments can be applied for the upgrade of a road to a higher surface standard. This is the case when earth roads are gravelled and improved to a gravel standard or when a seal is applied to an earth or gravel road. The discussion on the present research centres on the application of maintenance treatments to improve the condition of roads and surface upgrades from earth to gravel roads for high traffic volumes. The approach, also detects candidate roads for surface upgrades from earth or gravel to surface treatment or pavement when a maximum traffic volume is reached.

Depending on the type of deterioration and condition of an unpaved road, treatments can be combined and grouped in three main types:

- Routine maintenance, which is applied on a proactive programmed basis when roads present incipient deterioration to extend a good performance over time.
- Rehabilitation, which combines reactive policies to improve the condition of a road in an advanced deterioration phase.
- Reconstruction or Emergency Maintenance, which is commonly applied in unpaved roads presenting excessive damage or wear, commonly related to severe drainage problems or abnormal use of the road.

In the present research the terms routine maintenance, rehabilitation and reconstruction will be used. In addition a fourth category was considered as minimum routine maintenance, required to warranty basic access in rural areas.

Maintenance strategies can be defined as all treatments undertaken to maintain and provide serviceable roads over their life cycle. Strategies may combine several treatments to improve specific functional and structural problems of a road. Agencies usually define strategies based on previous experiences, subject to available technologies and funding. Maintenance strategies should consider routine maintenance, rehabilitation and reconstruction to ensure a suitable condition level of roads throughout their service life.

6.2.2 Effects of Traffic on Maintenance

Several studies have evaluated the impact of traffic volumes on the effectiveness of certain maintenance treatments (Provencher, 1995; Visser, 1981; Kerali, 1991). In particular, during the development of HDM III models, the effects of blading frequency on roughness progression and gravel loss were studied in detail. From the study it was evidenced that a long term average roughness level is reached when a constant blading frequency is considered for a certain traffic volume. When the traffic decreases or the blading frequency increases the average roughness decreases and the long term average value advances in time. From economic analysis, the study concluded that a blading policy at intervals of 4,000 vehicles is close to optimal (Paterson, 1991).

Regarding traffic loads, studies have evidenced that no significant differences in the modeling of gravel loss and riding quality deterioration of rural gravel roads were found by separating the traffic into light and heavy vehicles. Moreover, travelling speeds may affect significantly the progression of roads deterioration, especially in the presence of dry conditions and independently, if light or heavy traffic is considered (NITRR, 2009).

In light of these recommendations and findings obtained from field evaluations, it was decided to consider different maintenance strategies for three traffic volumes. The estimation was made considering the recommendation of optimal frequencies suggested by Paterson (1991), for intervals of 4,000 vehicles.

6.2.3 Proposed Maintenance Strategies

Four budget levels were considered in the definition of maintenance strategies: Minimum (B_1), Low (B_2), Medium (B_3) and High (B_4).Taking into account that suitable maintenance equipment and funding may vary significantly between agencies in charge of rural roads in developing countries, budget levels were defined in terms of the quality of applied maintenance. This was concluded after reviewing the current state-of-the-practice, available literature and from field evaluations, where the effectiveness of treatments applied in unpaved roads significantly depend on available labour, materials and equipment. Frequency of treatment application is most common and usually programmed in terms of traffic volumes (Lebo, 2000; Paterson, 1991). Given this, budget levels were defined in terms of quality and how extensively maintenance treatments are applied as presented in Table 6.1. Names given to each treatment, budget level and combination of both are presented in parenthesis in the table.

Table 6.1 Maintenance Treatments per Funding Levels

Maintenance Treatment	Minimum Budget (B_1)	Low Budget (B_2)	Medium Budget (B_3)	High Budget (B_4)
Drainage Improvement/Culvert Replacement (D)	1 per 8 km, 10m long (DB_2)	1 per 8 km, 10m long (DB_2)	1 per 6 km, 10m long (DB_3)	1 per 4 km, 10m long (DB_4)
Grading (B)	Sporadic light blading to ensure minimum access (BB_1)	light blading (BB_2)	heavy blading or grading with localized compaction when required (BB_3)	heavy blading with reshaping, forming and compaction when required (BB_4)
Local Gravel/ Pothole Patching (R)	5m^3 per km (50 potholes/km of 1mx1mx10cm) (RB_2)	5m^3 per km (50 potholes/km of 1mx1mx10cm) (RB_2)	8m^3 per km (80 potholes/km of 1mx1mx10cm) (RB_3)	12m^3 per km (120 potholes/km of 1mx1mx10cm) (RB_4)
Gravelling (G)	50mm layer, 7m wide road, light blading for surface preparation (GB_2)	50mm layer, 7m wide road, light blading for surface preparation (GB_2)	100mm layer, 7m wide road, heavy blading for surface preparation (GB_3)	150mm layer, 7m wide road, heavy blading, reshaping and forming for surface preparation (GB_4)

In addition to budget and traffic scenarios, it was observed from the practice that routine maintenance was applied combining local gravel and minimum grading (RM1) or as a routine grading (RM2). The effects on roads condition for both approaches were captured on field evaluations. A minimum maintenance strategy (RMin) was also defined considering minimum blading criteria for routine maintenance, where only sporadic light blading is applied. This is considered as a minimum routine maintenance warranting basic access in rural areas.

The three strategies were defined in terms of three traffic volumes: Low (LT), Moderate (MT) and High (HT). With this, nine strategies were defined per budget scenario for gravel and earth roads, considering different traffic and routine maintenance approaches, as presented in Tables 6.2 and 6.3.

Table 6.2 Maintenance Strategies for Gravel Roads

Strategy	Low Traffic-LT (<100 AADT)	Moderate Traffic-MT (100-200 AADT)	High Traffic-HT (>200 AADT)
Gravel Minimum Strategy (GRMin)	GRMin-LT Minimum: 2MinB/year Rehabilitation: 2B+10%G Reconstruction: 2B+30%G+C	GRMin -MT Minimum: 6MinB/year Rehabilitation: 6B+25%G Reconstruction: 6B+75%G+C	GRMin -HT Minimum: 10MinB/year Rehabilitation: 12B+40%G Reconstruction: 12B+100%G+C
Gravel PM Strategy 1 (GRM1)	GRM1-LT Routine 1: 2BLB+2R/year Rehabilitation: 2B+10%G Reconstruction: 2B+30%G+C	GRM1-MT Routine 1: 6BLB+6R/year Rehabilitation: 6B+25%G Reconstruction: 6B+75%G+C	GRM1-HT Routine 1: 10BLB+10R/year Rehabilitation: 12B+40%G Reconstruction: 12B+100%G+C
Gravel PM Strategy 2 (GRM2)	GRM2-LT Routine 2: 4B Rehabilitation: 2B+10%G Reconstruction: 2B+30%G+C	GRM2-MT Routine 2: 12B Rehabilitation: 6B+25%G Reconstruction: 6B+75%G+C	GRM2-HT Routine 2: 20B Rehabilitation: 12B+40%G Reconstruction: 12B+100%G+C

Table 6.3 Maintenance Strategies for Earth Roads

Strategy	Low Traffic (<50 AADT)	Moderate Traffic (AADT 50-100)	High Traffic (100> AADT)
Earth Minimum Strategy (ERMin)	ERMin-LT Minimum: 2MinB/year Rehabilitation: 2B+10%G Reconstruction: 2B+30%G+C	ERMin -MT Minimum: 6MinB/year Rehabilitation: 6B+25%G Reconstruction: 6B+75%G+C	ERMin -HT Minimum: 10MinB/year Rehabilitation: 12B+40%G Reconstruction: 12B+100%G+C
Earth Strategy 1 (ERM1)	ERM1-LT Routine 1: 1BLB+1R/year Rehabilitation: 2B+2R Reconstruction: 2B+2R+C	ERM1 -MT Routine 1: 4BLB+4R/year Rehabilitation: 6B+6R Reconstruction: 6B+6R+C	ERM1 -HT Routine 1: 6BLB+6R/year Rehabilitation: 12B+12R Reconstruction: 12B+12R+C
Earth Strategy 2 (ERM2)	ERM2-LT Routine 2: 2B Rehabilitation: 2B+2R Reconstruction: 2B+2R+C	ERM2 -MT Routine 2: 6B Rehabilitation: 6B+6R Reconstruction: 6B+6R+C	ERM2 -HT Routine 2: 12B Rehabilitation: 12B+12R Reconstruction: 12B+12R+C

Regarding budget levels, the minimum maintenance strategy was only defined for the minimum budget level, while the other two strategies were estimated for Low, Medium and High Budget. From this, 21 scenarios were considered in the analysis for each road type, totaling in 42 scenarios (3*ERMin+9*ERM1+9*ERM2 for earth and 3*GRMin+9*GRM1+9*GRM2 for gravel). The type of treatment applied in each scenario varies depending on the budget level considered.

6.2.4 Maintenance Costs

Maintenance costs were estimated for each scenario considering unit prices specified in 2007 by the Ministry of Public Works of Chile (MOP, 2007) for maintenance performed by the agency. These prices were corrected to the present by considering the annual consumer price index (IPC) recommended by the Central Bank of Chile for each year (INE, 2011). Unit prices per treatment are presented in Table 6.4. Prices defined by the MOP are provided in terms of materials and occasional replacement of equipment parts. Detailed estimation of treatment costs per budget level are presented in Appendix C.

Table 6.4 Maintenance Treatment Costs

Maintenance Treatment	UNIT	CAD$
Local Gravel/ Pothole Patching	m^3	15.58
Light Blading	km	89.79
Culvert Replacement	m	296.49
Gravel Application	m^3	22.69

Upgrade treatments and costs were also estimated from the available literature. These are special projects for improving the surface standard from earth to gravel, and from gravel to surfacing or double treatment. These should be evaluated under a project level analysis, recommended when high traffic levels justify upgrading the roads surfacing. Upgrade costs are presented in Appendix C.4.

6.3 Development of Optimal Maintenance Standards

6.3.1 Definition of Maintenance Standards

Maintenance policies should consider the application of treatments within suitable service levels, subject to the effects of each treatment on the functional and structural condition of roads. Maintenance standards can be defined as maintenance strategies where threshold values are defined for the application of the different types of treatments considered. Standards may vary depending on agencies strategic policies, such as desired service level of the network, access and mobility standards, type of network, among others.

From developed curves, which are presented in Figures 5.2 and 5.3, three deterioration stages were identified for earth and gravel roads, as discussed in section 5.3.6. The type of maintenance considered during the life cycle of a road should be defined in terms of the deterioration types and severities observed. It is expected that routine maintenance should be applied at the first deterioration stage, where UPCI values drop due to the appearance of functional related deteriorations such as gravel loss, corrugations and raveling. Rehabilitation should be considered in a second stage of deterioration, where structural problems start to appear, such as rutting and pothole formation. Rehabilitation should be applied as a corrective policy to avoid severe structural deterioration that may cause impassability. Finally, reconstruction or emergency maintenance should be applied in those sections presenting accessibility problems caused by severe structural problems such as deep potholes, rutting and erosion.

Threshold levels for each maintenance type were defined considering the three deterioration phases discussed previously. UPCI trigger values were first obtained from the statistical analysis of maintenance applications, considering maximum and minimum application values and treatments effects on roads condition, as presented in Chapter 5. These were then contrasted to trends observed in performance curves (Figures 5.2 and 5.3), and adjusted accordingly. Finally, threshold levels for routine maintenance, rehabilitation and reconstruction were defined. Performance "jump" values were defined per treatment type and budget levels, subject to the quality and effectiveness of each maintenance treatments. Recommended application ranges per strategy considering threshold values and performance "jump" values per budget level are presented in Table 6.5 and 6.6, for gravel and earth roads respectively.

Table 6.5 Application Ranges and Performance Jump Values for Gravel Roads

		UPCI Jump Values per Budget Level			
Maintenance type	Application Ranges (UPCI)	Minimum	Low	Medium	High
RMin: Minimum Routine	10-4	1.0			
RM1: Local Gravel and Minimum Grading	10-5.5		1.5	2.5	3.0
RM2: Routine Grading	10-5.5		2.5	3.5	4.0
Rehabilitation	4-5.5	4.0	4.0	5.0	5.5
Reconstruction	<4	5.0	5.0	6.0	6.5

Table 6.6 Application Ranges and Performance Jump Values for Earth Roads

		UPCI Jump Values per Budget Level			
Maintenance type	Application Ranges (UPCI)	Minimum	Low	Medium	High
RMin: Minimum Routine	10-4	1.0			
RM1: Local Gravel and Minimum Grading	10-5		1.5	2.5	3.0
RM2: Routine Grading	10-5		2.5	3.5	4.0
Rehabilitation	4-5	3.5	3.5	4.5	5.0
Reconstruction	<4	5.0	5.0	5.75	6.25

When a road is in a relatively good condition prior to the need for maintenance, the maximum condition level achieved will depend on the type of treatment considered. It is commonly observed, for example, that the application of routine maintenance does not warranty a maximum condition equivalent to a new road. This trend is observed in paved and unpaved roads, and has been considered by most models and management systems (Paterson, 1991; Kerali, 1991; Kerali, 2000; Provencher, 1995). Maximum condition levels achieved by maintenance strategies have been defined for the study, based on the analysis of condition and maintenance data. Table 6.7 presents maximum values considered per strategy for gravel and earth roads.

Table 6.7 Maximum Condition Levels per Strategy

	UPCI Maximum Values per Budget Level			
Maintenance type	Minimum	Low	Medium	High
RMin: Minimum Routine	8.00			
RM1: local gravel and minimum grading		8.25	9.25	9.50
RM2: Routine Grading		8.25	9.25	9.50
Rehabilitation	8.75	8.75	9.50	9.75
Reconstruction	9.00	9.00	9.75	10.00

Final considerations regarding the effectiveness of minimum and routine maintenance are their effectiveness over time after successive treatment applications. In particular, studies have demonstrated that when a constant blading frequency is considered for a certain traffic volume, a long term average roughness level is reached. During the development of HDM performance models, Paterson (1991) demonstrated that the effectiveness of blading decreases until this average level is reached. These findings were proved in the field, where it was observed that the effectiveness of blading decreased when no other treatment was considered. Given this, it was considered that for the analysis of minimum and routine maintenance their effectiveness in terms of UPCI "jump" was reduced in 5% starting from the second application when no rehabilitation was considered. The 5% was considered as a realistic approach for a 10 year analysis period (20 semi-annual cycles), where the successive applications of routine maintenance would be ineffective if no rehabilitation is performed to improve roads structure and drainage.

6.3.2 Cost-Effectiveness Analysis of Proposed Maintenance Standards

Cost effectiveness is calculated as effectiveness divided by the life-cycle cost of each strategy. Effectiveness can be defined as the area under the performance curve and above a minimum service level, which is weighted by section length and traffic (Haas, 1994; Wei, 2004). This area can be interpreted as the benefits of road users given the performance of a road in the long term. A minimum service level for rural roads can be defined as the minimum condition that ensures all-weather access. From available data and analysis of developed performance curves (Figures 5.2 and 5.3), this is observed for UPCI values above 4. Below this level of service roads require reconstruction or emergency maintenance. Effectiveness is estimated considering the following formula:

$$Effectiveness = \left\{ \sum_{Treat.Semi-Year}^{UPCI_T \geq UPCI_M} (UPCI_T - UPCI_M) - \left(\sum_{UPCI_N \geq UPCI_M}^{Treat.Semi-Year} (UPCI_M - UPCI_N) \right) \right\} \times AADT \times Length\ of\ Section \tag{6}$$

Where:

$UPCI_T$ = UnPaved Road Condition Index (UPCI) after treatment for each year until UPCI minimum is reached;
$UPCI_M$ = minimum acceptable condition level (UPCI<4);
$UPCI_N$ = yearly UPCI from the needs year to the treatment year;
AADT = annual average daily traffic; and
Length of section = road length.

Given that the comparison between maintenance strategies was performed under the same basis, considering 1 km of road and under the same traffic condition, the last term of Equation 6 can be eliminated. In addition, the analysis considered a semi-annual period given the climate seasonal effects on roads deterioration, therefore, the areas per period were estimated as the mean values observed within a six-month cycle. The minimum acceptable UPCI value was considered as 4. With this, effectiveness calculation was estimated in terms of unit effectiveness and the formula was simplified as follows:

$$Unit\ Effectiveness = \left\{\sum_{n=1}^{20}\left(\frac{(UPCI_B+UPCI_A)}{2}\right) - 4\times 20\right\} \quad (7)$$

Where:

n= Semi-annual cycle of six months for a 10 year analysis period (n= 1, 2, 3…20);
UPCIB = Condition immediately before applying a treatment;
UPCIA = Condition immediately after applying a treatment.

Effectiveness calculations for each maintenance strategy considering three different climates are presented in Appendix G.1 and G.2 for gravel and earth roads respectively.

For the calculation of the life-cycle costs of each strategy, the present worth of costs was considered (PWC). The discount rate defined for the analysis was 8%, based on the practice of the MOP and recommendations from agencies in developing countries (Almonte, 2001; Mideplan, 2004). Present worth of costs was calculated considering all treatments applied within the life cycle of a road under each specific strategy. A life cycle analysis period of 10 years and a semi-annual basis was considered. Equation 8 presents the formula considered.

$$PWC = \sum_{n=1}^{20}\frac{1}{(1+i)^n}\times Treatment\ cost\ (n) \quad (8)$$

Where:

PWC = Present worth of costs;
n= Semi-annual cycle of six months for a 10 year analysis period (n= 1, 2, 3…20);
i = Discount rate, 8%;
Treatment cost (n) = Costs of treatments considered in the strategy applied in cycle n

Having the Effectiveness and PWC for each strategy Cost Effectiveness (CE) was calculated following Equation 9, as recommended by the literature (TAC, 1997; Haas; 1994)

$$CE = Effectiveness/PWC \qquad (9)$$

Cost Effectiveness of the three maintenance strategies (RMin, RM1 and RM2) were calculated for all scenarios included in the experiment factorial, considering: four budget scenarios (minimum, low, medium and high), three traffic levels (low, moderate, high), two types of structures (earth and gravel) and three climates (dry, Mediterranean, humid). From the comparison between budget levels, unfeasible scenarios, where PWC of minimum budgets were higher than low budgets, were detected and eliminated from the analysis. Results are presented in Appendix G3 and G4, for gravel and earth roads respectively. Unfeasible scenarios were observed only in earth roads, where minimum maintenance caused access problems (UPCI < 4), which required the application of several reconstructions during the whole life cycle. These cases are marked in red in the tables presented in Appendix G.4.

6.3.3 Optimal Maintenance Standards

Marginal Cost Effectiveness (MCE) is defined as a heuristic technique used to obtain near optimal maintenance standards for specific conditions. The cost effectiveness analysis method was used to compare the different strategies defined per scenario (Haas, 1994). This method has been largely used by several agencies to as a basis for priority programming.

MCE is calculated as the ratio obtained from dividing the difference between the effectiveness of a basis strategy (E_{basis}) minus the effectiveness of an alternative strategy (E_{alt}), divided by the difference of the PWC of the basis (PWC_{basis}) minus the PWC of the alternative (PWC_{alt}). This is presented in Equation 10.

$$MCE = (E_{basis}-E_{alt})/(PWC_{basis}-PWC_{alt}) \qquad (10)$$

The most cost effective strategy is selected from the analysis. If MCE is negative or if the effectiveness of the alternative is less than the basis, then the basis strategy is selected.

The MCE analysis was considered to identify which strategy was more cost-effective for the low, medium and high budget levels. Given that the minimum strategy is only considered as a basis at a minimum funding level, strategies RM1 and RM2 were included in the analysis. Tables 6.8 and 6.9 present a summary of the MCE analysis and selected strategies per scenario for gravel and earth roads.

Table 6.8 MCE Analysis for Gravel Roads

		Dry Climate			Mediterranean Climate			Humid Climate		
	Budget Level	Low	Medium	High	Low	Medium	High	Low	Medium	High
Traffic										
Low (<100 AADT)	Selected Strategy	GRM2	GRM2	GRM1	GRM1	GRM2	GRM1	GRM1	GRM2	GRM1
	MCE	0.0005	0.0003	-0.00004	-0.0001	0.0002	-0.0001	-0.0005	0.0001	-0.0001
Moderate (100-200 AADT)	Selected Strategy	GRM2	GRM2	GRM1	GRM1	GRM2	GRM1	GRM1	GRM2	GRM1
	MCE	0.0001	0.00006	-0.00001	-0.00003	0.00003	-0.00002	-0.00011	0.00002	-0.00002
High (>200 AADT)	Selected Strategy	GRM2	GRM2	GRM1	GRM1	GRM1	GRM1	GRM1	GRM2	GRM1
	MCE	0.00007	0.00005	-0.00001	-0.00002	0.00003	-0.00001	-0.00008	0.00001	-0.00001

Table 6.9 MCE Analysis for Earth Roads

		Dry Climate			Mediterranean Climate			Humid Climate		
	Budget Level	Low	Medium	High	Low	Medium	High	Low	Medium	High
Traffic										
Low (<50 AADT)	Selected Strategy	ERM2	ERM1	ERM2	ERM2	ERM2	ERM1	ERM2	ERM2	ERM1
	MCE	-0.002	-0.001	-0.001	-0.002	-0.004	-0.001	-0.002	-0.004	-0.001
Moderate (50-100 AADT)	Selected Strategy	ERM2	ERM2	ERM2	ERM2	ERM2	ERM2	ERM2	ERM2	ERM2
	MCE	-0.0003	-0.0001	-0.00005	-0.0004	-0.0005	-0.0002	-0.0004	-0.0005	-0.0002
High (>100 AADT)	Selected Strategy	ERM2	ERM1	ERM1	ERM1	ERM1	ERM1	ERM2	ERM2	ERM1
	MCE	0.0004	-0.0001	-0.00002	-0.0004	-0.0003	-0.00007	-0.0004	-0.0004	-0.00007

From the analysis it was observed that some MCE values were positive, given by higher effectiveness of the basis and lower costs of the alternative. In these cases, the selection of either the most effective or less expensive alternative relies on the road manager. In this research, the alternative presenting the highest effectiveness was selected as the optimal, therefore the basis strategy was defined as the optimal. It was also observed that some MCE values were negative, given by lower effectiveness of the basis and lower costs of the alternative. In these cases, the alternative presented highest effectiveness and was therefore selected as the optimal.

Optimum budget levels were identified from the comparison of cost effectiveness for all budget levels per scenario. From this it was concluded that for gravel roads the optimum funding level for dry climate was the minimum budget and for Mediterranean and humid climates was the low budget. For earth roads the optimum budget level for dry climate was the minimum budget and for Mediterranean and humid climates was the medium budget. Unfeasible minimum funding scenarios in earth roads were observed in Mediterranean and humid climates under low and moderate traffic levels.

Given that traffic volumes are considered in the analysis in terms of AADT, it is recommended that for high volumes of heavy traffic (commonly greater than 20%) the optimal standards for the immediately higher level of traffic be considered. This could be adopted, for example, for seasonal variations on heavy traffic volumes due to harvesting or forestry production. For example, if a gravel road presents low volume traffic of 50 AADT where 30% of the total traffic is trucks, it is recommended to consider maintenance standards for a moderate traffic level.

A summary of the results obtained from the cost-effectiveness analysis is presented in Tables 6.10 and 6.11. Optimum recommended standards per climate and traffic are coloured in light grey in the tables and unfeasible scenarios minimum budget scenarios in earth roads are coloured in dark grey.

Table 6.10 Optimum Standards for Gravel Roads

		Dry Climate				Mediterranean Climate				Humid Climate			
Traffic	Analysis	Min Budget	Low Budget	Med. Budget	High Budget	Min Budget	Low Budget	Med. Budget	High Budget	Min Budget	Low Budget	Med. Budget	High Budget
Low Traffic (<100 AADT)	Optimal Strategy	GRMin	GRM2	GRM2	GRM1	GRMin	GRM1	GRM2	GRM1	GRMin	GRM1	GRM2	GRM1
	Mean UPCI	6.40	7.16	7.74	7.67	6.13	6.24	7.02	6.86	6.06	6.17	6.64	6.49
	Unit Effect.	48	63	75	73	43	125	140	137	41	123	133	130
	PWC CAD$	1556	2359	3538	5994	1556	2203	3538	5994	1603	2203	3538	5994
	CE	0.031	0.027	0.021	0.012	0.027	0.057	0.040	0.023	0.026	0.056	0.038	0.022
Mod. Traffic (100-200 AADT)	Optimal Strategy	GRMin	GRM2	GRM2	GRM1	GRMin	GRM1	GRM2	GRM1	GRMin	GRM1	GRM2	GRM1
	Mean UPCI	6.40	7.16	7.74	7.67	6.13	6.24	7.02	6.86	6.06	6.17	6.64	6.49
	Unit Effect.	48	63	75	73	43	125	140	137	41	123	133	130
	PWC CAD$	4480	7076	10614	17982	4480	6608	10614	17982	4598	6608	10614	17982
	CE	0.011	0.009	0.007	0.004	0.009	0.019	0.013	0.008	0.009	0.019	0.013	0.007
High Traffic (>200 AADT)	Optimal Strategy	GRMin	GRM2	GRM2	GRM1	GRMin	GRM1	GRM1	GRM1	GRMin	GRM1	GRM2	GRM1
	Mean UPCI	6.40	7.16	7.74	7.67	6.13	6.24	6.65	6.86	6.06	6.17	6.64	6.49
	Unit Effect.	48	63	75	73	43	125	133	137	41	123	133	130
	PWC CAD$	7404	11793	17689	29971	7404	11014	17032	29971	7592	11014	17689	29971
	CE	0.89	0.73	0.58	0.33	0.78	1.55	1.07	0.63	0.74	1.53	1.03	0.59

Table 6.11 Optimum Standards for Earth Roads

		Dry Climate				Mediterranean Climate				Humid Climate			
Traffic	Analysis	Min Budget	Low Budget	Med. Budget	High Budget	Min Budget	Low Budget	Med. Budget	High Budget	Min Budget	Low Budget	Med. Budget	High Budget
Low Traffic (<50 AADT)	Optimal Strategy	ERMin	ERM2	ERM1	ERM2	ERMin	ERM2	ERM2	ERM1	ERMin	ERM2	ERM2	ERM1
	Mean UPCI	6.97	7.46	7.84	8.01	6.57	7.00	7.81	7.92	6.53	6.87	7.78	7.87
	Unit Effect.	59	69	77	80	51	140	156	158	51	137	156	157
	PWC CAD$	830	1221	1772	3627	3101	1824	1927	3302	3118	1910	1927	3302
	CE	2.44	1.93	1.48	0.76	0.57	2.62	2.77	1.64	0.55	2.46	2.76	1.63
Mod. Traffic (50-100 AADT)	Optimal Strategy	ERMin	ERM2	ERM2	ERM2	ERMin	ERM2	ERM2	ERM2	ERMin	ERM2	ERM2	ERM2
	Mean UPCI	6.97	7.46	7.79	8.01	6.57	7.00	7.81	8.08	6.53	6.87	7.78	8.06
	Unit Effect.	59	69	76	80	51	140	156	162	51	137	156	161
	PWC CAD$	2991	3663	5836	10880	6841	5472	5780	10978	6968	5730	5964	10978
	CE	1.35	1.29	0.89	0.50	0.51	1.75	1.85	1.00	0.50	1.64	1.78	1.00
High Traffic (>100 AADT)	Optimal Strategy	ERMin	ERM2	ERM1	ERM1	ERMin	ERM1	ERM1	ERM1	ERMin	ERM2	ERM2	ERM1
	Mean UPCI	6.97	7.46	7.84	7.86	6.57	6.60	7.45	7.92	6.53	6.87	7.78	7.87
	Unit Effect.	59	69	77	77	51	132	149	158	51	137	156	157
	PWC CAD$	4977	7325	10635	19024	10406	11850	12815	19814	10823	11460	11560	19814
	CE	1.63	1.29	0.99	0.55	0.67	1.52	1.59	1.09	0.64	1.64	1.84	1.08

6.4 Summary of the Chapter

The experiments and analysis required for the development of the Network Maintenance Module are presented in this chapter. Maintenance treatments and strategies were defined considering recommendations from literature, current state-of-the-practice and data analysis. Standards were defined considering application threshold ranges for routine maintenance, rehabilitation and reconstruction.

The cost-effectiveness analysis method was used to compare proposed strategies under different scenarios. These included the consideration of four budget levels (minimum, low, medium, high), three climates (dry, Mediterranean, humid), three traffic levels (low, moderate, high) and two types of structure (gravel and earth).

Marginal cost effectiveness was considered in the selection of the optimal standard per scenario. Finally the optimum funding level was identified for each scenario. Cases where the minimum budget was higher than the present worth costs for low budget, were eliminated from the analysis.

Chapter 7

Development of the Long Term Prioritization Module

7.1 Introduction

Priority programming aims to define optimal road maintenance plans and programs during a certain analysis period, considering restrictions such as available funding or desired network service level. The life cycle analysis developed for the proposed management system is presented in this Chapter. A sustainable priority indicator had to be developed to rank maintenance projects in terms of a sustainable and a cost-effective approach. The proposed prioritization procedure considers an incremental search technique to select optimal maintenance strategies for available funding. The analysis is made in a short term analysis period, for annual and semi-annual planning, and a long term basis for the life cycle analysis of a network.

The sustainable priority indicator and life cycle analysis are finally integrated to the management system for rural road networks through the Long Term Prioritization Module.

7.2 Development of a Sustainable Priority Indicator

The problem when prioritizing projects and selecting roads to maintain in a rural road network is that not all costs and benefits can be quantified in the economic analysis. The reason for this relates to the calculation of optimal maintenance standards considered in the Network Maintenance Module, and presented in the previous Chapter. These are selected considering a cost-effectiveness method based on roads condition and the present worth of costs of maintenance during the life cycle of roads. The selection of maintenance alternatives is based on an objective method that includes benefits in a non-monetary form. With this, optimal maintenance standards per road are recommended. However, the problem is only partially solved since at the network level projects should also be prioritized in terms of the importance of roads, ideally under a sustainable approach.

Several ranking and multi-criteria analysis methods have been developed to assist managers in prioritizing road networks. These have been developed mostly in terms of experience and subject to local conditions.

A study was conducted in Canada in 2007 for the design of guidelines for surface type selection of unpaved roads. The study considered expert opinion using a Delphi technique (Hein, 2007). A panel of eight experts decided the type of selection factors and their relative importance to rank unpaved networks. As a result, the following factors and weights (indicated in brackets) were defined (TAC, 2012):

1. Traffic volumes adjusted for the presence of commercial vehicles (25).
2. Impact on nearby residents based on the number of residences close to the highway (10).
3. Impact on local business activities based on the presence of five different industries (10).

4. Impact on long distance travel based on the percentage of long distance commercial vehicles (10).
5. Total agency initial and life cycle costs of upgrading a surface-treated pavement (45).

A prioritization method developed in Chile, in 2008, proposed a ranking method which considered economic, social and technical variables for the prioritization of maintenance projects at the network level. The method included:

1. Social Variables (30%): Benefited population (40%), % very poor population (20%) and presence of school (40%)
2. Economic Variables (35%): AADT (25%), Available funding for road (20%) and Type of Economic activities-Agriculture, Fishing, Tourism, Forestry, Mining, Urban (20%), NPV from HDM-4 (35%)
3. Technical Variables (35%): Surface type (25%), Surface condition (35%), Drainage Condition (20%) and Safety (20%)

A third example of ranking method applied for network prioritization was developed in Paraguay for as rural roads project developed by the Ministry of Public Works and Communications with a loan from the Inter-American Development Bank (MOPC, 2009). The method considers spatial, economic, social, technical and environmental factors. The rank is estimated as the sum of normalized values of each aspect, which is estimated as the ratio of the value observed in a road and the maximum value observed for that aspect in the network under study.

The described methods have in common that sustainable aspects have been considered in the prioritization process. However, they lack an objective evaluation method for the selection of most effective alternatives and do not take in consideration the life cycle of roads for long term decision making.

The method proposed in the present research accounts for sustainable aspects, life cycle analysis and objective effectiveness measures. The Sustainable Priority Indicator (SPI) is the result of multiplying the unit cost effectiveness (Unit CE) of the optimal strategy selected for a specific road, the road length, the typical AADT of the road and the proportion of population that lives in the road. With this a long term approach is considered, where cost-effectiveness analysis is performed for the whole life cycle of a road. In addition, objective measures of technical, social and economic aspects are being considered. In particular, most of the sustainable aspects proposed by other methods are being incorporated in the proposed indicator. The SPI is estimated with the following formula:

$$\text{SPI} = \text{Unit CE} \times \text{Road Length} \times \text{AADT} \times \%\text{Population} \quad (12)$$

Where:

SPI = Sustainable Priority Indicator;

Unit CE = Unit cost effectiveness of optimal strategy for the road;

Road Length = Length of the road measured in kilometres;

AADT = Average Annual Daily Traffic

% Population = Proportion of population living in the road, obtained as the percentage of population living in a radius of one kilometer from the road compared to the total rural population living in the network under study.

The two most critical social aspects for rural roads management, accessibility and mobility, are objectively accounted by the method. Accessibility is being considered in terms of the proportion of population living in a road and by considering minimum UnPaved Roads Condition thresholds in the cost-effectiveness analysis. Mobility is being considered in terms of traffic volumes and in terms of acceptable service levels defined in maintenance strategies which are considered in the cost-effectiveness analysis. The alternative of including the Rural Access Index as a possible social indicator was discarded. This was explained by the possible bias that could cause in priority planning by privileging access of basic roads without considering the context of mobility and condition of the whole network (Raballand, 2010).

The proposed indicator has the flexibility to be adapted to other conditions than the ones presented in the study. In particular, the proportion of population can be replaced by other sustainable indicator defined in terms of percentage or a ratio. It is recommended that for this, multicriteria analysis techniques based on participatory methods should be considered by agencies in charge of rural networks. It is advised that the life cycle cost-effectiveness analysis, traffic and roads length should be accounted as a basis for the prioritization procedure.

7.3 Prioritization Procedure

The technique selected for the prioritization procedure can be defined as an incremental sustainable cost-effectiveness method, based on the proposed indicator (SPI). The procedure involves searching cost-effective road projects for the short and long term for the life cycle analysis of a road network, considering the optimal maintenance standards included in the Network Maintenance Module as a basis. For this, the procedure begins with the calculation in a one-cycle basis the net present cost of maintaining the network under the four budget levels included in the maintenance standards. This analysis is carried out per road, considering the most cost effective strategy defined for each specific scenario.

For the short term analysis, the user defines any funding level above the minimum budget, to ensure a basic access standard for the cycle under study. The user is advised on the optimum budget level recommended for the scenario. A base budget is defined, which is the budget level immediately below the funding selected by the user. The remaining funding, which is the difference between the available funding and the base budget, is considered in the prioritization. For this, the SPI of each road is calculated and the network is ranked starting from the highest SPI. Roads are selected for improvement to the budget level immediately above the base budget. With this, the approach is to select better quality treatments for priority roads. The system searches for candidate roads considering the priority rank. The improvement of priority roads is performed until the remaining funding is exhausted. Any possible difference between used budget and available funding can be moved forward to the next cycle or year. The process is repeated for the life cycle analysis of a road network, considering an annual or a semi-annual basis, as it has been recommended in the study.

The prioritization procedure has been programmed in visual basic and can be easily operated in an Excel Worksheet. The phases of the management system considered in the prioritization procedure are summarized in Figure 7.1.

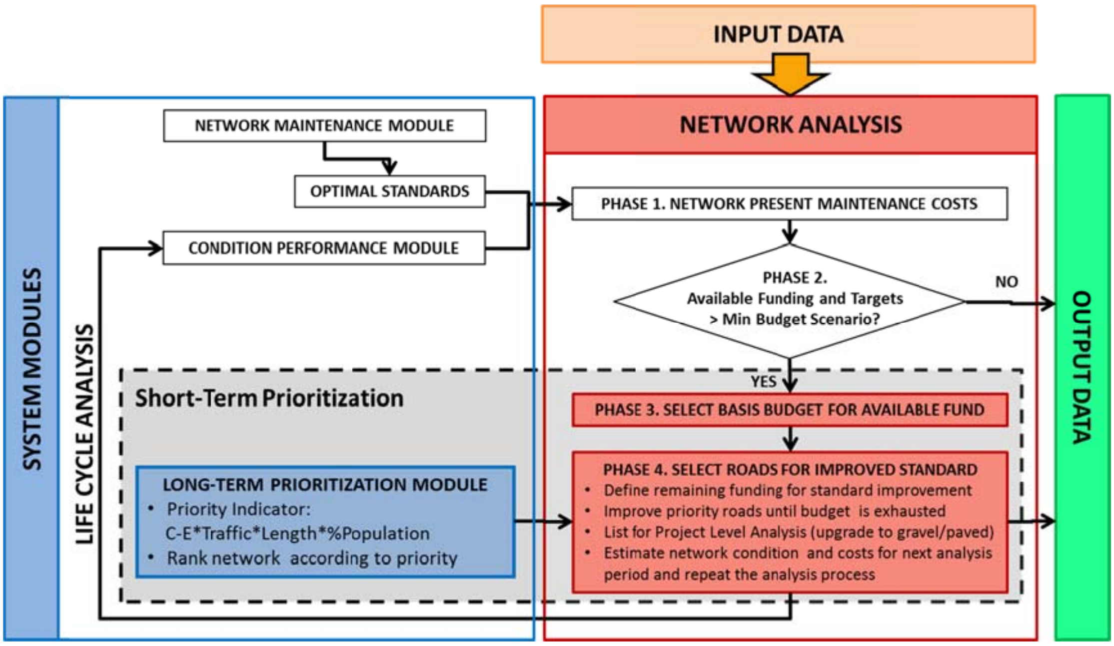


Figure 7.1 Short and Long Term Prioritization Procedure

The short term prioritization (shaded in the figure) involves the last two phases of the network analysis interface, Phase 3 and Phase 4, and the Long Term Prioritization Module. For the life cycle analysis, the prioritization requires the interaction of the three System Modules and all phases of the Network analysis interface. A macro with the performance models had to be programmed so that the roads condition could be updated after each cycle.

The analysis considers input data defined by road user, which includes: roads inventory data, network condition data and strategic level data. The algorithm considered for the visual basic program, for short term prioritization and life cycle analysis, is described as follows:

1. From Input Data and Network Maintenance Module, determine network present maintenance costs considering optimal standards for Minimum (B_1), Low (B_2), Medium (B_3) and High (B_4) Budgets;
2. Identify optimum budget level considering network traffic, climate and roads structures;
3. Compare available funding to Minimum Budget (B_1), if insufficient, strategic standards should be adjusted. If sufficient go to next step;
4. If Minimum Budget (B_1) ≥ Available Funding, determine base budget for available funding. Base budget is selected as follows:

$$B_i \leq \text{Available Funding} < B_{i+1} \quad (13)$$

   Where:

   B_i = Base Budget;

   i = Budget level (1=Minimum, 2=Low, 3=Medium, 4=High);

5. Define remaining budget for maintenance standard improvement given by:

$$\text{Remaining Funding} = \text{Available Funding} - B_i \quad (14)$$

   Where:

   B_i = Base Budget;

   i = Budget level (1=Minimum, 2=Low, 3=Medium, 4=High);

6. From Long Term Prioritization Module, estimate the Sustainable Priority Indicator (SPI) per roads as defined in Equation 12;
7. Rank network from 1 to n (where n = number of roads in the network) according to sustainable priority, starting from the road with highest SPI;
8. Select roads with highest SPI and apply improved optimal maintenance standard considering Budget Level B_{i+1}. Improve priority roads to B_{i+1} optimal standard until remaining funding is exhausted or until remaining funding is insufficient to improve priority roads to B_{i+1} optimal standard;
9. Identify roads presenting high traffic volumes, above 200 AADT. Recommend list for project level analysis for possible upgrade from gravel or earth to paved standard;
10. For earth roads or weak structure roads presenting high traffic volumes above 200 AADT, and that are not selected for project level analysis, consider upgrade to gravel standard;
11. Calculate network condition and costs for the analysis cycle;
12. Estimate network condition for next analysis cycle with the Condition Performance Module. Update costs and traffic for next cycle considering discount rate and traffic growth rate obtained from Input Data;

13. Forward to next analysis cycle remaining funding if available funding was not exhausted;
14. Repeat the analysis process starting from Phase 1 and considering as input data condition, traffic and maintenance costs obtained from stage 12.

The prioritization algorithm has been integrated to the management computer tool developed in the research, which is described in detail in Chapter 8.

7.4 Summary of the Chapter

Optimal standards per road were defined in the Network Maintenance Module and presented in Chapter 6. For the successful maintenance of roads at the network level, however, the network has to be sustainably prioritized in order to define suitable maintenance standards according to roads priority. For this, a sustainable priority indicator has been developed which considers for each roads the cost-effectiveness of selected optimal standards, traffic, length and proportion of rural population living in the road.

Short term prioritization procedure and life cycle analysis has been developed, which considers the proposed indicator to rank roads in the network. Roads presenting high priority are selected for standard improvement. A prioritization algorithm was defined and programmed in Visual Basic. From its application within the proposed management system, networks are prioritized and maintained accordingly in the short and the long terms during the whole life cycle of the network.

Having all System Modules developed, namely the Condition Performance Module, Network Maintenance Module and the Long Term Prioritization Module, the final stage for the development of the proposed management system involves the integration of all system components in a user-friendly computer tool.

Chapter 8
Application and Validation of the Sustainable Management System for Rural Road Networks

8.1 Introduction

Six experiments were carried out for the development of the proposed management System Modules. Previous chapters presented the analysis of each experiment, resulting in the development and validation of the Condition Performance Module, Network Maintenance Module and Long Term Prioritization Module.

The current chapter presents the analysis and outcomes of a seventh experiment, which aims to apply and validate the proposed management system in rural road networks. For this, the first task was to develop an easy-to-use computer tool that integrates all system components and modules. The system was then applied and validated for two rural networks located in Chile and Paraguay. A sensitivity analysis was finally carried out to validate the management system, where the different variables considered in the System Modules were assessed. Findings from the analysis are finally presented and recommendations are made to improve the proposed sustainable management system for rural road networks.

8.2 Development of a Computer Tool

8.2.1 Characteristics of the Computer Tool

The computer tool developed in this research is intended to integrate the system components and display them in a friendly interface for potential users. The tool was programmed in Visual Basic, considering Microsoft Excel interface. The computer tool considers the four system components: Input Data, System Modules, Network Analysis Interface and Output Data. The user primarily interacts in the Network Analysis Interface; however, information of other system components is accessible and can be modified by users. The main characteristics of the tool are:

1. Adoptable: The tool can be easily and intuitively operated given that no complex procedures have to be followed for its use. Required input data is minimal and can be easily obtained from available information or data collected in the field. The Excel interface is widely known and familiar to potential users, opening the chances to be adopted by local road agencies in developing countries.
2. Adaptable: The tool considers all system scenarios, including: climates, budget levels, road structures and traffic volumes. It can be calibrated to local conditions where the user is able to modify input data and variables. Processes and macros programmed in Visual Basic are visible to users and can be adjusted if desired.
3. Efficient: The iteration process considered for the life cycle analysis is fast and simple. As an example, a network of 40 sections takes less than a minute to be analysed.

4. Cost-effective: The analysis performed with the tool considers a cost-effective approach for the selection of optimal standards per road and for the long term prioritization of the road network.
5. Effective outputs: Reports for the strategic and network management levels are obtained as an output of the analysis. For the strategic level, where information is accounted to the government and the public. Summarized data of roads condition and required funding are obtained on a short term and long term basis. For the network level, where maintenance programs should be defined, detailed data per road is obtained. This includes: list of maintenance treatments per road per year, roads condition per road per year and required funding per road per year. In addition, graphs with summarized data of the network condition and roads performance for the whole life cycle are displayed.
6. Auto-calibrated: The Network Condition Module can be calibrated from available input data. For this, a new network can be simulated considering different maintenance strategies. From the short term analysis, roads condition and present worth of costs are obtained. From the life cycle analysis, the whole life cycle effectiveness for proposed strategies is calculated. Having net present worth of costs and effectiveness, cost-effectiveness values can be obtained for the proposed strategies. If the new strategies are more cost-effective than available strategies these can replace optimal maintenance standards included in the Network Maintenance Module.
7. Integrated: The tool integrates all system components and modules, and is able to interact with other management levels. Output data from the strategic level is used in the analysis at the network level. Outputs from the network analysis serve as feedback to improve strategic policies and as input data for the project level analysis.

8.2.2 Network Analysis Process

The computer tool considers the same information flow and analysis process as the management system. The main difference between both is that information required for the management process is considered as part of the system but is an input for the computer tool. With this, models, procedures and methodologies are particular to the system.

The computer tool integrates the four components defined for the system: Input Data, System Modules, Network Analysis Interface and Output Data. For each of the system components and modules a separate worksheet has been included in the computer tool. The tool is centered on the Network Analysis Interface, which interacts with the other three system components. The network analysis process is a synopsis of the proposed management system. The process considers seven steps, which are summarized in Figure 8.1 and described as follows.

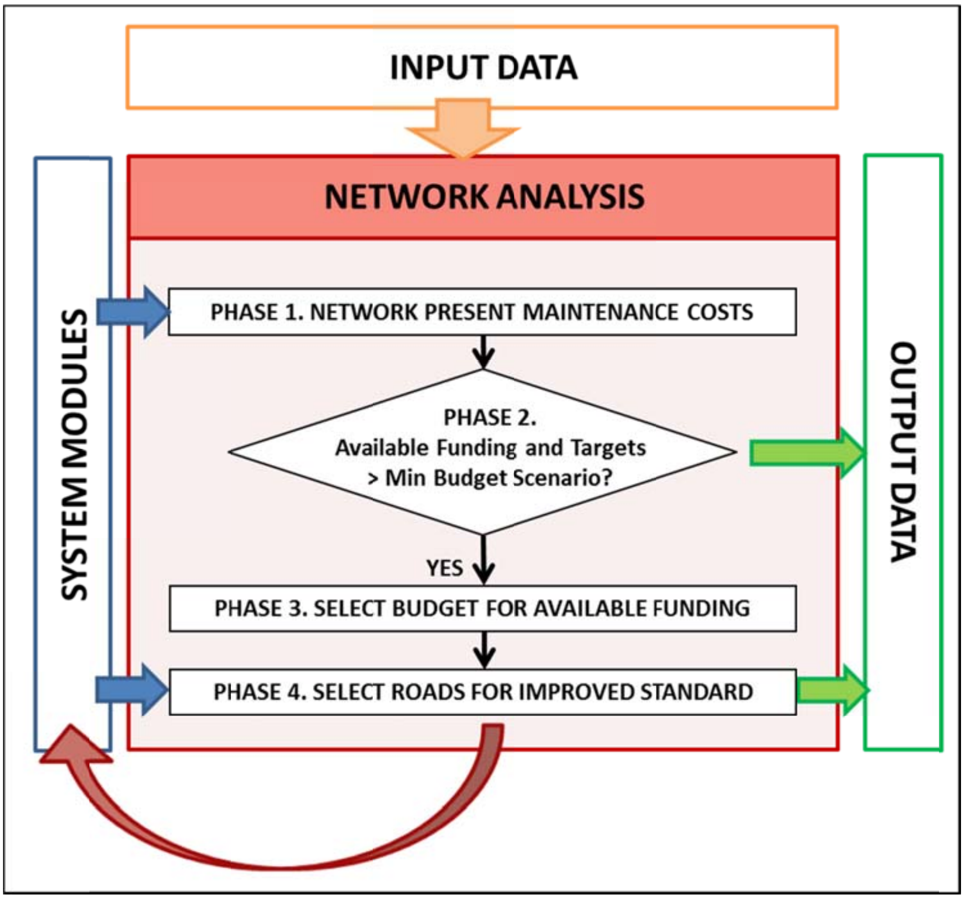


Figure 8.1 Network Analysis Process

1. User enters Input Data in the "Data Worksheet". This should include at least the following information:
   - Inventory Data: roads name and code; roads length; roads surface type (earth or gravel) or structure type (weak or strong); population living per road; traffic volumes per road; traffic growth rate; previous maintenance activities; type of climate (dry, Mediterranean or humid).
   - Network Present Condition: Condition per road obtained from field evaluations performed in the field following the UPCI methodology (MOP, 2008; Chamorro, 2009)
   - Strategic Level Data: Minimum UPCI value to warranty basic access (if other than 4 as predefined in the system); analysis period and cycle; discount rate for the analysis cycle.
2. User enters possible modifications to the System Modules. This should only be considered if the network under study has differences to predefined conditions of System Modules.

Adjustments to System Modules require prior calibration for the successful analysis of the network. Possible data to be adjusted includes:

- Condition Performance Module: Adjustments to performance curves given by new climate types or new road structures; adjustments to effects of maintenance in roads condition and adjustments to effectiveness of routine strategies (predefined as 95%). For the calibration of performance curves and effects of maintenance it is recommended to collect data for at least one year considering a minimum of three field evaluations and develop new models as presented in Chapter 5.
- Network Maintenance Module: Adjustments to traffic volumes, treatment costs, maintenance strategies, effectiveness of maintenance frequencies, budget levels and threshold values considered in maintenance standards. Adjustments to the Network Maintenance Module and the Condition Performance Module require reassessment of cost-effectiveness values for the new condition. As described in Chapter 7, these can be calibrated with the use of the developed algorithm included in the tool.
- Long Term Prioritization Module: Sustainable Priority Indicator (SPI) and the prioritization procedure can be adjusted to local conditions. As described in Chapter 7, this indicator can incorporate new variables for the sustainable prioritization of a network, however, it is recommended to consider at least the cost-effectiveness of optimal maintenance standards, roads length and traffic.

3. The tool calculates network present maintenance costs and network condition for the analysis cycle, based on data entered in the previous steps. Optimal maintenance costs per budget level and optimum budget level are displayed in the Network Analysis Interface worksheet as reference for the first analysis cycle.
4. User enters available funding to the Network Analysis Interface worksheet. If the entered funding is less than the minimum funding level, the tool displays an "Invalid Entry" advice.
5. The tool calculates for the entered funding the Base Budget, which will be the basic maintenance that roads in the network will have if they are not improved to a higher standard after the prioritization procedure.
6. If available funding is a valid entry, the user clicks the "Run" button to perform the life cycle analysis. The iterations for the long term prioritization are made following the algorithm described in Chapter 7.
7. Output data obtained from the network analysis is displayed in the "Output Data" worksheet, this considers:
    - Table with the maintenance program and condition per road for each semi-annual cycle for the complete analysis period.
    - Graphs displaying the condition per road and network for the complete analysis period.

- Table with total funding required for the network maintenance for each semi-annual cycle for the complete analysis period.
- List of roads requiring project level analysis, which are possible candidates for pavement upgrade.

Appendix H presents images of the computer tool interface. The outputs obtained from the analysis of two case studies are presented in the following section.

8.3 Application and Validation of the Management System and Computer Tool

Case studies applied in Chile and Paraguay were considered for the validation of the management system and computer tool. Detailed data of the network were presented in Chapter 4 and Appendix E.

8.3.1 Chile Case Study

8.3.1.1 Analysis Process

The analysis process considered the seven steps presented in Figure 8.1.

1. Input Data:
    - Network characteristics and present condition data are illustrated in Table 8.1. From the complete network, four earth roads were not assessed for the case study, which explains differences with Tables 4.7 and 4.8 presented in Chapter 4. The proportion of population per road was obtained from the Municipality and confirmed during field evaluations. Given that the network is located in an undulated area, it was estimated in terms of all the population living in the vicinity of the road under study, considering a radius of maximum five kilometers.
    - Climate was defined as Mediterranean, presenting mean monthly precipitations ranging between 20 mm and 200 mm depending on the season.
    - Minimum UPCI of 4 was defined to warranty 100% basic access.
    - Analysis period: six-month short term analysis cycles and 10 year life cycle analysis period.
    - Discount Rate of 8% was considered.
    - Maintenance costs provided by the MOP were considered in the analysis.

2. System Modules: No changes were included to the System Modules, given that performance models, recommended maintenance standards and long term prioritization procedure are applicable to the network under study.

Table 8.1 Computer Tool Input Data: Chile Case Study

Road Data						Condition Data	
Section Code	Road Length (km)	Surface Type	Traffic AADT	Total Population	% Population	UPCI	Condition
1	0.550	Earth	4	4	0.1%	4.9	Regular
2	13.900	Gravel	100	210	3.3%	8.3	Very Good
3	2.000	Gravel	30	44	0.7%	6.1	Good
4	2.800	Earth	6	28	0.4%	7.1	Good
5	1.400	Earth	14	30	0.5%	2.1	Very Poor
6	0.400	Earth	10	21	0.3%	7.6	Good
7	0.500	Earth	10	30	0.5%	6.7	Good
8	9.700	Gravel	70	560	8.7%	9.5	Very Good
9	2.000	Earth	14	75	1.2%	7.7	Good
10	0.850	Earth	8	10	0.2%	4.4	Regular
11	5.000	Earth	12	20	0.3%	5.4	Regular
12	1.500	Earth	30	40	0.6%	4.0	Regular
14	4.000	Gravel	50	80	1.2%	7.7	Good
15	7.700	Gravel	100	648	10.0%	7.1	Good
16	3.300	Gravel	30	40	0.6%	3.4	Poor
17	1.100	Earth	6	20	0.3%	5.6	Very Poor
18	1.700	Earth	6	16	0.2%	5.8	Good
19	3.200	Gravel	20	36	0.6%	8.3	Very Good
20	5.800	Gravel	40	80	1.2%	7.7	Good
21	11.700	Gravel	80	320	5.0%	9.5	Very Good
22	6.800	Earth	40	105	1.6%	7.1	Good
25	1.200	Earth	16	6	0.1%	7.6	Good
26	11.200	Gravel	60	120	1.9%	8.4	Very Good
27	3.000	Earth	20	52	0.8%	8.9	Very Good
28	5.300	Gravel	80	400	6.2%	7.0	Good
30	3.000	Earth	30	120	1.9%	9.2	Very Good
31	2.000	Earth	6	20	0.3%	6.3	Good
32	5.400	Earth	60	200	3.1%	6.2	Good
33	1.600	Earth	30	80	1.2%	6.7	Good
34	10.200	Gravel	60	260	4.0%	5.0	Regular
36	4.900	Gravel	40	100	1.5%	9.2	Very Good
37	15.900	Gravel	220	1000	15.5%	6.2	Good
38	15.900	Gravel	260	1000	15.5%	5.9	Good
39	11.000	Gravel	100	680	10.5%	6.3	Good
Network	**Total length: 176.500**	**Gravel: 16 Earth: 18**	**Mean AADT: 52**	**Total Pop: 6,455**	**100%**	**Mean UPCI: 6.7**	**Mean Condition: Good**

3. Required funding for each budget level was calculated for the first analysis period by the tool and is presented in Table 8.2. The optimum budget level, in terms of cost-effectiveness and considering the present characteristics of the network, was defined as the Medium Budget for gravel and earth roads. This may be considered by the user as a reference to select the available funding level.

Table 8.2 Required Funding per Budget Level: Chile Case Study

Required Funding	CAD$
Minimum Budget	21,162
Low Budget	33,183
Medium Budget (optimum)	51,050
High Budget	268,714

4. Available funding level: the MOP assigns an annual budget of CAD$ 240,000 to maintain the network, therefore, a semi-annual fund of CAD$ 120,000 was considered for the analysis per cycle. Funding is available for upgrading earth roads to gravel roads when traffic volumes exceed 200 AADT. Gravel roads exceeding 300 AADT are evaluated at the project level for upgrading to sealed standard.
5. Given that the available funding was higher than the minimum budget level the analysis continued.
6. The computer tool selected the Medium Budget as the Base Budget for gravel and earth roads. As presented in Table 8.2, the available funding is between the Medium and High budgets, where the analysis considers the optimum budget as basis.
7. Given that the available funding was a valid entry, the life cycle analysis was performed for a ten year period (20 semi-annual cycles).
8. Output data obtained from the network analysis is presented in Appendix I. A summary of network condition performance and maintenance costs are presented in Figures 8.2 to 8.5.

8.3.1.2 Analysis of Results

a) Condition Performance

The case study applied in Chile is an example of a rural road network in a high-income developing country, where basic access and mobility can be warranted for the long term. As targeted at the strategic level, 100% accessibility policy was successfully implemented as no road presented a UPCI value below 4.

From Figure 8.2 it is observed that gravel and earth roads were maintained in good condition during the life cycle, as defined by the UPCI methodology and presented in Chapter 4. The network presented a mean UPCI of 6.7, maintaining its mean initial condition and ensuring mobility to road users along the life cycle. The gravel network presented a mean UPCI of 6.8 and the earth network a mean UPCI of 6.5. The good mean condition obtained from the analysis is explained by the fact that High to Medium Budget maintenance standards were affordable with the available funding.

It is observed that the selected 10 year analysis cycle was realistic. The complete deterioration cycle of earth roads was captured, where the roads had to be rehabilitated and reconstructed after reaching a minimum acceptable condition. The complete deterioration cycle of gravel roads was also detected. In the long term the gravel road network does not decline below a UPCI value of 5.5, to ensure mobility in roads presenting higher traffic volume. The UPCI threshold of 5.5 is the minimum acceptable level for routine maintenance where structural problems are starting to appear.

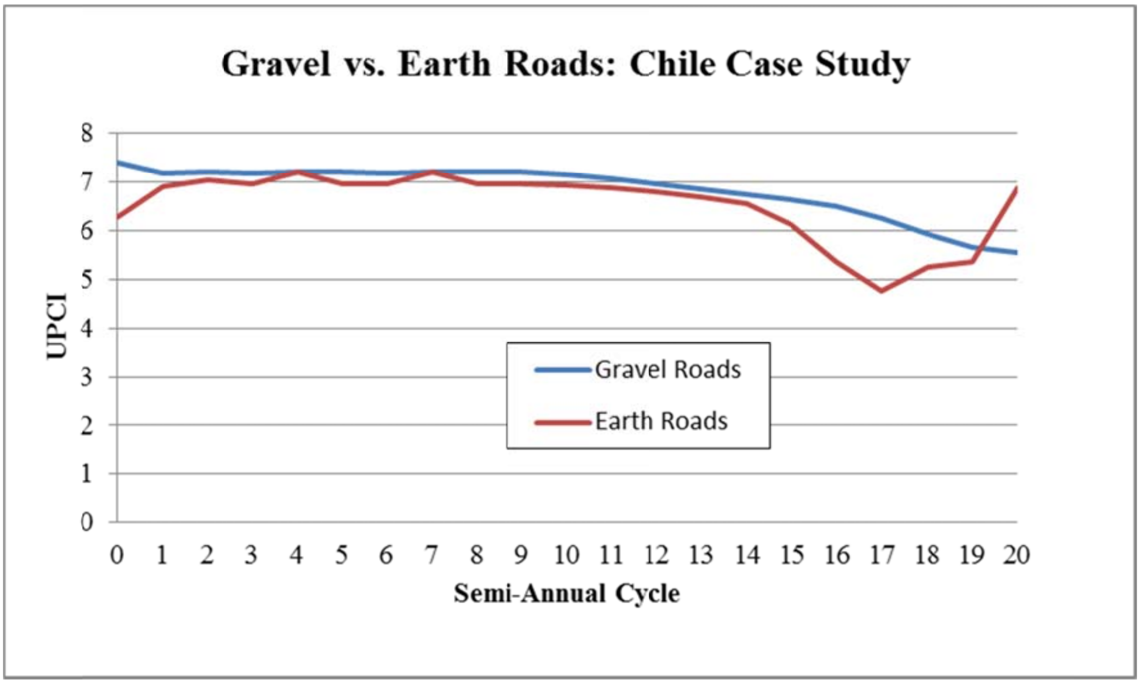


Figure 8.2 Gravel vs. Earth Roads Performance: Chile Case Study

Figures 8.3 and 8.4 present the effects of funding levels on roads condition for gravel and earth roads, respectively. From the 34 roads evaluated, 20 roads were maintained with a High Budget standard (13 gravel roads and 7 earth roads) and 12 roads were maintained with a Medium Budget standard (1 gravel road and 11 earth roads). Two roads, test sections 36 and 37, presented volume traffics above 300 AADT during the first year of analysis. These roads were recommended for pavement upgrade after a detailed project level analysis and were eliminated from the network analysis after the second year.

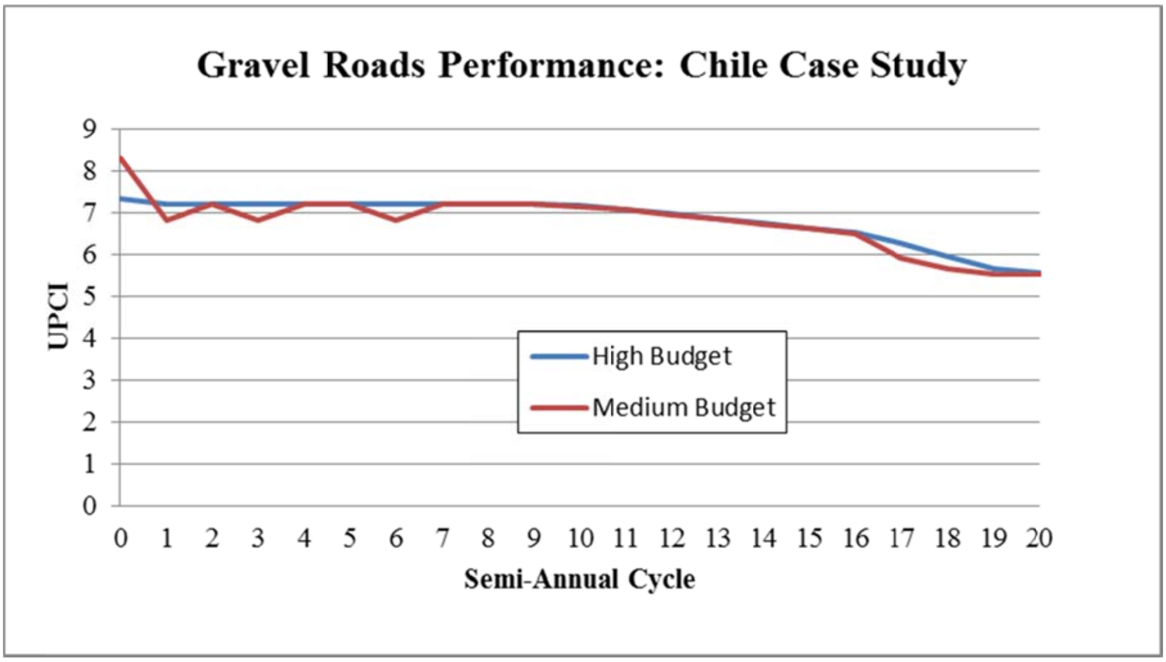


Figure 8.3 Gravel Roads Performance: Chile Case Study

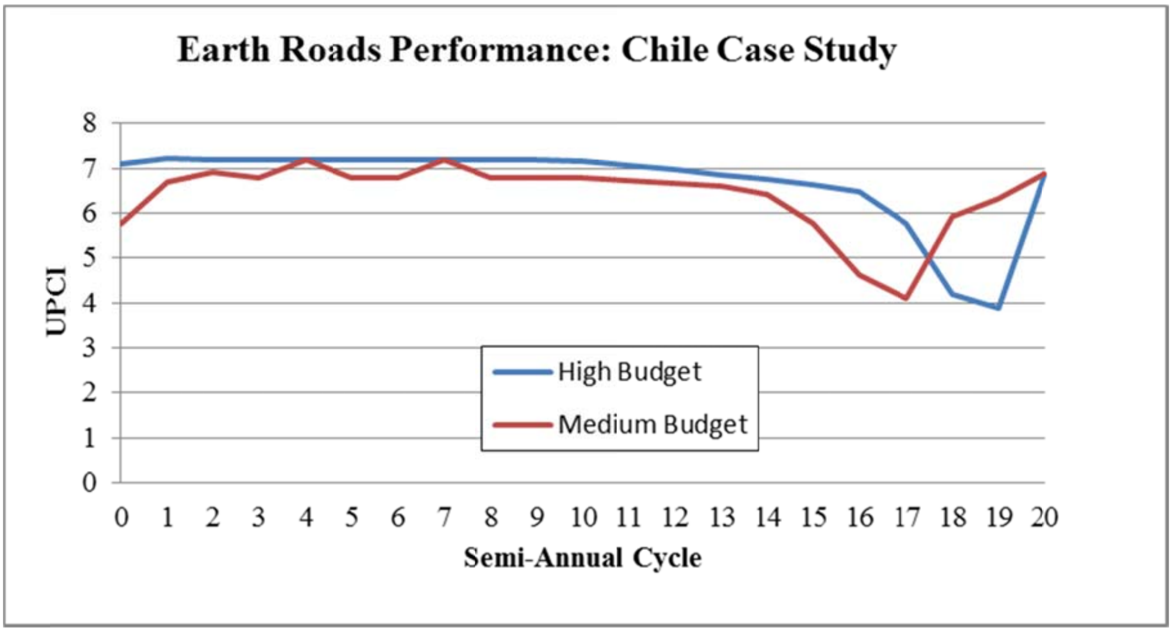


Figure 8.4 Earth Roads Performance: Chile Case Study

Network long term condition performed as expected according to field observations and reviewed literature. A constant condition of a mean UPCI value of 7 was observed for the first six to seven years of analysis for gravel and earth roads. A deterioration phase was then observed in both cases. A gradual deterioration starting in the sixth year was observed in gravel roads. As presented in Figure 8.3, the condition drops from a mean UPCI value of 7 to a mean value of 5.5 at the tenth year. Earth roads, however, presented an accelerated deterioration phase starting at the seventh year. In the case of roads maintained with a medium budget, the minimum condition (UPCI = 4) was reached during the eight year of analysis. Earth roads maintained with a high budget reached the minimum condition during the ninth analysis year. In both cases this triggered reconstruction strategies, which in the case of high maintenance standards was delayed in one year. Reconstruction is evidenced in the curves by the rise from a mean UPCI of 4 to 7 at the end of the analysis period. This trend is explained by the long term performance of earth roads, presented in Chapter 5. Earth roads when not maintained tend to deteriorate rapidly in a period of two years. With a preservation policy in the long term it was possible to maintain the earth network in an acceptable level for eight years. However, as the effectiveness of simple grading decreases over time, the condition dropped considerably caused by the appearance of structural problems during the last years of analysis.

Roads maintained with a medium budget presented a cyclic oscillating trend during the first four years of analysis. This can be explained by a reactive tendency, where roads that reached the UPCI condition of 5.5 are rehabilitated, rising the mean condition of the network to an UPCI value of 7. This phenomenon is not observed in roads maintained with a high budget standard, where condition curves present smooth slopes. This is explained by the effectiveness of high budget maintenance, which does not allow a drop below 5.5 in the roads condition.

b) Maintenance Costs

Available funding defined for the analysis considers the maintenance policy of the agency that manages the network. Comparing the initial condition to the mean performance, during the 10 year analysis period, it is observed that the network condition was preserved in the long term. This proves that maintenance policies and effects on the roads condition developed in the research are consistent with the current state-of-the-practice.

Figure 8.5 presents the maintenance costs incurred by the agency during the whole life cycle of the network. Three costs are presented, real expenses per cycle, expenses per cycle considering forwarded funds from previous cycle, and annual expenses. The tool was designed with a rolling short term budget, considering that most agencies may differ funds between cycles. This was specially designed to account for the fact that a semi-annual basis was considered in the analysis; however, funding is usually available in an annual basis. When considering an annual analysis period, it is observed that in average a discounted annual budget of CAD 240,000 is spent (expressed as actual cost considering an 8% discount rate). This would be the ideal scenario for the MOP, where a fixed annual budget of CAD 240,000 is assigned to maintain the network within a year.

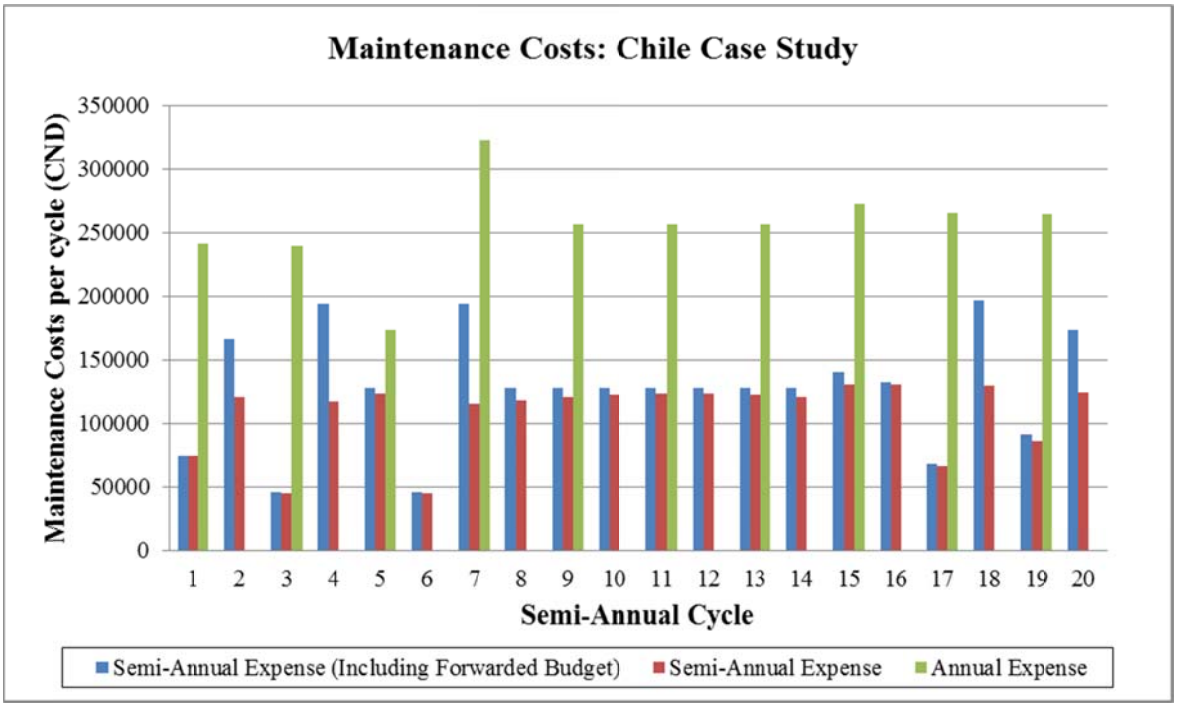


Figure 8.5 Maintenance Costs: Chile Case Study

When comparing performance curves and maintenance costs, it is observed that low expenditures in cycles 3 and 6, followed by high expenses in cycles 4 and 5, are consistent with the cyclic trend observed in medium budget performance curves. Reconstruction performed in cycles 18 and 20 are observed in the total costs of both cycles. However, the impact of reconstruction is not significant with respect to the total network costs. This is explained by the fact that reconstruction is performed in earth roads only, which are shorter than gravel roads and demand lower reconstruction costs (drainage improvement, local gravel and heavy blading).

c) Network Prioritization

Data considered in the calculation of the Sustainable Priority Indicator (SDI) and prioritization rank is presented in Appendix I.1.4. It is observed that roads were adequately classified in terms of their importance, presenting good balance of earth and gravel roads maintained with a high standard. One secondary gravel road was classified with less importance, while seven tertiary earth roads were classified with high importance. This evidences that, network classification in terms of roads category or surface type can be useful but does not reliably detect sustainable aspects for network prioritization. For example, roads 26 (gravel) and road 32 (earth) present the same traffic volumes (60 AADT), the gravel road is more than 50% longer and the earth road has 50% more population. With a traditional prioritization method, the gravel road would have been selected for a high standard maintenance and the earth road for a lower standard. However, both roads have been ranked similarly by the SDI; the earth road is ranked 9 and the gravel road is ranked 10. With the sustainable approach it has been possible to capture the importance of tertiary roads in providing access to rural population, which may not be reflected in a measure in terms of motorized traffic, such as traffic volume. A similar case is observed for two secondary gravel roads, roads 2 and 15. Both roads present traffic volumes of 100 AADT. However, road 15 presents 3 times the population of road 2 and is half its length. With the sustainable approach it has been possible to differentiate both cases, giving higher priority to road 15 (ranked 2) rather than road 2 (ranked 5). In this case the rank helped prioritizing two similar roads, helping road managers in selecting the most sustainable option when funds are limited.

8.3.2 Paraguay Case Study

8.3.2.1 Analysis Process

1. Input Data: Network characteristics and current condition data are presented in Table 8.3. The proportion of population per road was obtained from the MOPC and was estimated in terms of the population living in a radius of one kilometer from the road under study (MOPC, 2009).

Table 8.3 Computer Tool Input Data: Paraguay Case Study

Road Data						Condition Data	
Section Code	**Road Length (Km)**	**Surface Type**	**Traffic AADT**	**Total Population**	**% Population**	**UPCI**	**Condition**
1	2.700	Earth	100	95	0.9%	3.9	Poor
2.1	2.733	Gravel	212	771	7.6%	3.1	Very Poor
2.2	5.467	Gravel	212	1542	15.2%	7.0	Good
3	6.300	Gravel	150	1157	11.4%	3.0	Very Poor
4	8.600	Earth	286	1000	9.9%	7.4	Good
5	4.600	Earth	100	180	1.8%	1.0	Very Poor
6	11.260	Earth	150	265	2.6%	6.2	Regular
7	14.600	Gravel	252	1385	13.7%	3.6	Poor
8	14.700	Earth	250	430	4.2%	6.4	Regular
9	3.800	Earth	150	65	0.6%	4.5	Regular
10	6.100	Earth	75	75	0.7%	5.4	Regular
11	6.100	Earth	50	90	0.9%	3.6	Poor
12	6.500	Earth	90	225	2.2%	3.1	Poor
14	8.200	Earth	50	565	5.6%	1.7	Very Poor
16	6.300	Earth	50	565	5.6%	1.3	Very Poor
17	2.600	Earth	30	100	1.0%	1.0	Very Poor
18	5.300	Earth	50	155	1.5%	1.4	Very Poor
19	0.800	Earth	40	85	0.8%	1.6	Very Poor
20.1	3.600	Earth	20	45	0.4%	2.9	Very Poor
20.2	3.600	Earth	50	55	0.5%	6.5	Good
21	3.700	Earth	70	410	4.1%	3.7	Poor
22	11.000	Earth	83	760	7.5%	4.3	Poor
23	3.100	Earth	60	100	1.0%	5.6	Regular
Network	**Total length: 141.66**	**Gravel: 4 Earth: 19**	**Mean AADT: 112**	**Total Pop: 10,120**	**100%**	**Mean UPCI: 3.8**	**Mean Condition: Poor**

- Climate was defined as Humid, given that the area presents sub-tropical humid climate with a long rainy season and mean monthly precipitations over 300 mm.
- Minimum UPCI was defined as 3.0 to warranty 80% basic access.
- Analysis period: six-month short term analysis cycles and 10 year life cycle analysis.
- Discount Rate of 8% was considered.
- Maintenance costs provided by the MOPC were similar to maintenance costs considered in the Chile Case study. To maintain the same comparative basis between both case studies, the MOP costs defined in the Chile case study were considered in the analysis.

2. System Modules: Threshold values per strategy were reduced in the maintenance standards included in the Network Maintenance Module. This considered the 80% basic access strategic target and the fact that Paraguay is a middle income developing country with lower funding than Chile, where the recommended standards were developed. Table 8.4 presents the modified standards for earth and gravel roads, where reconstruction is triggered below a condition of 3, rehabilitation is applicable in a range from 4.5 to 3, and routine maintenance is applied for a condition over 4.5.

Table 8.4 Adjusted Maintenance Standards: Paraguay Case Study

Maintenance type	Application Ranges (UPCI)
RMin: Minimum Routine	10-3
RM1: local gravel and minimum grading	10-4.5
RM2: Routine Grading	10-4.5
Rehabilitation	3-4.5
Reconstruction	<3

3. Required funding for each budget level was calculated for the first analysis period, which is presented in Table 8.5. The optimum budget level, in terms of cost-effectiveness and considering the present characteristics of the network, was defined as the Medium Budget for gravel and earth roads. This information is displayed as reference to the user for selecting the available funding level.

Table 8.5 Required Funding per Budget Levels: Paraguay Case Study

Required Funding	**CAD$**
Budget Minimum	126,063
Budget Low	133,182
Budget Medium (optimum)	182,068
Budget High	182,068

4. Available funding level: the MOPC assigns an annual budget of CAD$ 80,000 to maintain the network, therefore, a semi-annual fund of CAD$ 40,000 per semi-annual cycle was considered for the analysis. Funding is available for upgrading earth and gravel roads to sealed standard when traffic volumes exceed 400 AADT prior evaluations at the project level.
5. Given that the available funding is lower than the minimum budget level, adjustments to funding policies at the strategic level had to be made. For this, the network was simulated for the Minimum Budget Level presented in Table 8.5, evidencing that after the first cycle the network required minimum maintenance budget less than CAD$ 40,000 per cycle. This evidences that the network in its current condition was not warrantying basic access to the population, so most roads required reconstruction and rehabilitation after the first cycle.
6. From the analysis, funding of CAD$130,000 was defined for the first cycle and CAD$ 40,000 per cycle for the rest of the analysis period. The required budget levels for the second period of analysis are presented in Table 8.6.

Table 8.6 Funding per Budget Levels, Second Analysis Period: Paraguay Case Study

Required Funding	CAD$
Budget Minimum	26,426
Budget Low	39,453
Budget Medium (optimum)	61,326
Budget High	268,769

7. The computer tool selected the Low Budget as the Base Budget and the Medium Budget as the optimum for gravel and earth roads. Given that the available funding is between the Low and Medium budgets, roads presenting higher priority were be maintained with the optimum budget level.
8. Given that the available funding was a valid entry for the second analysis period, the life cycle analysis was performed for a ten year period (20 semi-annual cycles).
9. Output data obtained from the network analysis is presented in Appendix I. A summary of network condition performance and maintenance costs are presented in Figures 8.6 to 8.8.

8.3.2.2 Analysis of Results

a) Condition Performance

The case study applied in Paraguay is an example of a rural road network in a middle-income developing country, where basic access and mobility cannot be afforded for the 100% of the population. As targeted at the strategic level, an 80% accessibility policy was implemented considering an acceptable UPCI value above 3 for the network.

From Figure 8.6 it is observed that gravel and earth roads were maintained in regular condition during the life cycle analysis, as defined by the UPCI methodology and presented in Chapter 4. It is observed, however, that the network was preserved in a good condition between the second and sixth analysis years.

The network was improved from an initial poor condition of 3.8 to a mean UPCI value of 6. From the analysis, the gravel network presented a mean UPCI of 6.3 and the earth network a mean UPCI of 6.0. The main improvement of the network was performed during the first year of analysis due to an extensive rehabilitation and reconstruction process. After this, the condition was maintained for the next seven years of analysis considering cost-effective routine maintenance and minimum rehabilitation. Starting at the eighth year of analysis, earth roads presented a drop in their condition, caused by the presence of structural problems.

From the figure it is observed that the selected 10 year life cycle was realistic for earth roads. The complete deterioration cycle was captured, where the roads reached a minimum acceptable condition at the end of the analysis period. Gravel roads were mostly maintained with routine maintenance. The complete performance cycle for gravel roads, where the minimum acceptable condition is reached, is not observed since maintenance threshold values were reduced. After rehabilitation and reconstruction held within the first analysis year, none of the four gravel roads under study reached the minimum condition for a reconstruction.

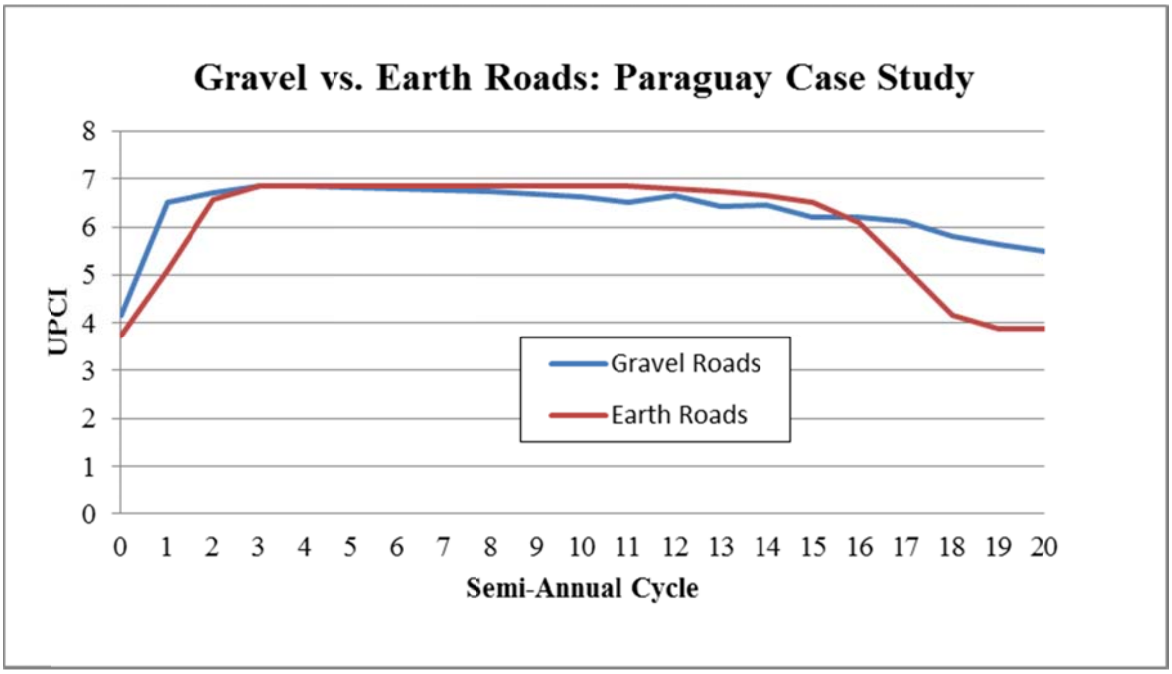


Figure 8.6 Gravel vs. Earth Roads Performance: Paraguay Case Study

Figures 8.7 and 8.8 present the effects of funding levels on roads condition for gravel and earth roads, respectively. From the 23 roads evaluated, 3 roads were maintained with a Medium Budget standard (1 gravel road and 2 earth roads) and 20 roads were maintained with a Low Budget standard (1 gravel road and 11 earth roads). No road was recommended for an upgrade to sealed standard, explained by the fact that the 400 AADT policy defined by the agency is high with respect to the practice in other countries.

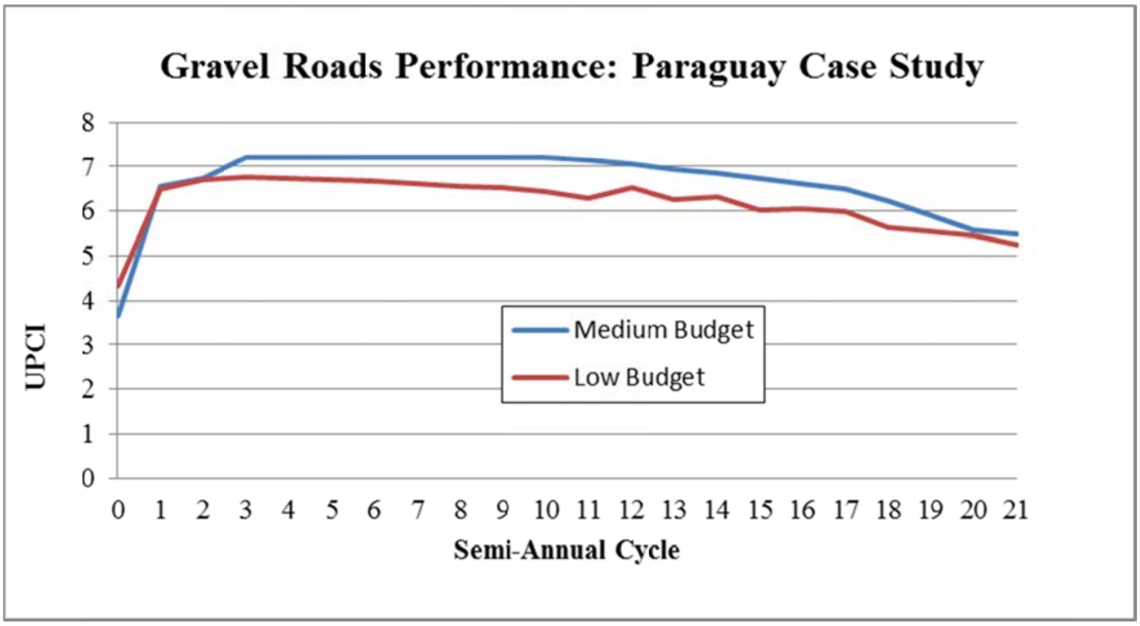


Figure 8.7 Gravel Roads Performance: Paraguay Case Study

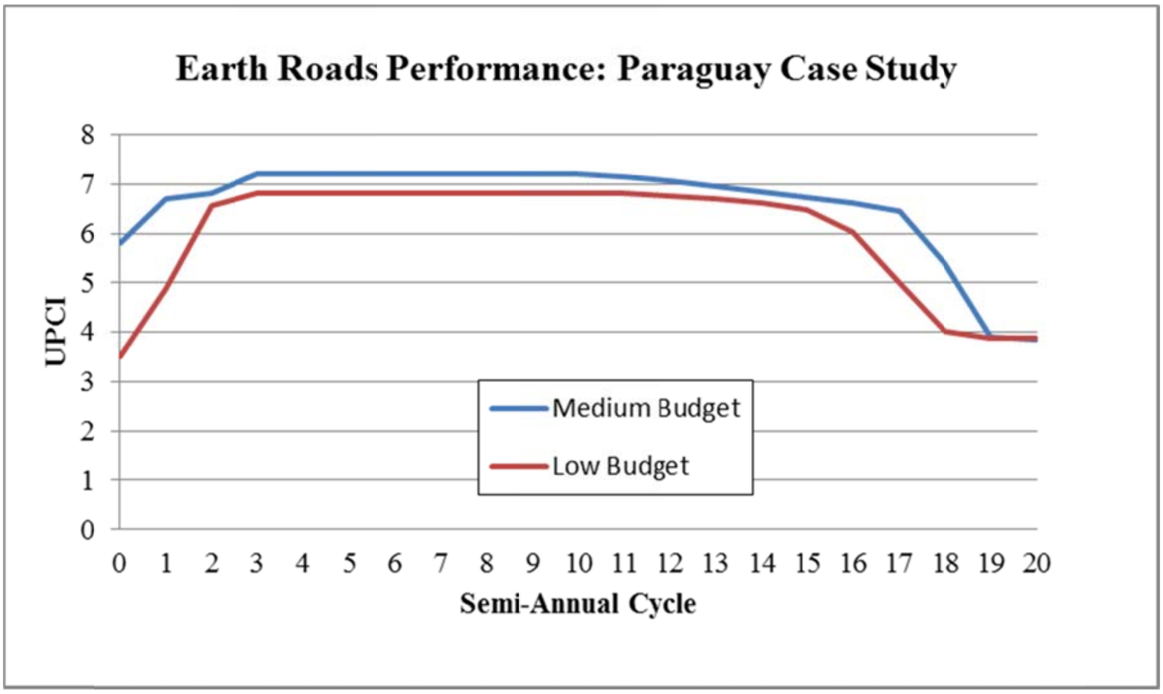


Figure 8.8 Earth Roads Performance: Paraguay Case Study

As it is observed in detail from Figure 8.7, gravel roads presented a three phase long term performance. During the first two years, the mean condition raised from a mean UPCI value of 4 to 7. This was produced by rehabilitation and reconstruction applied in sections presenting poor initial condition. Then, a mean constant condition of 6.8 was observed from the second to the seventh year of analysis. The third phase presents a gradual deterioration until a mean value of 5.3 is reached at the end of the analysis period.

Earth roads presented a four phase deterioration cycle as observed from Figure 8.8. The first two phases are similar to the trend observed in gravel roads. The third phase evidences an accelerated deterioration starting at the eighth analysis year. Earth roads maintained with a low budget reached a minimum condition below 4 at the ninth year of analysis, while roads maintained with a medium budget reached this level one year after. A fourth phase is observed during the last analysis year, where a steady mean deterioration of 3.8 is observed. This trend is typical of earth roads once important structural problems have appeared, as it is observed from performance curves presented in Chapter 5. An inflection point is produced in the deterioration curve at an UPCI value between 3.5 and 4 for humid climates, after which roads deterioration progresses at an average rate of 1 UPCI every two years if no rehabilitation is considered. Given that the reconstruction threshold was reduced to an UPCI value of 3, earth roads would continue deteriorating until reaching this value if no rehabilitation is considered. At this point, structural problems are in an advanced stage, which require important funding to improve the roads condition, as it happened during the first analysis year of this case study.

A cyclic oscillating trend was observed in gravel roads maintained with low budget between the fifth and eighth analysis years. This tendency is caused by rehabilitations applied to roads 2.2 and 3 after reaching the routine maintenance minimum threshold.

b) Maintenance Costs

Funding of CAD$ 40,000 per cycle, as initially defined from strategic targets was only bearable after rehabilitating and reconstructing road sections with severe damages. An initial investment of CAD$ 129,230 for the first cycle was required to ensure a long term performance of the network, meeting mobility and accessibility targets defined at the strategic level. The computer tool was flexible and able to perform a short term analysis to identify required funding for the first cycle, to then perform a life cycle analysis.

Figure 8.9 presents maintenance costs incurred by the agency during the whole life cycle of the network. It is observed that available funds were almost completely exhausted after each cycle. Minimum funds were deferred to the next cycle, reason why the red and blue bars presented in the graph are almost the same. This is explained by the fact that the available funding was close to the minimum, where all funds per cycle had to be spent in order to maintain the network in an acceptable condition. Having a constant expenditure per cycle is the ideal scenario for an agency. The slight increase of expenses in the long term is explained by the 8% discount rate considered in the analysis.

In general terms, the network demanded very low investment once improved. The reason for this is that the network is mainly composed by earth roads, which demand less maintenance funding than gravel roads.

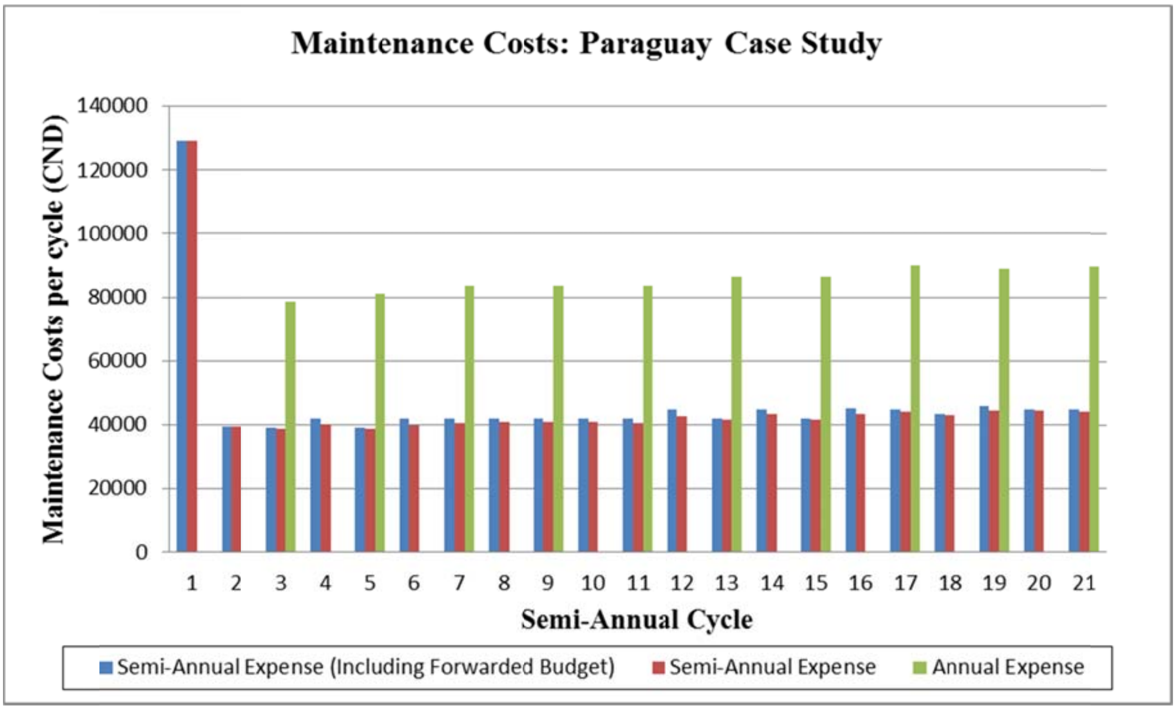


Figure 8.9 Maintenance Costs: Paraguay Case Study

c) Network Prioritization

Data considered in the calculation of the Sustainable Priority Indicator (SDI) and prioritization rank is presented in Appendix I.2.4. It is observed that only three roads were selected for a higher maintenance standard. The reason for this was that the available funding after the first cycle was very close to the Low Budget which was used as the Base Budget for the prioritization of the network.

From Figure 8.8 it is observed that the initial condition of earth roads maintained with Medium Budget presented a mean UPCI value of 6, while earth roads maintained with Low Budget had a mean initial condition of 3.5. This empirically proves that roads selected with high importance by the long term prioritization procedure were also those defined as priority roads by the local agency, given that they were maintained with a higher standard.

8.3.3 Comparative Analysis between Case Studies

From the analysis of both networks it can be concluded that different scenarios can be evaluated by the computer tool and management system. While both networks had similar extents, performance and required funding differed significantly. This is explained by three facts: strategic targets, available funding, and proportion of earth and gravel roads in each network.

Strategic targets were defined accordingly to the socio-economic reality of each country. A more flexible access standard was set in the case of Paraguay given by limited funds available for rural roads management. In addition, a geographical aspect justifies this decision. The network under study in Chile is located in an undulated to mountainous terrain, where no alternative roads exist. Opposite to this condition, the network in Paraguay presents a flat terrain, where various routes are accessible by the rural population. This is a constant condition observed in both countries given their topographies and distribution of population in the rural network.

Regarding available funding, there is an important socioeconomic difference between both countries. Chile is a high income developing country with a GDP per capita of approximately CAD$ 16,200. Meanwhile, Paraguay is considered a middle income developing country with a GDP per capita of approximately CAD$ 3,660. This is also observed in the distribution of population living in rural areas and the level of poverty. The rural network in Chile has a density of 36.57 habitants per road-kilometer, while the network in Paraguay presents a density of 71.44 habitants per road-kilometer, being twice as dense as the Chile case study. Considering this, it is realistic to expect maintenance standards ranging from High to Medium Budget for rural networks in Chile, while reasonable standards for Paraguay should range between Low to Medium Budget.

Finally, it is observed that total maintenance expenses in both networks are noticeably different. While the mean expenditure per cycle in Paraguay was CAD$ 40,000, the network in Chile required CAD 120,000 per cycle. This difference is partly explained by the higher maintenance standard defined for the Chile case study. However, the main difference observed between funding requirements is explained by the proportion of gravel roads in each network. While in Paraguay 20% of the total extent of the network are gravel roads, in the Chile case 62% of the network are gravel roads. Gravel roads require higher maintenance costs than earth roads and usually present higher traffic volumes, demanding higher grading frequencies.

Figure 8.10 presents a comparison between the mean conditions of both networks. From the curves it is observed that the Paraguay network presents a mean UPCI condition of 0.6 UPCI points below the Chilean network. The difference, however, increases during the first and last years of analysis. While the Paraguay network presents a poor initial condition, requiring high initial investment, the Chilean network has a good condition, where a constant budget could be defined starting from the first analysis cycle. Once the Paraguay network was maintained in a regular standard, both networks presented a very similar performance. However, due to the low effectiveness of maintenance treatments considered for a Low Budget level, and the lower maintenance standards applied to the network, the mean condition decreased rapidly during the last two years of analysis.

In the case of the Chilean network, a higher budget level and maintenance standards resulted in the condition improvement observed between the eighth and ninth analysis years. This avoided a considerable condition loss at the end of the analysis period.

Two different maintenance policies are evidenced from the analysis. The Chilean case study represents a proactive maintenance policy where the network is preserved in the longer term. While the Paraguay case study represents a more reactive policy where a minimum maintenance standard is applied until major rehabilitation is required at the end of the analysis period. The first is a more sustainable and cost-effective approach for the life cycle, being recommended when funding is available.

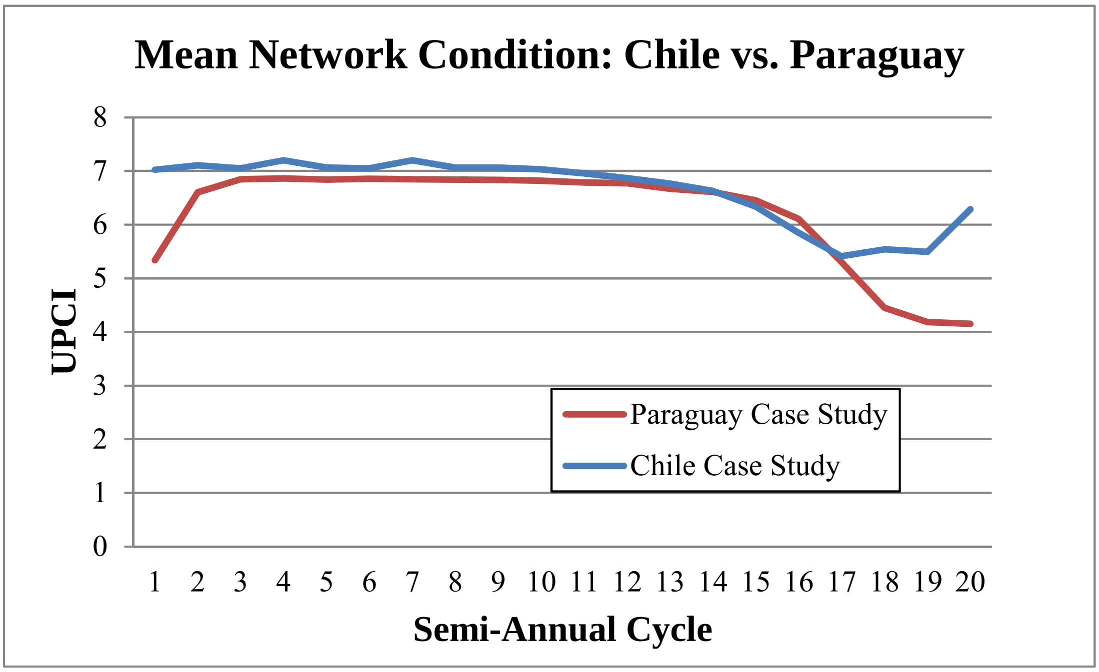


Figure 8.10 Network Performance: Chile vs. Paraguay Case Studies

8.4 Sensitivity Analysis of the Management System

A sensitivity analysis was performed to determine the impact of changes in input data and to provide recommendations to managers for the suitable definition of strategic targets. The analysis considered the Ceteris Paribus method, where one variable is modified at a time while the rest of parameters and variables are maintained constant. A base case was defined to which two modified scenarios were compared with. Modified scenarios represented input data with higher and lower values. The base case selected was the Chilean network, given that presents diversity in the condition of roads and a balanced proportion of gravel and earth roads.

Input data selected for the sensitivity analysis was: climate, budget and discount rate. Climate was selected to identify possible sources of error when managers are uncertain of typical conditions of the evaluated network. While budget and discount rates may be modified during the analysis by managers, requiring recommendations for the proper selection of strategic targets. Modifications to maintenance standards were excluded from the analysis since they were compared in the Case Studies, where conclusions were drawn from the effects of variations of standard thresholds over maintenance costs and network performance.

The base case presented Mediterranean climate, Medium to High Budget (CAD$ 120,000 per cycle) and a discount rate of 8%. Modified scenarios considered for each case and conclusions obtained from the sensitivity analysis are presented as follows. Appendix I presents detailed results obtained from the analysis.

8.4.1 Climate

Modified scenarios selected for the analysis were dry and humid climates, which were contrasted to Mediterranean climate. A summary of results in terms of unit cost-effectiveness, real maintenance expense and mean condition per scenario are presented in Table 8.7. Unit cost effectiveness was obtained from the analysis per cycle considering Equation 9. Figure 8.11 presents results of sensitivity analysis in terms of condition performance per cycle.

From the analysis of mean data it is observed that no important difference exists between scenarios. Dry climate presents slightly higher unit cost effectiveness compared to the two other climates. This is explained by the fact that within the condition range observed in the network, which fluctuated between UPCI values of 7.5 and 5, routine maintenance is performed in most roads during the first eight years of analysis. Routine maintenance presents a higher cost-effectiveness as applied at a high condition level with minimum costs. This is observed as a linear trend in performance curves in Figure 8.11. This trend is maintained until the minimum threshold is reached by most roads, requiring rehabilitation in the eighth and ninth analysis years. This produces a drop in the condition of the network, where a minimum condition of 5 is reached. Reason for this the mean condition with dry climate is slightly lower than the two other types of climate, however, the mean effectiveness per cycle is higher.

Mediterranean and humid climates perform similarly within UPCI values of 7.5 and 5 as observed in performance curves presented in Chapter 5. Because of this, they present similar mean values and performance curves. Rehabilitation is required during the first eight years of analysis in some roads, which is observed as two irregularities in cycles 4 and 7 in Figure 8.11. Because of these rehabilitations the drop in the mean condition between years eight and nine is smoother than for dry climate, where a minimum UPCI value of 5.5 is reached.

Table 8.7 Summary of Sensitivity Analysis: Climate

Scenario	Mean
Unit Cost Effectiveness (Dry)	0.00007
Real Expense (Dry)	$ 124,268
Mean Condition (Dry)	6.6
Unit Cost Effectiveness (Mediterranean)	0.00006
Real Expense (Mediterranean)	$ 127,434
Mean Condition (Mediterranean)	6.7
Unit Cost Effectiveness (Humid)	0.00006
Real Expense (Humid)	$ 127,434
Mean Condition (Humid)	6.7

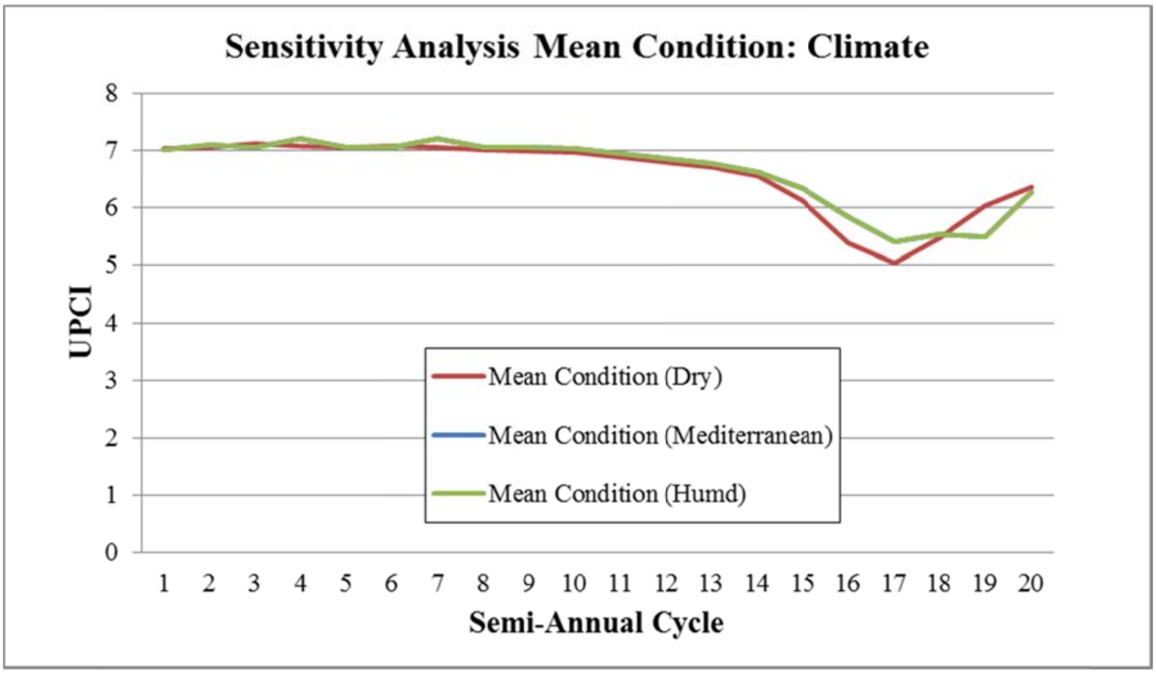


Figure 8.11 Effects of Climate on Network Performance

8.4.2 Budget

The modified scenarios for the analysis were obtained from Table 8.2, where a Low Budget of CAD$ 45,000 and a High Budget of $CAD 300,000 were selected. As discussed previously, a funding level of CAD$ 120,000 ranges between a Medium to High Budget for the Chilean road network. A summary of results in terms of unit cost-effectiveness, real maintenance expense and mean condition per scenario are presented in Table 8.8. Figure 8.12 presents results of sensitivity analysis in terms of condition performance per cycle.

Table 8.8 Summary of Sensitivity Analysis: Budget

Scenario	Mean
Unit Cost-Effectiveness (CAD$ 45,000)	0.00014
Real Expense (CAD$ 45,000)	$ 48,013
Mean Condition (CAD$ 45,000)	6.59
Unit Cost-Effectiveness (CAD$ 120,000)	0.00006
Real Expense (CAD$ 120,000)	$ 127,434
Mean Condition (CAD$ 120,000)	6.65
Unit Cost-Effectiveness (CAD$ 300,000)	0.00003
Real Expense High Budget (CAD$ 300,000)	$ 265,592
Mean Condition High Budget (CAD$ 300,000)	6.73

From the analysis of mean data it is observed that the network is maintained in an overall better condition with the High Budget and in a poorer condition with a Low Budget. It is observed however that Low Budget is more cost-effective than High Budget. From the life cycle analysis and additional iterations, it was estimated that optimum cost-effectiveness is obtained for a funding level of CAD$ 51,000, which is close to the selected Low Budget. The Medium Budget level of $CAD 120,000 was more than twice this optimum value reason why its cost-effectiveness is less than half the cost-effectiveness of Low Budget.

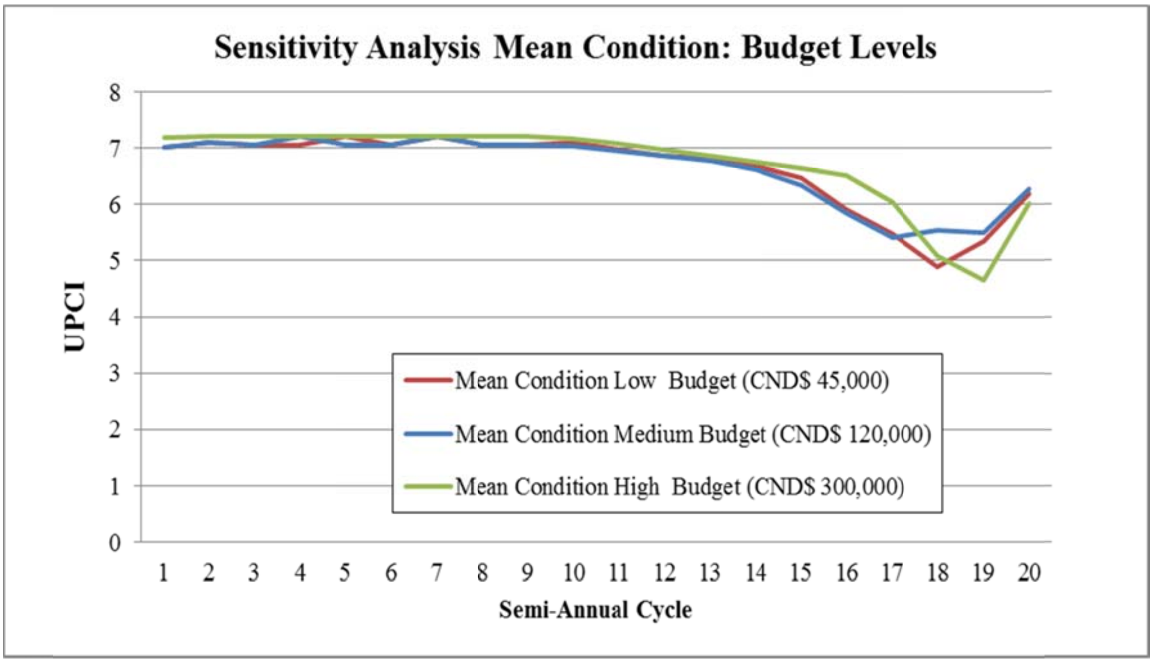


Figure 8.12 Effects of Budget Levels on Network Performance

From Figure 8.12 it is observed that High Budget does not produce significant improvements in the network performance over time. The main reason is that during the first eight years of analysis routine maintenance is applied, where the effectiveness of High Budget standards is not substantially higher than those applied under Medium and Low Budgets. In addition, a maximum condition level is not reached under routine maintenance. Routine maintenance is applied for a longer period of time with High Budget, after which rehabilitation and reconstruction of most sections is performed during the last cycle where a minimum condition of 4.7 in average is reached. Low and Medium Budget demand rehabilitation of some sections during the first eight years of analysis. This is observed in Figure 8.12 as two irregularities in cycles 5 and 7. Low Budget requires the application of rehabilitation in more sections over time, which is observed in cycles 6, 11 and 15. In the longer term, however, these rehabilitations produce a smoother drop in the deterioration trends observed at the end of the analysis period, where the minimum condition reached with a Low Budget is 4.9 and with a Medium Budget is 5.4.

The effects of budget differ between gravel and earth roads. A difference ranging from 0.5 to 1.5 in the UPCI value is observed in earth roads between two funding levels. This was also observed in the two case studies. Gravel roads performance, however, is less susceptible to changes in budget levels. This is the reason why overall performance of the network is not substantially susceptible to variations in the budget level, as observed from Figure 8.12.

8.4.3 Discount Rate

Discount rate may be significant when having different expenditures during different years. It is mostly expected that when high discount rates apply, short term policies become more competitive. Whereas, maintenance policies that last longer become less attractive given that their benefits occur far in the future, when a higher discount rate is applied.

For the analysis, a discount rate 5% higher and 5% lower than the basis was considered, where the basis was defined as 8% similar to the case studies. With this, a 3% discount rate was considered for a low scenario and 13% for a high scenario. Mean results are presented in Table 8.9.

Table 8.9 Summary of Sensitivity Analysis: Discount Rate

Scenario	Mean
Unit Cost-Effectiveness (Discount Rate 3%)	0.000074
Real Expense (Discount Rate 3%)	$ 121,479
Mean Condition (Discount Rate 3%)	6.63
Unit Cost-Effectiveness (Discount Rate 8%)	0.000062
Real Expense (Discount Rate 8%)	$ 127,434
Mean Condition (Discount Rate 8%)	6.65
Unit Cost-Effectiveness (Discount Rate 13%)	0.000057
Real Expense (Discount Rate 13%)	$ 133,207
Mean Condition (Discount Rate 13%)	6.65

From the analysis it is observed that no significant difference exists in terms of cost-effectiveness and condition between the three scenarios. This is explained by the fact that a constant available fund of CAD$ 120,000 is considered in the analysis, which is corrected for each period with the discount rate. With this, the decision on best maintenance practices does not depend on the discount rate but on cost-effective technical decisions.

From Table 8.9, slightly higher cost-effectiveness is observed for the lower discount rate. This is explained by the fact that costs are expressed in terms of present worth for a similar effectiveness basis. Similar trends were observed on roads performance, where slight fluctuations were observed caused by differences in available funding between cycles.

8.5 Findings from the Application and Validation of the Management System and Computer Tool

From the two case studies and sensitivity analysis, the following findings were obtained about the management system:

1. The management system and computer tool produced reliable results, where performance models, maintenance standards and the long term prioritization of two road networks were consistent to what was expected.
2. The system and tool demonstrated to be adaptable to real scenarios presenting different characteristics. This was proved from the application of the tool to the Chile and Paraguay Case studies, which presented different climates, road structures, available funding, socio-economic characteristics, traffic levels, network conditions and expected performance.
3. Collected data was sufficient to perform the analysis of two networks, where non-expensive evaluation techniques were applied in the field. The UnPaved Roads Condition Index (UPCI) demonstrated to be an objective and reliable method to assess current condition and predict future performance of a road network.
4. The long term performance of gravel and earth roads was logical and realistic. In both case studies the condition was consistent to the expected deterioration over time due to the effects of traffic, environment and applied maintenance.
5. Maintenance standards defined from cost-effectiveness analysis were successfully applied in both case studies. The effects of modifying threshold levels of maintenance strategies were compared between both networks. From the analysis it was observed that social targets defined in terms of access and mobility can be consistently incorporated in the analysis in terms of performance thresholds.
6. The Sustainable Prioritization Indicator (SPI) was sensitive to capture the importance of rural roads in a network. Cases such as earth roads with high social importance and roads commonly ranked in higher categories but with limited social impact were detected and consistently ranked by the indicator.
7. From the sensitivity analysis the effects of climate were studied. The main variations between climates were observed in the long term. It is recommended that the developed performance models and standards are validated in other scenarios than the conditions where they were developed.
8. Effects of different budget levels were evaluated with sensitivity analysis. Findings were consistent to recommendations made for optimum maintenance standards. In most scenarios it was observed that Medium and Low Budgets are more cost-effective than High Budget. High Budgets ensure higher long term performance, however, this is not proportional to the extra funding required to achieve a better standard.
9. The effects of budget differ between gravel and earth roads. A difference ranging from UPCI values between 0.5 and 1.5 were observed for earth roads in both case studies

when comparing two funding levels. Gravel roads performance, however, was less susceptible to changes in budget levels.

10. It is recommended to analyse in more detail the effects of budget levels for different maintenance standards and maintenance costs. From the case studies it was observed that the effects of funding levels over performance may differ when maintenance standards are modified.
11. From sensitivity analysis of discount rate it was observed that it does not affect maintenance decisions in the long term. This is explained by the fact that the prioritization process considers a base budget that is constant in terms of present worth costs. With this, the network is maintained subject to cost-effective technical and social requirements rather than long term economic speculations.
12. Overall, it is concluded that the developed system reliably incorporated sustainable aspects for life cycle management of rural roads in developing countries; integrating social, technical, economic and institutional aspects. It is recommended, however, to investigate in the future possible methods to integrate environmental aspects in the prioritization process.

From the application and validation of the computer tool, the following findings were obtained:

1. The computer tool was practical and intuitively adopted and operated. Input data was easily entered to the software, where no extensive processing was required in advance.
2. The computer tool demonstrated to be efficient, where limited time was required to perform life cycle analysis.
3. Reports produced by the tool were suitable for the strategic and network management levels. Graphs that can be easily interpreted and tables with a summary of performance and maintenance recommendations are some of the outputs obtained from the software.
4. The tool was easily adapted to different scenarios, where modifications in an input variable were easily included to the analysis.
5. The life cycle analysis can be performed in a short and long term basis. This is especially useful when short term variations have to be included in the analysis. This was observed in the Paraguay case study, where fluctuations to the available fund had to be included during the first analysis cycle.
6. Optimum maintenance standards can be adjusted by iterating different traffic, road structures and budget scenarios. It is recommended that maintenance standards are calibrated and adjusted accordingly to local conditions.

Chapter 9
Conclusions and Recommendations

9.1 Conclusions

The main objective of developing a sustainable rural roads management system for agencies in developing countries was successfully accomplished by the research. For this, practical management system components and an applied computer tool were effectively developed and validated. The system demonstrated to be adaptable to different scenarios, in terms of climate, budget, traffic and road types.

For the successful development and validation of the management system, the following specific objectives were achieved:

- A sustainable framework for the management of rural road networks was developed. The framework considered the development of three System Modules: Condition Performance Module, Network Maintenance Module and Long Term Prioritization Module.
- For the development of the Condition Performance Module the UnPaved Roads Condition Index methodology was applied and validated at the network level.
- Condition performance models for weak structures (or earth roads) and strong structures (or gravel roads) representative of dry, Mediterranean and humid climates were successfully developed and validated. Models were developed from the probabilistic analysis of field evaluation, and calibrated with Markov chains and Monte Carlo simulation. Developed models were incorporated to the Condition Performance Module considered in the management system.
- Maintenance strategies applied to different scenarios were compared with cost-effectiveness analysis. Scenarios defined for the analysis included: two structure types (weak and strong), three climates types (dry, Mediterranean and humid), three traffic volumes (low, moderate and high) and four budgetary scenarios (minimum, low, medium and high). Optimal maintenance standards were developed from the analysis and were incorporated in the Network Maintenance Module included in the management system.
- A sustainable prioritization methodology was developed and incorporated to the Long Term Prioritization Module of the management system. For this, a Sustainable Priority Indicator (SPI) was developed, which considered the cost-effectiveness of selected optimal standards, traffic volumes, roads length and proportion of rural population living in the vicinity of a road. A sustainable prioritization procedure was programmed for the life cycle management of rural road networks.

- Developed System Modules were successfully integrated in an easy-to-use and simplified management tool. The tool combined four system components: Input Data, System Modules, Network Analysis Interface and Output Data.
- The developed tool was applied and validated in two road networks, in Chile and Paraguay. In addition, a sensitivity analysis was considered for the evaluation of variations of input parameters considered in the management system. As a result, the management system and tool were successfully validated in rural road networks in developing countries.

The reliability of the proposed management system relied on the design of consistent experiments for the development of System Modules. Seven experiments were defined for this. The following four experiments were considered for developing the Condition Performance Module: Validation of UnPaved Roads Condition Index (UPCI) methodology, development of unpaved roads condition performance models, definition of maintenance effects on roads condition and validation of unpaved roads condition performance models and effects of maintenance on roads condition. For the development of the Network Maintenance Module, an experiment was carried out to define the optimal maintenance standards. For the Long Term Prioritization Module, an experiment was designed to develop an engineering based sustainable priority procedure. The management system with all these modules and components were integrated into a computer tool. It was further calibrated and validated for two road networks in developing countries. A final sensitivity analysis was performed to complement the validation process.

The experiments carried out in the research considered inventory and strategic level data obtained from local agencies. Network condition data was collected in the field considering the UPCI methodology. Findings from the developed experiments were published in three refereed journals, including: the proposed management system framework, the UnPaved Roads Condition Index (UPCI) methodology, and the development and validation of condition performance curves. (Chamorro, 2009a; Chamorro, 2009b; Chamorro, 2011)

A summary of the findings obtained from the development and validation of each System Module, management system and computer tool are described as follows.

9.1.1 Development and Validation of the Condition Performance Module

The Condition Performance Module was developed for the analysis of network condition performance and prediction in the long term. The network evaluation methodology recommended in the research was the UnPaved Roads Condition Index (UPCI), which was successfully validated from field evaluations.

Having a validated evaluation methodology, unpaved roads condition performance models were developed. Performance models were obtained from the statistical analysis of the road deterioration observed in a thirteen month period. The modelling technique selected was Markov chain models, which can reliably predict the stochastic nature and non-linear performance of unpaved roads over time. Performance curves for strong structures or gravel roads and weak structures or earth roads were finally calibrated from Monte Carlo simulation.

Data that was not considered in the development of performance curves was analysed in detail to define maintenance recommendations. Maintenance effects on roads condition were obtained from the analysis; in addition, trigger values for different maintenance strategies were defined.

The unpaved roads condition performance models and effects of maintenance on roads condition were validated from data collected in the field. For this, data obtained from two evaluations, distanced in 24 months, was compared with the use of performance models. From the analysis, condition performance models and maintenance recommendations were successfully validated.

9.1.2 Development and Validation of the Network Maintenance Module

The Network Maintenance Module considered in the management system includes maintenance treatments and strategies, optimal maintenance standards and maintenance costs. Maintenance treatments and strategies were defined considering recommendations from literature, current state-of-the-practice and field data analysis. Standards were defined considering the application of threshold values for routine maintenance, rehabilitation and reconstruction.

The cost-effectiveness analysis method was used to compare proposed strategies under different scenarios. These included the consideration of four budget levels (minimum, low, medium, high), three climates (dry, Mediterranean, humid), three traffic levels (low, moderate, high) and two types of structure (gravel and earth).

Marginal cost effectiveness was considered in the selection of the optimal standard per scenario. The optimum funding level was identified for each scenario. Cases where the minimum budget was higher than the present worth costs for low budget, were eliminated from the analysis.

9.1.3 Development and Validation of the Network Maintenance Module

Rural road network have to be sustainably prioritized for the successful maintenance of roads at the network level. For this, a sustainable priority indicator was developed which considered the cost-effectiveness of selected optimal standards, traffic, length and proportion of rural population living in the vicinity of the road.

A short and long term prioritization procedure was developed, which considered the proposed indicator to rank roads in the network. From the analysis, roads presenting high priority are selected for standard improvement. A prioritization algorithm was developed and programmed in Visual Basic. Its application in two case studies demonstrated that it was a consistent and reliable method to prioritize rural road networks, considering sustainable aspects in the short and the long terms.

9.1.4 Application and Validation of the Management System and Computer Tool

For the validation of the management system a final experiment was carried out which consistend in the application of the proposed system in two rural road networks in developing countries. For this, the first task was to develop an easy-to-use computer tool that integrated all system components and modules. The system was then applied and validated for two case studies located in Chile and Paraguay. A sensitivity analysis was finally carried out to validate the management system, where the different variables considered in the System Modules were assessed.

From the two case studies and sensitivity analysis, the following findings were obtained about the management system and computer tool:

- The management system and computer tool produced reliable results, where performance models, maintenance standards and the long term prioritization of two road networks were consistent to what was expected in terms of performance, funding and roads priority.
- The system and tool demonstrated to be adaptable to real scenarios presenting different characteristics. This was proved from the application of the tool to the Chile and Paraguay case studies, which presented different climates, road structures, available funding, socio-economic characteristics, traffic levels, network conditions and expected performance.
- The computer tool was practical and intuitively adopted and operated. Input data was easily entered to the software, where no extensive processing was required in advance.
- The tool demonstrated to be efficient, where limited time was required to perform life cycle analysis.
- The tool was found to be flexible and adaptable to different scenarios, where modifications in an input variable were easily included in the analysis. The analysis performed with the management tool can be performed in a short and long term basis. This is especially useful when short term variations have to be included in the analysis. This was observed in the Paraguay case study, where fluctuations to the available fund had to be included during the first analysis cycle.
- Collected data was sufficient to perform the analysis of two networks, where non-expensive evaluation techniques were applied in the field. The UnPaved Roads Condition Index (UPCI) demonstrated to be an objective and reliable method to assess current condition and predict future performance of a road network.
- The long term performance of gravel and earth roads was logical and realistic. In both case studies the condition was consistent to the expected deterioration over time due to the effects of traffic, environment and applied maintenance.
- Maintenance standards defined from cost-effectiveness analysis were successfully applied in both case studies. The effects of modifying threshold levels of maintenance strategies were compared between both networks. From the analysis it was observed that

social targets defined in terms of access and mobility can be consistently incorporated in the analysis in terms of performance thresholds.

- The Sustainable Prioritization Indicator (SPI) was sensitive to capture the importance of rural roads in a network. Cases such as earth roads with high social importance and roads commonly ranked in higher categories but with limited social impact were detected and consistently ranked by the indicator.
- From the sensitivity analysis the effects of climate were studied. The main variations between climates were observed in the long term. It is recommended that the developed performance models and standards are validated in other scenarios than the conditions where they were developed.
- Effects of different budget levels were evaluated with sensitivity analysis. Findings were consistent to recommendations made for optimum maintenance standards. In most scenarios it was observed that Medium and Low Budgets are more cost-effective than High Budget. High Budgets ensure higher long term performance, however, this is not always justified in view of extra funding required to achieve a better standard.
- The effects of budget differ between gravel and earth roads. A difference ranging from UPCI values between 0.5 and 1.5 were observed for earth roads in both case studies when comparing two funding levels. Gravel roads performance, however, was less susceptible to changes in budget levels.
- From sensitivity analysis of discount rate it was observed that it does not affect maintenance decisions in the long term. This is explained by the fact that the prioritization process considers a base budget that is constant in terms of present worth costs. With this, the network is maintained subject to cost-effective technical and social requirements rather than long term economic speculations.
- Reports produced by the tool were suitable for the strategic and network management levels. Graphs that can be easily interpreted and tables with a summary of performance and maintenance recommendations are some of the outputs obtained from the software.
- Overall, it is concluded that the developed system reliably incorporated sustainable aspects for long term management of rural roads in developing countries, integrating social, technical, economic and institutional aspects. It is recommended, however, to investigate in the future possible methods to integrate environmental aspects in the prioritization process.

9.2 Recommendations

The following recommendations were drawn from the research:

- The condition performance curves developed in the study can be used by agencies in developing countries to predict the future condition of their road networks and develop maintenance programs. It is highly recommended to validate the UPCI methodology and performance curves when applying them in a network presenting different traffic, structures and climate conditions.
- The Network Condition Module can be calibrated from available input data. For this, a

new network can be simulated considering different maintenance strategies. From the short term analysis, roads condition and present worth of costs are obtained. From the life cycle analysis, the whole life cycle effectiveness for proposed strategies is calculated. Having net present worth of costs and effectiveness, cost-effectiveness values can be obtained for the proposed strategies. If the new strategies are more cost-effective than available strategies these can replace optimal maintenance standards included in the Network Maintenance Module.

- Optimum maintenance standards can be adjusted by iterating different traffic, road structures and budget scenarios. It is recommended that maintenance standards are calibrated and adjusted according to local conditions.
- Two modifications to the UPCI methodology were recommended from the research and communicated to the Ministry of Public Works of Chile (MOP). First, include the presence of fine aggregates as part of the oversized aggregates (OA) dummy variable. Secondly, corrections to the condition limits assigned to extreme defect values were recommended to MOP.
- It is recommended to analyse in more detail the effects of budget levels for different maintenance standards and maintenance costs. From the case studies it was observed that the effects of funding levels over performance may differ when maintenance standards are modified.

9.3 Future Research and Developments

The development of this research has left several challenges for future studies, among these:

- It is recommended to develop a condition indicator and condition performance models for surfacing treatments. With this, the scope of the research could be extended to higher volume traffics. The analysis can be performed following the same procedure and considering the System Components and Modules. It is advised however that maintenance standards should be recalibrated considering a new scenario with surface standard improvement.
- Comparison to project level decision making tools, such as the proposed by MWH and the World Bank are recommended, when including surfacing improvements to the management system (MWH, 2004).
- It is recommended in future research to compare the outcomes of the management system to strategic analysis performed with HDM-4 v.2 and analysis performed with RONET. The purpose of this would be to compare the differences between the analysis procedures and performance of both systems (Kerali, 2000; Archondo-Callao, 2007).
- It is recommended to perform project level economic analysis with RED considering the outcomes of network evaluations performed with the developed management system (Archondo-Callao, 2004).

References

Archondo-Callao, R. 1999. Roads Economic Decision model (RED) for economics evaluation of low volume roads. SSATP Technical Note 18, The World Bank, Washington, D.C., USA.

Archondo-Callao, R. 1999. Unpaved Roads' Roughness Estimation by Subjective Evaluation. Infrastructure Notes No. RT-2. The World Bank, Washington, D.C., USA.

Archondo-Callao, R. 2000. Road User Charge model. SSATP Technical Note 28. The World Bank, Washington, D.C., USA.

Archondo-Callao, R. 2004. Economically Justified Levels of Road Works Expenditures on Unpaved Roads, Transport Note No. TRN-2, The World Bank, Washington, D.C., USA.

Archondo-Callao, R. 2007a. RONET Version 1.0 User Guide. SSATP Working Paper No. 85-A. The World Bank, Washington, D.C., USA.

Archondo-Callao, R. 2007b. RONET Case Studies. SSATP Working Paper No.85-B. The World Bank, Washington, D.C., USA.

Archondo-Callao, R. 2007c. RONET Version 1.01, 11/11/2007 – Main Module update history.

Austroads, 1989. Rural Road Design: Guide to the Geometric Design of Rural Roads, 7th ed. Austroads, Sydney, New South Wales, Australia, 1989.

Brundtland, H. 1987. Our Common Future, Oxford University Press, for the World Commission on Environment and Development. Oxford, England.

Baker, J. 2000. Evaluating the Impact of Development Projects on Poverty — A Handbook for Practitioners. Directions in Development Series, Washington, D.C., USA.

Benmaamar, M. 2006. Financing of Road Maintenance in Sub-Saharan Africa", Discussion Paper No. 6 Road Management and Financing – RMF Series, Sub-Saharan Africa Transport Policy Program with the contributions of the European Commission, the Governments of Denmark, France, Ireland, Norway, Sweden, and The World Bank.

Cafiso, S., Di Graziano, A., Kerali, H and Odoki, G. 2003. Multicriteria Analysis Method for Pavement Maintenance Management. Transportation Research Record: Journal of the

Transportation Research Board No. 1816. Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 73-84

Chamorro, A. and Tighe, S. 2009a. Development of a Management Framework for Rural Roads in Developing Countries: Integrating Socioeconomic Impacts. Transportation Research Record: Journal of the Transportation Research Board, No. 2093, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 99–107.

Chamorro, A. and Tighe, S. 2011. Unpaved Roads Condition Performance Models for Network Level Management. Transportation Research Record: Journal of the Transportation Research Board No. 2204. Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 21-28. DOI 10.3141/2204-03

Chamorro, A., de Solminihac, H., Salgado, M. and Barrera, E. 2009b. Development and Validation of a Method to Evaluate Unpaved Road Condition with Objective Distress Measures. Transportation Research Record: Journal of the Transportation Research Board, No. 2101, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 10–16.

Dercon, S. 2001. Economic Reform, Growth, and the Poor: Evidence from Rural Ethiopia. Presented at World Institute for Development Economics Research (WIDER) Conference on Economic Growth and Poverty Reduction, Helsinki, Finland.

Dercon, S. and Hoddinott, J. 2005. Livelihoods, Growth, and Links to Market Towns in 15 Ethiopian Villages. FCND Discussion Paper 194. Food Consumption and Nutrition Division, International Food Policy Research Institute, Washington, D.C., USA.

Dingen, R. 2000. A guide to integrated rural accessibility planning in Malawi. International Labour Organization, Zimbabwe.

Doré G. and Zubeck H., 2009. Cold regions pavement engineering, New York: McGraw-Hill/ASCE Press. USA.

Eaton, R. A., Gerard, S., Dattilo, R. S. 1987. A method for rating unsurfaced roads. Transportation Research Record No.1106, Fourth International Conference on Low-Volume Roads, Volume 2. 1987. Washington, D.C., USA.

Eaton, R. A. 1988. Development of the Unsurfaced Roads Rating Methodology. Special Report 88-5. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H., USA.

Eaton, R. A., Gerard, S. and Cate. D. W. 1987. Rating Unsurfaced Roads. Special Report 87-154. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H., USA.

Eaton, R. and Beaucham, R. 1992. Unsurfaced Road Maintenance Management. Special Report 92-26. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H, USA.

Essakali, M. D. 2005. Rural Access and Mobility in Pakistan: A Policy Note. Transport Note TRN-28. World Bank, Washington, D.C., USA.

Fan, S., and Chan-Kang, C. 2004. Road Development, Economic Growth, and Poverty Reduction in China. DSGD Discussion Paper 12. Development Strategy and Governance Division, International Food Policy Research Institute, Washington, D.C., USA.

Fan, S., Hazell, P. and Thorat, S. 1999. Linkages Between Government Spending, Growth, and Poverty in Rural India. Research Report 110. International Food Policy Research Institute, Washington, D.C., USA.

Fan, S., P. L. 2004. Huong, and T. Q. Long. Government Spending and Poverty Reduction in Vietnam. Project Report. International Food Policy Research Institute, Washington D.C., USA., and Central Institute for Economic Management, Hanoi, Vietnam.

Fernando, E. and Hudson, W.R. 1983. Development of a Prioritization Procedure for the Network Level Pavement Management System. Center for Transportation Research, The University of Texas at Austin, Austin, Texas, U.S.A.

FHWA 2002. PASER Gravel Roads Manual: Pavement Surface Evaluation and Rating, Wisconsin Transportation Information Center, Madison, Wisconsin, USA.

FHWA, 2003. Economic Analysis Primer, U.S. Department of Transportation, Federal Highway Administration, Office of Asset Management, Washington D.C., USA.

Gaël Raballand, Patricia Macchi, and Carly Petracco 2010. Rural Road Investment Efficiency Lessons from Burkina Faso, Cameroon, and Uganda, The International Bank for Reconstruction and Development, The World Bank. Washington D.C., USA.

GDPTRW 2008. Job creation, skills development and empowerment in road construction, rehabilitation and maintenance. Gauteng Department of Public Transport, Roads and Works, Pretoria, South Africa.

Giummarra, G 2003. Establishment of a Road Classification System and Geometric Design and Maintenance Standards for Low-Volume Roads. Transportation Research Record: Journal of the Transportation Research Board, No. 1819, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 132–140.

Giummarra, G. 2000. Unsealed Roads Manual: Guidelines to Good Practice. ARRB Transport Reasearch Limited, Vermont South, Victoria, Australia.

Giummarra, G., Martin, T., Hoque, Z. and Roper, R. 2007. Establishing Deterioration Models for Local Roads in Australia. Transportation Research Record: Journal of the Transportation Research Board, No. 1989, Vol. 2, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 270–276.

Grootaert, C. and Malmberg, C. 2002. Socioeconomic Impact Assessment of Rural Roads: Methodology and Questionnaires, World Bank Roads and Rural Transport TG and the Transport Economics and Poverty TG

Haas, R., Hudson R., Zaniewski, J. 1994. Modern Pavement Management. Krieger Publishing Company. Malabar, FL, United States.

Hein D.K, D.J. Swan and J.J. Hajek. 2007. Selection of Surface Type for Low-Volume Roads. Paper presented at the Transportation Association of Canada, Saskatoon, SK.

IDA 2007. IDA at Work Website, Rural Roads: Linking People to Markets and Services http://www.worldbank.org/ida

INE 2002. Censo Nacional 2002. Instituto Nacional de Estadísticas de Chile, Gobierno de Chile, Santiago, Chile. www.ine.cl

INE 2011. Instituto Nacional de Estadísticas de Chile, Gobierno de Chile, Santiago, Chile. Web page www.ine.cl accessed in October 2011.

Jahren,C. 2001. Best Practices for Maintaining and Upgrading Aggregate Roads in Australia and New Zealand, P2002-01. Minnesota Department of Transportation, Minnesota, United States.

Jalan, J. and Ravallion, M. 2002 Geographic Poverty Traps? A Micro Model of Consumption Growth in Rural China. Journal of Applied Econometrics, Vol. 7, 2002, pp. 329–346.

Johansson, S. 2006. Socio-Economic Impacts of Road Conditions on Low Volume Roads. Executive Summary. ROADEX III Project. Northern Periphery Nations, European Regional Development Fund, E.U.

Jones, D J. 1998. The use of sand cushioning for unsealed road maintenance in arid areas. Proceedings of 19th Australian Road Research Board Conference, Sydney, Dec, 1998, pp. 64-80.

Jones, D J. 2001. Dust and dust control on unsealed roads. PhD Thesis, University of the Witwatersrand, Johannesburg, South Africa.

Jones, D J. 2003. Toward fit-for-purpose certification of road additives. Transportation Research Record, 1819 (2), TRB, National research Council, Washington, D.C., USA.

Jones, D J. and Paige-Green, P. 2000. Pavement management systems: Standard visual assessment manual for unsealed roads (TMH12). Pretoria: Transportek, CSIR (CR-2000/66), South Africa.

Jones, D J. and Ventura, D F C. 2004. A procedure for fit-for-purpose certification of non-traditional road additives. Pretoria: Transportek, CSIR. (CR-2004/45v2), South Africa.

Jones, D. 2002. Protocols for unsealed roads in KwaZulu Natal. Pretoria: CSIR Transportek. (CR2002-13), South Africa.

Jones, D., Paige-Green, P. and Sadzik, E. 2003. Development of Guidelines for Unsealed Road Assessment Transportation Research Record: Journal of the Transportation Research Board, No. 1819, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 287-296

Karan, M. 1977 Municipal Pavement Management System, PhD Thesis. University of Waterloo, Waterloo, Canada.

Keller, G. 2008 Unpaved roads design manual. U.S Forest Services. U.S.A

Kerali, H. G. R. 2000. Overview of HDM-4. The Highway Development and Management Series, Volume one, World Road Association, PIARC. World Bank, Washington D.C., USA.

Kerali, H. R., Snaith, M. S. and Koole, R. C. 1991 Economic Viability of Upgrading Low-Volume Roads. Transportation Research Record: Journal of the Transportation Research Board, No. 1291, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 34–40.

Lebo, J. and Schelling, D. 2000. Design and Appraisal of Rural Transport Infrastructure, Ensuring Basic Access for the Rural Communities, Technical Paper No 496, World Bank, Washington, D.C., USA.

Levy, H. 2004. Rural Roads and Poverty Alleviation in Morocco. Presented at Scaling Up Poverty Reduction: A Global Learning Process and Conference, Shanghai, China.

MacLeod, D.R. and W. Hidinger. 2008. Asset Management of Gravel Airstrips in The Yukon Canada, Proceedings. 7th International Conference on Managing Pavements, Calgary, Canada.

McPherson, Kevin and Bennett, Christopher R. 2005. Success factors for Road Management Systems. East Asia Pacific Transport Unit, The World Bank, Washington D.C., USA.

Mideplan 2004 Precios Sociales para la Evaluación Social de Proyectos, Ministerio de Planificación, Gobierno de Chile. Santiago, Chile

Ministry of Public Works of Chile (MOP) and DDQ Consultants 2008. Modelos de Deterioro de Caminos No Pavimentados, Final Report. Ministerio de Obras Públicas, Dirección Nacional de Vialidad, Santiago, Chile.

Ministry of Public Works of Chile (MOP). 2004. Instructivo para el Inventario de la Conservación Vial. Ministerio de Obras Públicas, Dirección Nacional de Vialidad, Subdirección de Mantenimiento, Departamento de Conservación, Santiago, Chile.

MOP 2007. Manual de Carreteras Volumen 7. Ministerio de Obras Públicas de Chile, Santiago, Chile.

MOPC, 2009. Plan Vial Participativo de Caminos Vecinales: Alto Paraná. Ministry of Public Works and Communications, Asunción, Paraguay

MTO 1989. Manual for Condition Rating of Gravel Surface Roads, SP-025, Ministry of Transportation of Ontario, Downsview, Ontario, Canada.

Mushule, N. K. 2000. Development of a Sustainable Network Level PMS for Tanzania: Concepts, Methods and Specifications. Ph.D. thesis. University of Dar es Salaam, Tanzania (in collaboration with the University of Birmingham, United Kingdom).

Mushule, N. K. and Kerali, H. R. 2001. Implementation of New Highway Management Tools in Developing Countries: A Case Study of Tanzania. Transportation Research Record 1344, pp. 51–60. TRB, National Research Council, Washington, D.C., USA.

MWH and World Bank 2005. Surfacing Alternatives for Unsealed Rural Roads. Report sponsored by the Transport and Rural Infrastructure Services Partnership (TRISP). TRISP-DFID/ World Bank Partnership. MWH New Zealand Ltd. and World Bank. Auckland, New Zealand

Namur, E. and de Solminihac, H. 2009 Roughness of Unpaved Roads: Estimation and Use as an Intervention Threshold. Transportation Research Record: Journal of the Transportation Research Board, No. 2101, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 10–16.

Netterberg, F and Paige-Green, P. 1988. Wearing courses for unsealed roads in southern Africa: A review. Proceedings of 8th Quinquennial Convention of South African Institute Civil Engineers and Annual Transportation Convention, Vol 2D, Paper 5, Pretoria, South Africa.

NITRR. 2009. Unsealed roads: Design, construction and maintenance TRH 20 Technical Recommendations for Highways (TRH), National Institute for Transport and Road Research, CSIR, Republic of South Africa, Pretoria, South Africa.

Ortíz, J., Snaith, M. and Costello, S. 2004 Determination of highway maintenance standards through multicriteria analysis. Proceedings of the Institution of Civil Engineers Transport v. 152, Issue TR1. United Kingdom pp. 1-9

Paige-Green, P. 1989. The influence of Geotechnical Properties on the Performance of Gravel Wearing Course Materials PhD thesis. University of Pretoria, South Africa.

Paige-Green, P. and Netterberg, F. 1987 Requirements and Properties of Wearing Course Materials for Unpaved Roads in Relation to Their Performance. Transportation Research Record: Journal of the Transportation Research Board, No. 1106, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 208-214.

Paige-Green, P. and Visser, A 1991. Comparison of the Impact of Various Unpaved Road Performance Models on Management Decisions. Transportation Research Record: Journal of the Transportation Research Board, No. 1291, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 137-141.

Pankaj, T. 2000. Framework for Quantifying Social and Economic Benefits from Rural Road Development; Some Thoughts and Practical Insights. World Bank, Washington D.C., USA.

Parsley, L. and Robinson, R. 1982. The TRRL Road Investment Model for Developing Countries (RTIM2). Laboratory Report 1057. Transport and Road Research Laboratory, Crowthorne, U.K.

Paterson, W. 1991 Deterioration and Maintenance of Unpaved Roads: Models of Roughness and Material Loss. Transportation Research Record: Journal of the Transportation Research Board, No. 1291, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 143-156.

Pienaar, P. and Visser, A. 1995 Management of Tertiary Road Networks in Rural Areas of South Africa. Proceedings of the Sixth International Conference on Low-Volume Roads. Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 14–27.

Plessis-Fraissard, M. 2007. Planning Roads for Rural Communities Transportation Research Record: Journal of the Transportation Research Board, No. 1989, Vol. 1, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 1–8.

Provencher, Y. 1995 Optimizing Road Maintenance Intervals. Proceedings of the Sixth International Conference on Low-Volume Roads. Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 199–207.

Raballand, G., Macchi, P. and Petracco, C. 2010 Rural Road Investment Efficiency: Lessons from Burkina Faso, Cameroon, and Uganda. The International Bank for Reconstruction and Development. The World Bank, Washington D.C., USA.

Ravallion, M. 2001. "The Mystery of the Vanishing Benefits: An Introduction to Impact Evaluation." World Bank Economic Review, 15(1): 115-140. The World Bank, Washington D.C., USA.

Roberts, P., Shyam, K.C. and Rastogi, C. 2006. Rural Access Index: A Key Development Indicator. Transport Paper No 10, World Bank, Washington, D.C., USA.

Robinson, R., Danielson, U. and Snaith, M. 1998. Road Maintenance Management: Concepts and Systems. Palgrave Macmillan, United Kingdom.

SADC 2003. Low-volume Sealed Roads Guidelines, Southern African Development Community, Gaborone, Botswana.

Sayers, M., T. Gillespie, and C. Queiroz. 1986. The International Road Roughness Experiment. World Bank, Washington, D.C., USA.

Soria M. and Fontenele E. 2003. Field Evaluation of Method for Rating Unsurfaced Road Conditions. Transportation Research Record: Journal of the Transportation Research Board, No. 1819, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 267-272

SSATP 2008. A User Guide to Road Management Tools, Sub-Saharan Africa Transport Policy Program. The World Bank, Washington D.C., USA.

TAC, 1997 Pavement Design and Management Guide, Transportation Association of Canada, Ottawa, Canada.

TAC, 2012. Pavement Asset Design and Management Guide (In Press), Transportation Association of Canada, Ottawa, Canada.

Tack, J. and Chou, Y 2005. Pavement Performance Analysis Applying Probabilistic Deterioration Methods. Transportation Research Record: Journal of the Transportation Research Board, No. 1769, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 20–27.

Tighe, D. 2000. Accessibility Planning. Document presented to the PIARC C20 Committee on Appropriate Development. Last version revised September 2006.

Tighe, D. 2007. Rural Roads Website http://www.ruralroads.org/en/indexen.shtml

Tighe, S. and Gransberg, D. 2011. Sustainable Pavement Maintenance Practices. National Cooperative Highway Research Program Report 365. Transportation Research Board of the National Academies, Washington, D.C., USA.

TRL and DFID 2004. A Guide to Pro-poor Transport Appraisal: The Inclusion of Social Benefits in the Road Investment Appraisal. Overseas Road Note 22, Berkshire, UK.

Turay, S. 1990 A Road Network Improvement System (RONIS) for Low Volume Roads in Developing Countries. Ph.D. dissertation, Department of Civil Engineering, University of Waterloo, Ontario, Canada.

Turay, S. and Haas, R 1990. Road Network Investment System for Developing Countries. Transportation Research Record: Journal of the Transportation Research Board, No. 1291, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 20-33.

van Zyl, G., Henderson, M. and Uys, R 2007. Applicability of Existing Gravel-Road Deterioration Models Questioned. Transportation Research Record: Journal of the Transportation Research Board, No. 1989, Vol. 1, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 217–225.

Visser and Hudson 1983. Design and Maintenance Criteria for Unpaved Roads. The Civil Engineer in South Africa, Vol. 25, No. 3

Visser, A. 1981. An Evaluation of Unpaved Road Performance and Maintenance. PhD Thesis, University of Texas, Austin, USA.

Visser, A. and Curtayne, P. 1987. The Maintenance and Design System: A Management Aid for Unpaved Road Networks. Transportation Research Record: Journal of the Transportation Research Board, No. 1106, Vol. 1, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 217–225

Visser, A., Villiers, E. and van Heerden, M. 1995. Optimizing Resources Through Unpaved Road Management System in the Cape Province of South Africa. Proceedings of the Sixth International Conference on Low-Volume Roads. Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the National Academies, Washington, D.C., USA. pp. 170–177.

Watanatada, T., Harral, C., Paterson, W., Bhandari, A. and Tsunokawa, K. 1987. The Highway Design and Maintenance Standards Model. 2 Vols. Johns Hopkins University Press, Baltimore, Maryland, USA.

World Bank 2001. Roads Economic Decision Model (RED) for Economic Evaluation of Low-volume Roads http://www.worldbank.org/afr/findings/english/find179.htm

World Bank 2007. Rural Road Management, Sub-Saharan Africa Transport Policy Program (SSATP) Website http://go.worldbank.org/8NOWQG7HC0

Appendix A
Recommendations for Project Level Analysis

A. 1 Surfacing Alternatives for Unsealed Rural Roads (MWH, 2005)

From a sustainable and technical standpoint, various maintenance techniques are now available to mitigate environmental impacts during rural roads improvements. Furthermore, these have been defined under well-developed decision frameworks for the selection of economic and technically optimum alternatives. For example, the study “Surfacing Alternatives for Unpaved Rural Roads” developed by MWH New Zealand Ltd. and The World Bank, proposed a decision framework to assist in the selection of the most suitable surfacing option of unpaved rural roads. A graphical presentation of this framework is illustrated in Figure A.1 (MWH, 2005).

Beside the conventional economic and financial evaluation, a key feature of the decision framework is the inclusion of the socioeconomic and environmental impacts for rural road investment in developing countries. The framework considers three steps:

1. Establish the demand for paved surface;
2. List suitable surfacing options for given circumstances;
3. Financial and Economic Evaluation, for the selection of the most appropriate surfacing alternative.

For every step in the framework, there are various methodologies that could be employed. Basically the most appropriate will be utilized based on the situation but also for overall consistency between roads. To assess the demand for paved surface the process assigns scores to critical aspects, such as: topography, climate, soil conditions, motorized and non-motorized traffic demand, impact of dust, community impact, future traffic increase and availability of quality materials. Scores range from 1 to 5 and are summed up to obtain total scores. Minimum scores are proposed by the study to define the surfacing demand of each specific road or project. Thresholds differ depending on funding and development levels.

The surfacing options are selected on the basis of engineering criteria. The preliminary study in this research evaluated a wide variety of possible surfacing techniques. Tables were made identifying for every surfacing option key evaluation aspects, such as: production and laying equipment, imported material, skill level, traffic, gradient, flood resistance, dust suppression, use of finite resources and maintenance capacity. Surfacing options that obtain the highest number of applicable aspects are evaluated in the third step of the framework.

The third step of the methodology consists of the financial and economic analysis of the selected alternatives. The study proposes to estimate the net present value under a private perspective, or financial analysis. For a public approach, or economic analysis, the study proposes the use of benefit cost analysis (BCA). When comparing several options, it is recommended the use of incremental benefit-cost ratio (B/C) to observe further indication of the relative benefits of each surfacing option.

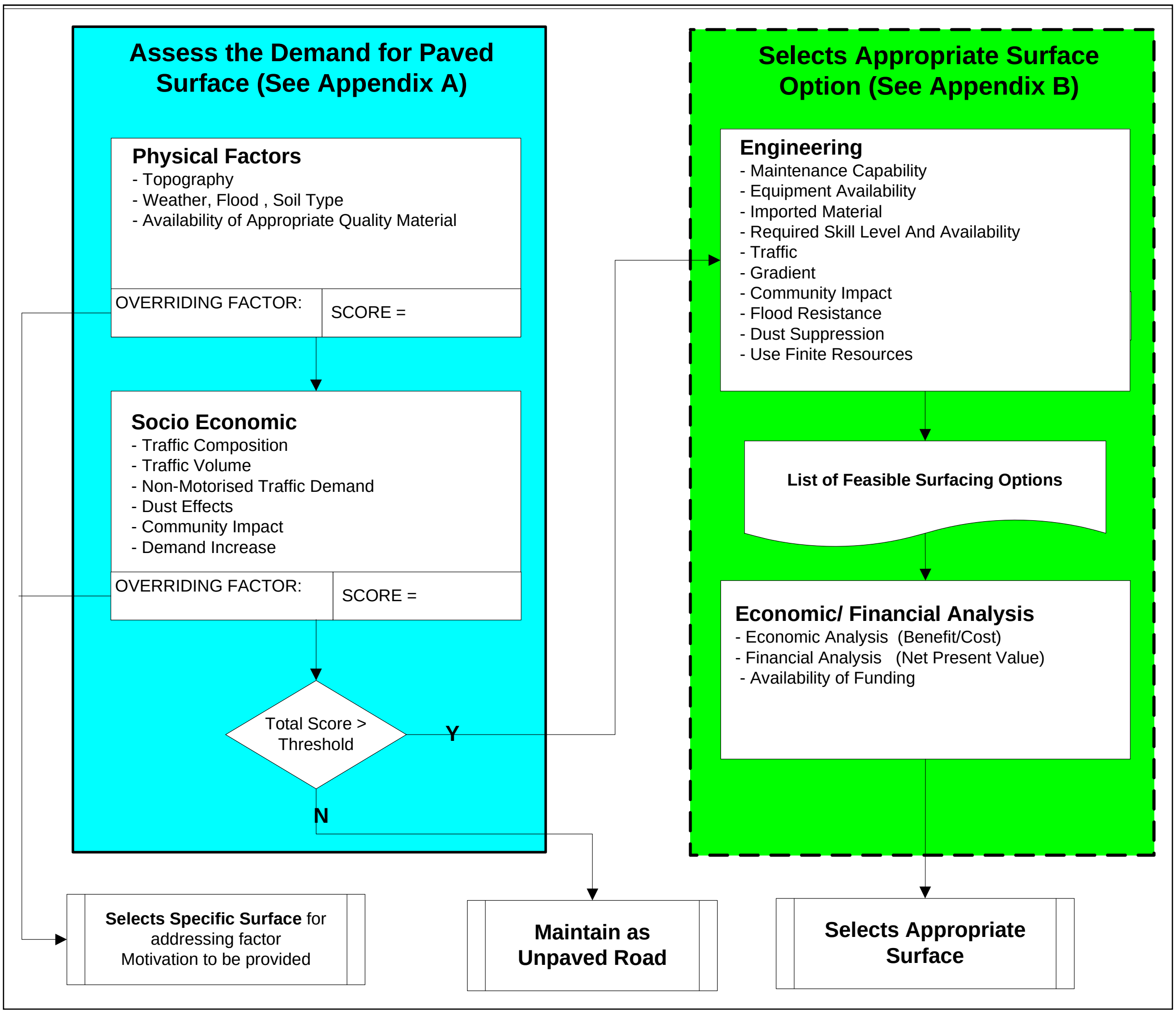


Figure A.1 Surfacing Alternative Decision Framework (MWH, 2005)

Appendix B

Example of Roads Structural Capacity Evaluations

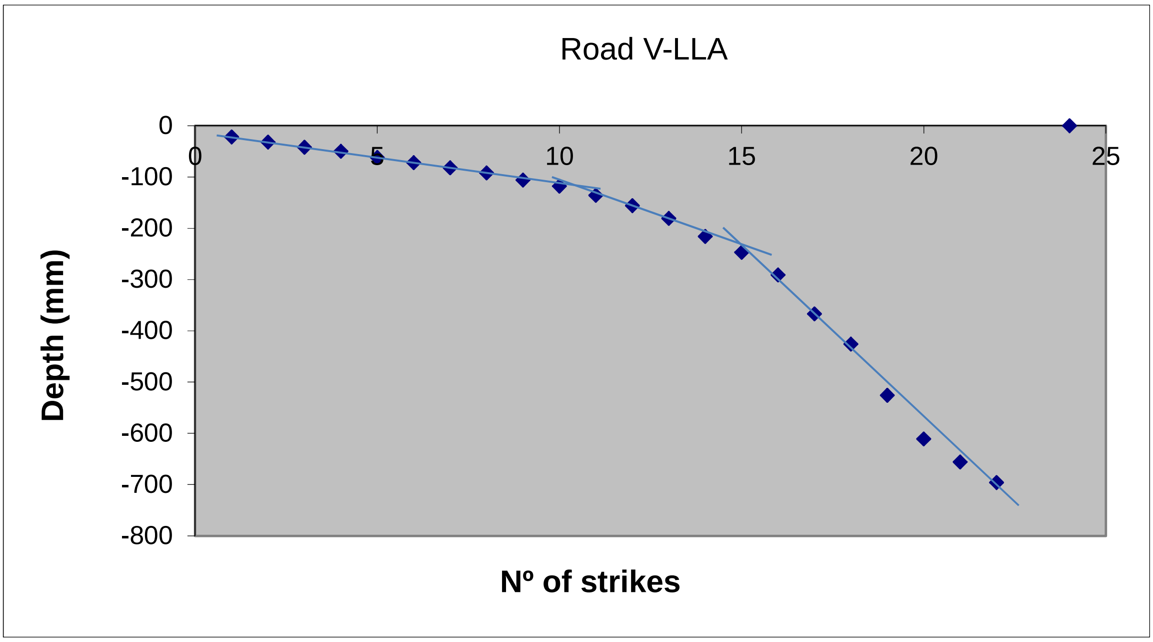
B.1. Structural Capacity Road V_LLA

Strikes	Cumulative Penetration (mm)	Penetration per Strike (mm)	Depth (mm)	Mean Ratio	**CBR (%)**
0	234		0		
1	256	22	-22	11.80	17.76
2	266	10	-32	11.80	17.76
3	276	10	-42	11.80	17.76
4	284	8	-50	11.80	17.76
5	296	12	-62	11.80	17.76
6	306	10	-72	11.80	17.76
7	316	10	-82	11.80	17.76
8	326	10	-92	11.80	17.76
9	340	14	-106	11.80	17.76
10	352	12	-118	11.80	17.76
11	370	18	-136	25.80	7.40
12	390	20	-156	25.80	7.40
13	415	25	-181	25.80	7.40
14	450	35	-216	25.80	7.40
15	481	31	-247	25.80	7.40
16	525	44	-291	64.14	2.67
17	601	76	-367	64.14	2.67
18	660	59	-426	64.14	2.67
19	760	100	-526	64.14	2.67
20	845	85	-611	64.14	2.67
21	890	45	-656	64.14	2.67
22	930	40	-696	64.14	2.67

Mean CBR (%)	**10.60**

Where:

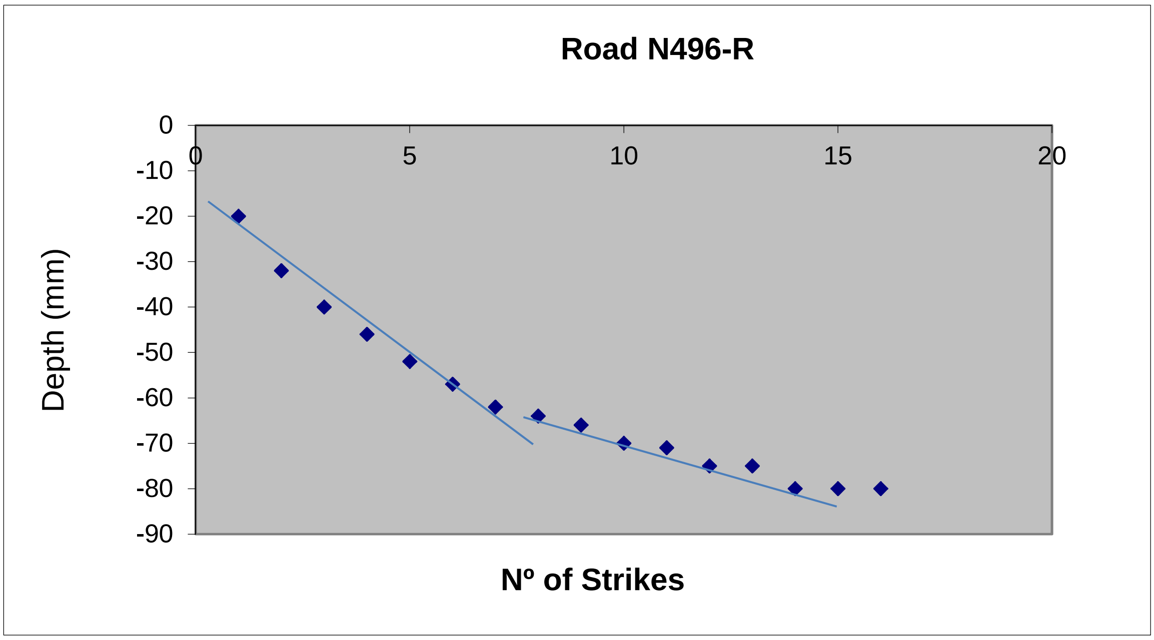
CBR % = $10^{(2.45-1.12*LOG(mean\ ratio))}$


Road V-LLA
0
-100
-200
-300
-400
-500
-600
-700
-800
Depth (mm)
0
5
10
15
20
25
Nº of strikes

B.2. Structural Capacity Road N 496_R

Strikes	Cumulative Penetration (mm)	Penetration per Strike (mm)	Depth (mm)	Mean Ratio	**CBR (%)**
0	230		0		
1	250.00	20.00	-20.00	16.00	12.63
2	262.00	12.00	-32.00	16.00	12.63
3	270.00	8.00	-40.00	6.00	37.89
4	276.00	6.00	-46.00	6.00	37.89
5	282.00	6.00	-52.00	6.00	37.89
6	287.00	5.00	-57.00	6.00	37.89
7	292.00	5.00	-62.00	6.00	37.89
8	294.00	2.00	-64.00	2.57	97.86
9	296.00	2.00	-66.00	2.57	97.86
10	300.00	4.00	-70.00	2.57	97.86
11	301.00	1.00	-71.00	2.57	97.86
12	305.00	4.00	-75.00	2.57	97.86
13	305.00	0.00	-75.00	2.57	97.86
14	310.00	5.00	-80.00	2.57	97.86
15	310.00	0.00	-80.00	2.57	97.86
16	310.00	0.00	-80.00	2.57	97.86

Mean CBR (%)	**68.46**



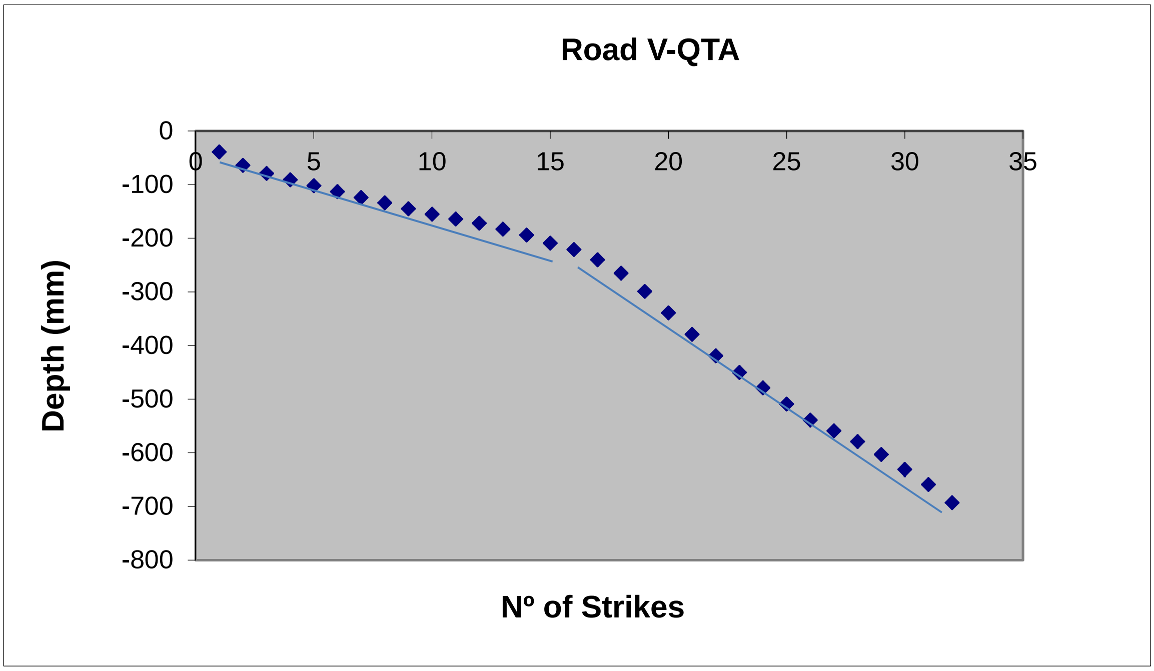
B.3. Structural Capacity Road V_QTA

Strikes	Cumulative Penetration (mm)	Penetration per Strike (mm)	Depth (mm)	Mean Ratio	**CBR (%)**
0	251		0		
1	290	39	-39	32	6
2	315	25	-64	32	6
3	330	15	-79	12	18
4	342	12	-91	12	18
5	353	11	-102	12	18
6	364	11	-113	12	18
7	375	11	-124	12	18
8	385	10	-134	12	18
9	396	11	-145	12	18
10	406	10	-155	12	18
11	415	9	-164	12	18
12	423	8	-172	12	18
13	434	11	-183	12	18
14	445	11	-194	12	18
15	460	15	-209	12	18
16	472	12	-221	12	18
17	491	19	-240	12	18
18	516	25	-265	30	6
19	550	34	-299	30	6
20	590	40	-339	30	6
21	630	40	-379	30	6
22	670	40	-419	30	6
23	701	31	-450	30	6
24	730	29	-479	30	6
25	760	30	-509	30	6
26	790	30	-539	30	6
27	810	20	-559	30	6
28	830	20	-579	30	6
29	854	24	-603	30	6
30	882	28	-631	30	6
31	910	28	-659	30	6
32	944	34	-693	30	6

Mean CBR (%)	**12**

Where:

CBR % = $10^{(2.45-1.12*LOG(mean\ ratio))}$



Road V-QTA
Depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
0
5
10
15
20
25
30
35
Nº of Strikes

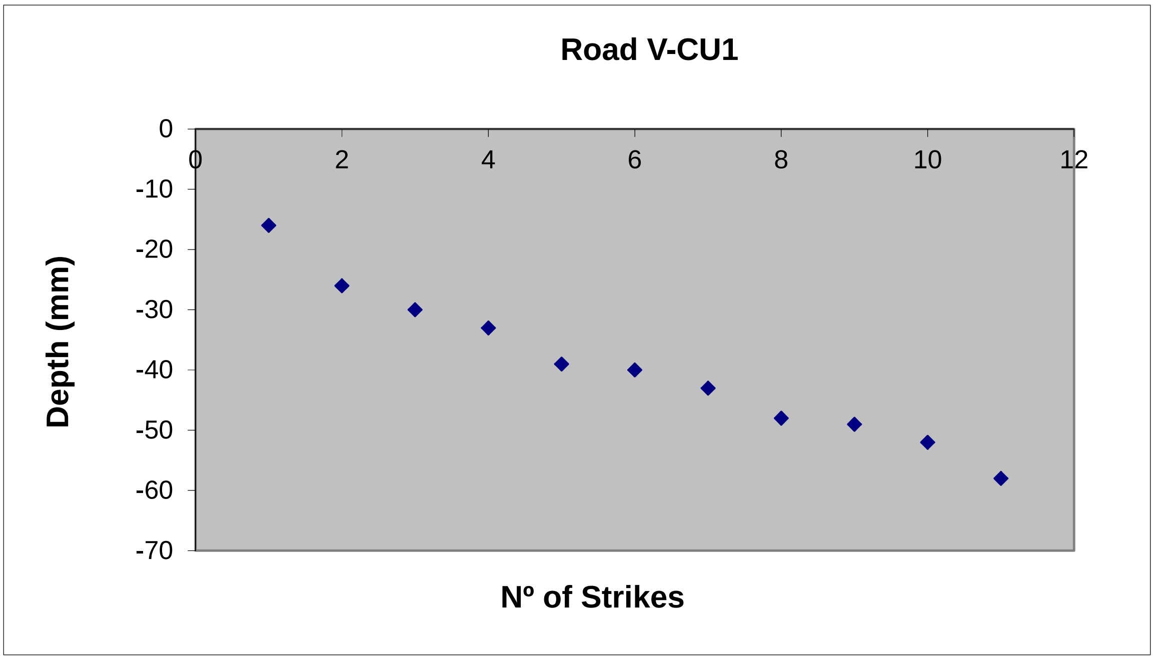
B.4. Structural Capacity Road V_CU1

Strikes	Cumulative Penetration (mm)	Penetration per Strike (mm)	Depth (mm)	Mean Ratio	**CBR (%)**
0	242		0		
1	258.00	16.00	-16.00	13.00	15.94
2	268.00	10.00	-26.00	13.00	15.94
3	272.00	4.00	-30.00	3.56	68.07
4	275.00	3.00	-33.00	3.56	68.07
5	281.00	6.00	-39.00	3.56	68.07
6	282.00	1.00	-40.00	3.56	68.07
7	285.00	3.00	-43.00	3.56	68.07
8	290.00	5.00	-48.00	3.56	68.07
9	291.00	1.00	-49.00	3.56	68.07
10	294.00	3.00	-52.00	3.56	68.07
11	300.00	6.00	-58.00	3.56	68.07

Mean CBR (%)	**58.59**

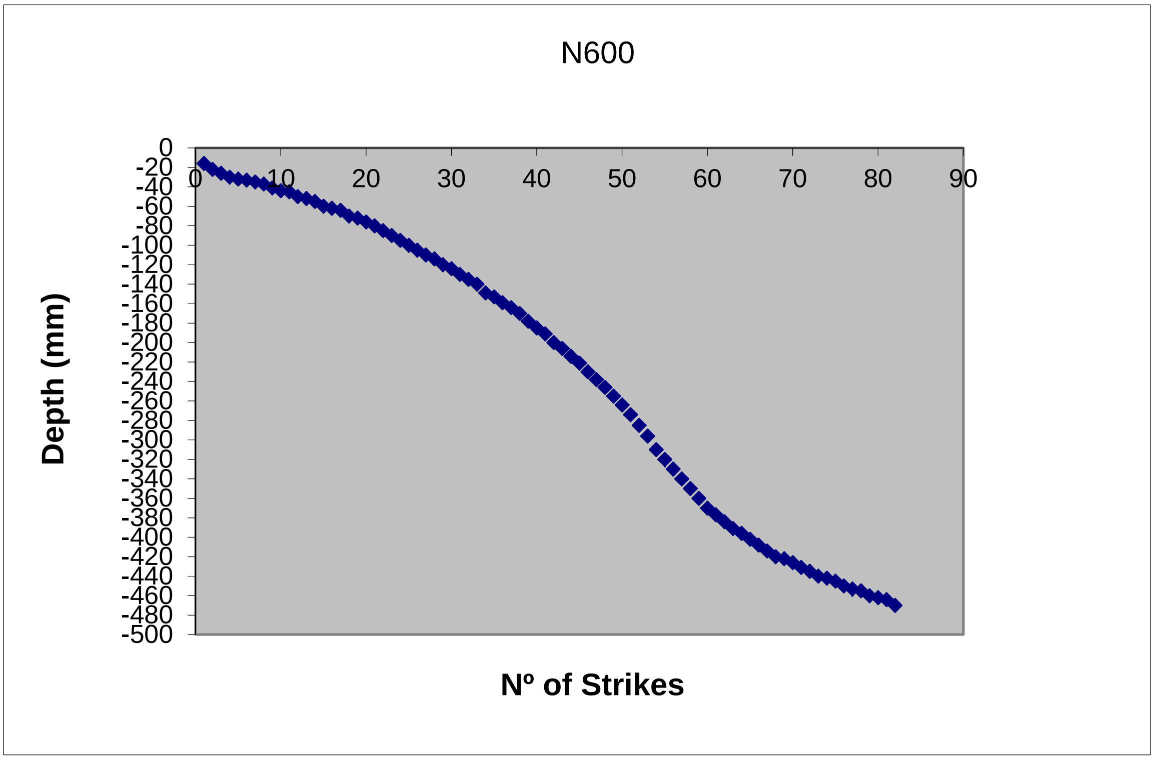
Where:

CBR % = $10^{(2.45-1.12*LOG(mean\ ratio))}$



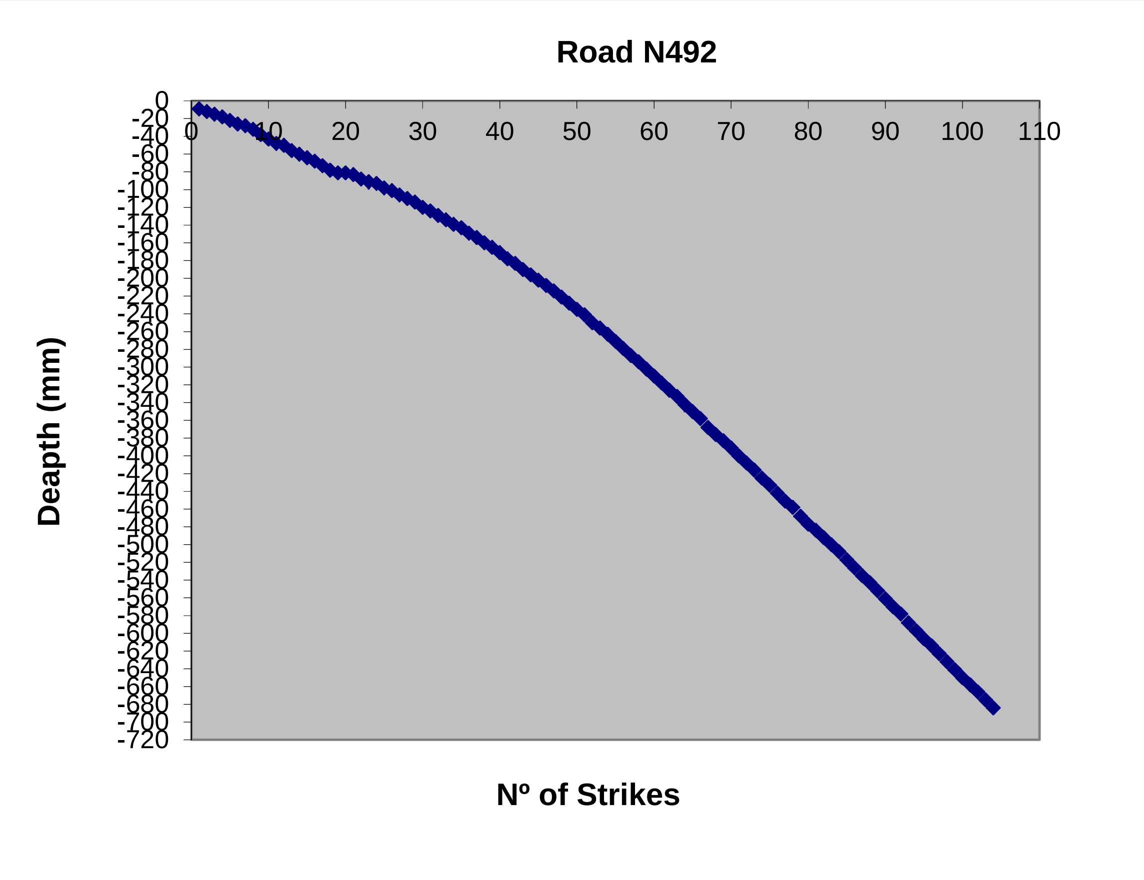
B.5. Structural Capacity Road N600

Strikes	Cumulative Penetration (mm)	Penetration per Strike (mm)	Depth (mm)	Mean Ratio	**CBR (%)**
0	240		0		
1	256.00	16.00	-16.00	16.00	12.63
2	262.00	6.00	-22.00	3.88	61.82
3	266.00	4.00	-26.00	3.88	61.82
4	270.00	4.00	-30.00	3.88	61.82
…	…	…	…	…	…
45	461.00	7.00	-221.00	7.29	30.44
46	470.00	9.00	-230.00	7.29	30.44
47	478.00	8.00	-238.00	7.29	30.44
48	486.00	8.00	-246.00	7.29	30.44
49	495.00	9.00	-255.00	7.29	30.44
50	504.00	9.00	-264.00	7.29	30.44
51	514.00	10.00	-274.00	10.60	20.03
52	525.00	11.00	-285.00	10.60	20.03
53	536.00	11.00	-296.00	10.60	20.03
54	550.00	14.00	-310.00	10.60	20.03
55	560.00	10.00	-320.00	10.60	20.03
56	570.00	10.00	-330.00	10.60	20.03
57	580.00	10.00	-340.00	10.60	20.03
58	590.00	10.00	-350.00	10.60	20.03
59	600.00	10.00	-360.00	10.60	20.03
60	610.00	10.00	-370.00	10.60	20.03
61	617.00	7.00	-377.00	6.25	36.19
62	624.00	7.00	-384.00	6.25	36.19
63	631.00	7.00	-391.00	6.25	36.19
64	636.00	5.00	-396.00	6.25	36.19
65	642.00	6.00	-402.00	6.25	36.19
66	648.00	6.00	-408.00	6.25	36.19
67	654.00	6.00	-414.00	6.25	36.19
68	660.00	6.00	-420.00	6.25	36.19
69	662.00	2.00	-422.00	3.57	67.74
70	666.00	4.00	-426.00	3.57	67.74
71	671.00	5.00	-431.00	3.57	67.74
72	675.00	4.00	-435.00	3.57	67.74
73	680.00	5.00	-440.00	3.57	67.74
74	682.00	2.00	-442.00	3.57	67.74
75	685.00	3.00	-445.00	3.57	67.74
76	690.00	5.00	-450.00	3.57	67.74
77	693.00	3.00	-453.00	3.57	67.74
78	695.00	2.00	-455.00	3.57	67.74
			Mean CBR (%)		**48.13**


N600
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
-260
-280
-300
-320
-340
-360
-380
-400
-420
-440
-460
-480
-500
0
10
20
30
40
50
60
70
80
90
Depth (mm)
Nº of Strikes

B.6. Structural Capacity Road N492

Strikes	Cumulative Penetration (mm)	Penetration per Strike (mm)	Depth (mm)	Mean Ratio	**CBR (%)**
0	242		0		
1	251.00	9.00	-9.00	4.23	56.03
2	254.00	3.00	-12.00	4.23	56.03
3	257.00	3.00	-15.00	4.23	56.03
4	260.00	3.00	-18.00	4.23	56.03
5	264.00	4.00	-22.00	4.23	56.03
6	268.00	4.00	-26.00	4.23	56.03
7	270.00	2.00	-28.00	4.23	56.03
8	274.00	4.00	-32.00	4.23	56.03
9	280.00	6.00	-38.00	4.23	56.03
10	285.00	5.00	-43.00	4.23	56.03
	…	…	…	…	…
35	385.00	4.00	-143.00	4.23	56.03
36	391.00	6.00	-149.00	4.23	56.03
37	396.00	5.00	-154.00	4.23	56.03
38	402.00	6.00	-160.00	4.23	56.03
39	407.00	5.00	-165.00	4.23	56.03
40	413.00	6.00	-171.00	6.33	35.66
41	420.00	7.00	-178.00	6.33	35.66
42	425.00	5.00	-183.00	6.33	35.66
43	432.00	7.00	-190.00	6.33	35.66
44	438.00	6.00	-196.00	6.33	35.66
45	444.00	6.00	-202.00	6.33	35.66
46	450.00	6.00	-208.00	6.33	35.66
47	456.00	6.00	-214.00	6.33	35.66
48	463.00	7.00	-221.00	6.33	35.66
49	470.00	7.00	-228.00	6.33	35.66
50	477.00	7.00	-235.00	6.33	35.66
51	483.00	6.00	-241.00	6.33	35.66
52	492.00	9.00	-250.00	8.36	26.13
53	498.00	6.00	-256.00	8.36	26.13
54	505.00	7.00	-263.00	8.36	26.13
55	513.00	8.00	-271.00	8.36	26.13
56	521.00	8.00	-279.00	8.36	26.13
57	529.00	8.00	-287.00	8.36	26.13
58	536.00	7.00	-294.00	8.36	26.13
59	544.00	8.00	-302.00	8.36	26.13
60	552.00	8.00	-310.00	8.36	26.13
			Mean CBR (%)		**38.44**


Road N492
Deapth (mm)
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
-260
-280
-300
-320
-340
-360
-380
-400
-420
-440
-460
-480
-500
-520
-540
-560
-580
-600
-620
-640
-660
-680
-700
-720
0 10 20 30 40 50 60 70 80 90 100 110
Nº of Strikes

Appendix C

Maintenance Treatment Costs and Costs per Budget Scenario

C.1 Unit Costs of Maintenance Treatments

Maintenance Treatment	UNIT	CAD$
Local Gravel/ Pothole Patching	m^3	15.58
Grading	km	89.79
Culvert Replacement	m	296.49
Gravel Application	m^3	22.69

C.2 Maintenance Activities and Costs for Low Budget

				Low Budget	
MAINTENANCE TREATMENT	**Maint Type**	**Surface**	**UNIT**	**CAD$**	**Assumption**
Minimum Grading Policy (0.5 LT. 2 MT. 3 HT)	**Basis**	**E/G**	km	89.79	Grading no compaction
Local Gravel/ Pothole Patching	**Routine/ Rehab**	**E/G**	km	77.92	5m^3 (50 potholes/km of 1mx1mx10cm)
Grading	**Routine/ Rehab**	**E/G**	km	89.79	light
Culvert Replacement	**Rehab**	**E/G**	km	370.61	1 per 8 km. 10m long
Graveling	**Rehab/ Upgrade**	**E/G**	km	7,939	50mm depth. 7m wide road

C.3 Maintenance Activities and Costs for Moderate Budget

MAINTENANCE TREATMENT	Maint Type	Surface	UNIT	Moderate Budget	
				CAD$	Assumption
Minimum Grading Policy (0.5 LT. 2 MT. 3 HT)	**Basis**	**E/G**	km		
Local Gravel/ Pothole Patching	**Routine/ Rehab**	**E/G**	km	124.68	$8m^3$ (80 potholes/km of 1mx1mx10cm)
Grading	**Routine/ Rehab**	**E/G**	km	134.68	heavy (with localized compaction)
Culvert Replacement	**Rehab**	**E/G**	km	494.14	1 per 6 km. 10m long
Graveling	**Rehab/ Upgrade**	**E/G**	km	15,879	100mm depth. 7m wide road

C.4 Maintenance Activities and Costs for High Budget

MAINTENANCE TREATMENT	Maint Type	Surface	UNIT	High Budget	
				CAD$	Assumption
Minimum Grading Policy (0.5 LT. 2 MT. 3 HT)	**Basis**	**E/G**	km		
Local Gravel/ Pothole Patching	**Routine/ Rehab**	**E/G**	km	187.02	$12m^3$ (120 potholes/km of 1mx1mx10cm)
Grading	**Routine/ Rehab**	**E/G**	km	269.37	heavy (with total compaction)
Culvert Replacement	**Rehab**	**E/G**	km	741.22	1 per 4 km. 10m long
Graveling	**Rehab/ Upgrade**	**E/G**	km	23,819.30	150mm depth. 7m wide road

C.4 Upgrade Treatments

Upgrade Treatments	**Maint Type**	**Surface**	UNIT	CAD$	Assumption
Upgrade Earth to Gravel	**Upgrade**	**E**	km	23,819	150mm depth. 7m wide road
Upgrade Earth to Gravel (with geometrical design)	**Upgrade**	**E**	km	83,991	150mm depth. 10m wide road
Upgrade Gravel to Double Surfacing	**Upgrade**	**G**	km	235,782	7 m wide

Appendix D

Sample of Condition Survey Sheet

GOBIERNO DE CHILE MOP Dirección de Vialidad

FICHA DE INSPECCION VISUAL DE CAMINOS NO PAVIMENTADOS

Hoja N° ___ de ___

Nombre del camino ___ Rol ___ Código ___

Encargado ___ Fecha ___ / ___ / ___

Ubicación		Ancho Calzada	Tipo de material	Perfil transversal (bombeo)		Drenaje		Calaminas	Ahuellamiento	Material grueso (**)		Baches			Erosión (***)		Observaciones particulares
								Profundidad	Profundidad	Tipo	Tamaño máximo		Dimensiones (cm)		Severidad (cm)		
K.I.	K.F.	m	N , S , E (*)	B	M	B	M	cm	cm	A: Afloramiento I: Inscrustacion	cm	N°	Diámetro	Profundidad	Ancho	Profundidad	

Notas Generales:

(*) Tipo de material: N=Natural , S=Seleccionado , E=Superficie Estabilizada

(**) Llenar solo para caminos de tierra

(***) Si fuera de la unidad de muestreo (50m) se registra gran erosión, se registra.

Appendix E

Case Studies Inventory and Field Data

E.1. Typical Surface Defects and Distresses observed in Chile Case Study

(a)

(b)

Figure E.1.1 Corrugations in Roads (a) N462 and (b) N480

(a)

(b)

Figure E.1.2 Erosion in Roads (a) N474 and (b) Local Road V_BAB

(a)

(b)

Figure E.1.3 Drainage Problems in Roads (a) N498 and (b) Local Road V_LLA

(a)

(b)

Figure E.1.4 Erosions Caused by Unstable River Banks and Drainage in Roads (a) N474 and (b) N620

E.2. Inventory Data Chile Case Study

Table E.2.1 Chile Case Study Inventory Data: Gravel Roads

Road Data									
Section Code	Road Code	Road Category	Road Length (m)	Surface Type	Traffic Volume (AADT)	Traffic Level	Traffic Characteristics	Population	Population Proportion %
2	N620	Secondary	13900	Gravel	100	Moderate	3 buses*2, forestry trucks, trucks with gravel from river, 1 ambulance*2, 2 school buses*2	210	3,8%
3	N496_R	Secondary	2000	Gravel	30	Low	Sum of traffic of two earth roads + 50% additional traffic	44	0,8%
8	N600	Secondary	9700	Gravel	70	Moderate	1bus*2, 2 school bus*2	560	10,0%
14	N490	Secondary	4000	Gravel	50	Low	2 commercial trucks (vegetable/chicken)*2	80	1,4%
15	N480	Secondary	7700	Gravel	100	Moderate	2 buses*2, important traffic of forestry trucks (3 forestry companies), important traffic of agricultural truck + workers bus, 2 school buses*2	648	11,6%
16	N462	Secondary	3300	Gravel	30	Low	1 ambulance*2, 1 school bus*2, muni, comerciantes	40	0,7%
19	N616	Secondary	3200	Gravel	20	Low	1 ambulance*2, commercial trucks	36	0,6%
20	N486	Secondary	5800	Gravel	40	Low	1bus*2, 1 ambulance*2, 2 school bus *2	80	1,4%
21	N466	Secondary	11700	Gravel	80	Moderate	3 school bus*2, 3*bus*2, 5 forestry trucks*2, 1 ambulance*2, important traffic from municipality of Trehuaco	320	5,7%
26	N482	Secondary	11200	Gravel	60	Moderate	2 school bus*2, 3*bus*2, 4 forestry trucks*2, 1 ambulance*2	120	2,2%
28	N478	Secondary	5300	Gravel	80	Moderate	2 school bus*2, 3*bus*2, 8 forestry trucks*2, 2 ambulance*2, important traffic from municipality	400	7,2%
34	N610	Secondary	10200	Gravel	60	Moderate	2bus*2, important traffic of forestry trucks, some traffic of busses with workers	260	4,7%
36	N510	Secondary	4900	Gravel	40	Low	1 school bus*2 until entrance of the road, traffic increases during summer	100	1,8%
37	N60-R	Secondary	15900	Gravel	220	High	3 school bus*2, 4*bus*2trips*2, 10 traffic of forestry trucks, 2 ambulance*2, important traffic from municipality	1000	17,9%
38	N60-R	Secondary	15900	Gravel	260	High	3 school bus*2, taxi, police, 7*bus*3trips*2, 10 traffic of forestry trucks, 2 ambulance*2, important traffic from municipality	1000	17,9%
39	N68	Secondary	11000	Gravel	100	Moderate	school bus*2, 2*bus*2, 2 ambulance*2, important traffic from municipality (less traffic since Confluencia Bridge is restricted to heavy traffic, forestry trucks)	680	12,2%

Table E.2.2 Chile Case Study Inventory Data: Earth Roads

Road Data									
Section Code	Road Code	Road Category	Road Length (m)	Surface Type	Traffic Volume (AADT)	Traffic Level	Traffic Characteristics	Population	Population Proportion %
1	V_LLA	Local	550	Earth	4	Low	Local traffic and municipal pickup ocassionaly	4	0,4%
4	N496_T	Secondary	2800	Earth	6	Low	Local traffic and municipal pickup ocassionaly	28	3,0%
5	V_QTA	Local	1400	Earth	14	Low	Local traffic and municipal pickup ocassionaly	30	3,2%
6	V_CU1	Local	400	Earth	10	Low	Local traffic and municipal pickup ocassionaly	21	2,3%
7	V_CU2	Local	500	Earth	10	Low	Local traffic and municipal pickup ocassionaly	30	3,2%
9	N498	Secondary	2000	Earth	14	Low	1 school bus*2	75	8,0%
10	V_BQH	Local	850	Earth	8	Low	1 ambulance*2	10	1,1%
11	N474	Secondary	5000	Earth	12	Low	Local traffic and municipal pickup ocassionaly	20	2,1%
12	V_BA1	Local	1500	Earth	30	Low	1 ambulance*2	40	4,3%
13	V_BA2	Local	1800	Earth	8	Low	Local traffic and municipal pickup ocassionaly	18	1,9%
17	V_BAB	Local	1100	Earth	6	Low	Local traffic and municipal pickup ocassionaly	20	2,1%
18	V_CAB	Local	1700	Earth	6	Low	NMT 2 horses carriages*2	16	1,7%
22	N492	Secondary	6800	Earth	40	Low	1 school bus*2, 1*bus*2, 1 ambulance*2	105	11,3%
24	V_HLB	Local	1700	Earth	10	Low	Local traffic and municipal pickup ocassionaly	10	1,1%
25	V_LNJ	Local	1200	Earth	16	Low	Local traffic and municipal pickup ocassionaly	6	0,6%
27	N500	Secondary	3000	Earth	20	Low	1 school bus*2, 1 ambulance*2	52	5,6%
29	V_PSA	Local	1300	Earth	16	Low	1 school bus*2, 1 ambulance*2, local traffic	20	2,1%
30	V_CHU	Local	3000	Earth	30	Low	1 ambulance*2, local traffic, police and municipal pickup ocassionaly	120	12,9%
31	V_AMI	Local	2000	Earth	6	Low	Local traffic and municipal pickup ocassionaly	20	2,1%
32	N494	Secondary	5400	Earth	60	Moderate	1 ambulance*2, local traffic and forestry trucks	200	21,4%
33	V_LPL	Local	1600	Earth	30	Low	1 school bus*2, 1 ambulance*2, forest guard	80	8,6%
35	V_RCM	Local	2000	Earth	10	Low	Local traffic	8	0,9%

E3. Condition Evaluation Data Chile Case Study

Table E.3.1 Chile Case Study Condition Evaluation: Gravel Roads (Field 1 and 2)

Road Data		Previous Maintenance and Condition Evaluations				Previous Maintenance and Condition Evaluations			
		sep-08				April-09			
Section Code	Road Code	Previous Maintenance	UPCI	Condition	Comments	Previous Maintenance	UPCI	Condition	Comments
2	N620	Grading May, June/08	7,1	Good	Drainage problem (lack of side drains and slope), w ater in w heelpath causes erosion	Local regravel and grading Aug/08, Sept 08, April/09 (el sauce). Grading Sept, Oct, Nov,	8,1	Very Good	Oversized granular material in Km 6.3 increses roughness in slope
3	N496_R	Bridge replaced June/08	3,5	Very Poor (w inter closure)	Section presents w inter closure due to mud, rest of road in better condition	Local regravel and grading Aug, Sept/08. Local grading Jan/09	8,4	Very Good	Lack of granular material, available gravel presents oversize. Poor drainage on w heelpaths. Km 0.3 and Km 1.4 presents important erosion, river protections should be reinforced. Km 0.6 w ith roughness problems due to presence of a rock.
8	N600		6,8	Good	Irregular transverse profile, rutting caused by lack of gravel. Erosion observed in first kilometer of the road.	Regravel and grading Sept/08. Local grading Jan, March/09	9	Very Good	Lack of granular material in several sections of the road causes corrugations. Rutting caused by accumulated material in the centre of the road. Grading suggested.
14	N490		6,3	Good	Erosion in sections w ith steep slopes	Grading Nov, Dic/08 , Jan, Feb, March/09 (local)	7,4	Good	Irregular transverse profile causes rutting in horizontal curves
15	N480	Grading June/08	6,5	Good	Corrugations in steep slopes	Grading Oct, Nov/08	4,8	Regular	Road w ith good profile, but presents important corrugations in sections w ith slopes
16	N462		3,9	Poor	Erosion and corrugations in steep slope		2,4	Very Poor	Corrugations in slopes. Local erosion problem due to poor side drainage.
19	N616	Regravel & grading Sept/08	8,3	Very Good	Grading and transverse slope required. Surface w ith good material.	Grading Jan/09	8,3	Very Good	Rutting, grading required. Good gravel accumulated in the sides of the road.
20	N486		4,7	Regular	Lack of material and side slope. Oversized aggregate produces rough surface.	Grading Oct, Nov/08; Culvert replacement Oct/08	5,5	Good	Corrugations, lack of gravel to improve irregular transverse profile.Oversized aggregates increase roughness of the road.
21	N466	Grading May, June, Sept/08	9,4	Very Good	Grading required, corrugations observed in steep slopes.	Grading Oct, Nov/08	6,3	Good	Road in a general good condition, specific sections present slight corrugations and rutting. Grading required, good material available in the sides of the road.
26	N482	Bridge colapsed Aug/08	7,2	Good	Lack of granular material, sections w ith erosion and oversized aggregates. Important bus traffic.	Local grading Feb, March/09. Local regravel March/09 (use of oversize river aggregate)	8	Very Good	Road presents oversized granular material. Drainage problems caused by gravel accumulate in the sides of the road.
28	N478	Grading May, Sept/08	N,E		Not evaluated, blader w orking	Grading and regravel 9/April/09	8	Very Good	Potholes in sections w ith poor compaction of granular material, observed as corrugations w ith extended w avelengths
34	N610	Grading May,June, Sept/08	10	Very Good	Road in good condition, some sections w ith local erosion problems.	Regravel Nov/08; Grading Oct, Nov/08. Local (Membrillar) grading in eroded section March/09	7,7	Good	Slight corrugation in slopes. Good profile and granular observed in the road
36	N510	Local regravel Aug/08	5,9	Good	Oversize granular material in all the section, poor roughness, local drainage problems during w inter.	Local grading March/09 (Rincomávida)	5,4	Regular	Potholes repaired w ith granular material. Side drains need to be cleared. Importnat rutting observed in some sections.
37	N60-R		N,E			Grading Sept, Oct, Nov/08. Local grading Jan/09 (Portezuelo-Panguilemu). Local regravel Feb/09 (Orilla)	10	Very Good	Grading required, good gravel accumulated in the sides of the road
38	N60-R		N,E			Grading Sept, Oct, Nov/08. Local grading Jan/09 (Portezuelo-Panguilemu).	8,26	Very Good	Irregular longitudinal profile, similar to corrugations, caused by poor compaction of granular material
39	N68		N,E			Grading Sept, Oct/08. Local regravel Feb/09 (Orilla)	10	Very Good	Grading required, good gravel accumulated in the sides of the road

Table E.3.2 Chile Case Study Condition Evaluation: Gravel Roads (Field 3 and 4)

Section Code	Road Code	sep-09				sep-10		oct-11				
		Previous Maintenance	UPCI	Condition	Comments	2010 Maint type	2010 Maint Effect	2011 Maintenance	2011 Maint type	2011 Maint Effect	UPCI	Condition
2	N620	Local regravel and grading (Sauce) April, June/09	6,2	Good	Poor drainage produces transverse erosion that crosses the road, culvert has to be extended. Beginning of section presents potholes of moderate severity.	Preventive Grading	3,5	Perfilado una vez al mes (sección prueba), ripio primeros 1,5 kms. Se realizó un ensanche local (global)	Preventive Grading-Rehabilitation	4,25	8,3	Very Good
3	N496_R	Local grading and regravel Aug/08. Local grading and regravel emergency area June, July/09. Grading week before evaluation (28/Sept/09)	2,8	Poor	One side of the road presents accumulated gravel, generating drainage problems and water accumulation in the wheel path. Road surface presents poor natural material.	Minimum Grading	1	1 Perfilado anual realizado por municipalidad	Minimum Grading	1	6,1	Good
8	N600	Bridge repaired (Cucha Urrejola) april/09, Rlocal regravel (Cucha and Llahuen) May, July/09. Local regravel in emergency section (Cucha Urrejola) Aug/09	5,7	Good	Effective road width is reduced by vegetation in side drains. Rutting starting to appear due to poor side slope. Corrugations starting to appear in wheelpaths with lack of gravel.	Local Regravel + Minimum Grading	2,5	3 Perfilados anuales vialidad, se tiró ripio en sectores con ensanche de vialidad	Local Regravel + Minimum Grading	2,5	9,5	Very Good
14	N490	Local grading and regravel (Carrullanca) April, May, June, Aug/09 and Mayo, Junio/09 (Bs As).	6,2	Good	Slight corrugations in internal wheelpath in horizontal curve. In the future, dainage problem could cause erosion in the side of the road.	Preventive Grading	3,5	2 Perfilados anuales realizados por municipalidad	Preventive Grading	3,5	7,7	Good
15	N480	Grading and regravel 5/July/09)	6,5	Good	Good side drains. Road requires gravelling of new material and grading material accumulated in the side. Compaction required in sections with corrugations.	Minimum Grading	1	2 Perfilados anuales vialidad	Minimum Grading	1	7,1	Good
16	N462	Grading May/09	4,2	Poor	Side erosion and corrugation in slopes, good drainage and profile though. Material required in slopes.	Preventive Grading	3,5	2 Perfilados anuales	Preventive Grading	3,5	3,4	Poor
19	N616		9	Very Good	Rutting caused by poor side slope. Good gravel, road in general is in very good condition	Minimum Grading	1	No se mantuvo en 2011	No maintenance	0	8,3	Very Good
20	N486	Local regravel May/09 and grading June, July/09 (Cabrería)	7,6	Good	Gravel required, corrugations and poor side slopes.	Preventive Grading	3,5	2 Perfilados anuales vialidad	Preventive Grading	3,5	7,7	Good
21	N466	Bridge and erosion repaired in Panguilemu+culvert replaced in Cabrería June/09. Regravel in river crossing in Panguilemu July, Aug, Sept/09	5,5	Good	Corrugations observed in horizontal curve.Side slopes need to be improved and side drains need to be cleaned. Road presents good condition in general.	Minimum Grading	1	4 perfilados anuales (Global)	Minimum Grading	1	9,5	Very Good
26	N482	Erosion repaired near school June/09, bridge repaired in Trancoyán Sept/09	6,5	Good	Wide and good side drains. Drainage problems caused by poor side slopes, potholes are starting to appear.	Preventive Grading	3,5	[illegible] Trancoyan. Tramo prueba ripio y perfiló Claro y	Rehabilitation	5	8,4	Very Good
28	N478	Grading Sept/09	5,8	Good	Gravel required. Side slope needs to be improved. Corrugations and potholes are starting to appear. Condition was poor before 18/Sept, water cumulation in one wheelpath was solved with grading.	Minimum Grading	1	2 Perfilados anuales por municipalidad	Minimum Grading	1	7,0	Good
34	N610	Grading April, Sept/09 and local regravel June, July/09	6,5	Good	Section with good gravel, profile and drainage. Main problem caused by moderate corrugations, which turn to be severe in steep slopes.	Minimum Grading	1	4 perfilados al año (Global)	Minimum Grading	1	5,0	Regular
36	N510	Local grading Rincomávida Aug/09	6,5	Good	Drainage in regular condition, side slope required. Rutting observed, grading required. Erosion is not transverse.	Minimum Grading	1	2 Perfilado anual realizado por municipalidad	Minimum Grading	1	9,2	Very Good
37	N60-R	Local grading Portezuelo-Chudal May, Aug, 10/sept/09	5,5	Good	Gravel required, potholes and corrugations formed by braking zone in the entrance of bridge.	Minimum Grading	1	3 Perfilado anual realizado por vialidad	Less than Minimum Grading	1	6,2	Good
38	N60-R		N.E.	N.E.		Minimum Grading	1	3 Perfilado anual realizado por vialidad	Less than Minimum Grading	1	5,9	Good
39	N68	Local regravel in Orilla May/09, Emergency regravel and grading of erosion in Orilla June/09	8,8	Very Good	Water accumulated in the side of the road caused by poor side slope to culvert. In the end of the section slight rutting (horizontal curve), gravel required to solve the problem	Minimum Grading	1	3 Perfilado anual realizado por vialidad	Minimum Grading	1	6,3	Good

Table E.3.3 Chile Case Study Condition Evaluation: Earth Roads (Field 1 and 2)

Section Code	Road Code	sep-08				April-09			
		Previous Maintenance	UPCI	Condition	Comments	Previous Maintenance	UPCI	Condition	Comments
1	V_LLA		5,8	Very Poor (w inter closure)	Very poor condition, w inter closure caused by poor drainage and mud.		7,4	Good	
4	N496_T		3,1	Very Poor (w inter closure)	Very poor condition, w inter closure caused by poor drainage and mud.	Local grading Jan/09	5,4	Regular	Local drainage problem in Km 0.6, culvert missing. Oversized gravel in surface. Narrow road w ith poor grading. Potholes starting to appear in slopes.
5	V_QTA		4,6	Very Poor (w inter closure)	Important erosion problems at the end of the road causes w inter closure.	Local grading Jan/09	6	Good	Erosion in slopes, drainage and transverse profile needs to be inproved in sections w ith problems.
6	V_CU1		7,7	Very Good	Local drainage problems	Local grading Jan, March/09	4,3	Regular	
7	V_CU2		4,9	Regular	Drainage problems in some sections, mud acummulated betw een w heelpaths. Very narrow road.	Local grading Jan, March/09	7,8	Good	
9	N498		2,8	Very Poor (w inter closure)	Excesive erosion in the w heel path produces road closure. Some sections present dangerous erosion in the side of the road. Gravel observed in some sections.	Grading Sept/08	9,2	Very Good	Excess of gravel accumulated in the side of the road, needs grading and conections w ith draining system. Some erosion caused by river need to be reinforced.
10	V_BQH		4,7	Regular	Potholes in w heelpaths and rutting caused by poor drainage. Access of an ambulance required.	Grading Aug/08	5,6	Good	
11	N474		2,3	Very Poor (perm. closure)	Extreme erosion of w heelpaths observed in slopes. Section in Km 2.1 presents dangerous erosion in the side of the road.	Grading and regravel Sept/08 (Sector Los Maquis), Grading Dic/08	6,4	Good	Recent grading improved erosion problem observed after w inter. Regular rutting observed w ithin and betw een w heel paths.
12	V_BA1		3,7	Very Poor (w inter closure)	Important erosion and w ater flow in centreline caused by poor drainage.	Grading Dic/08 and Jan/09	3,6	Poor	
13	V_BA2		3,7	Very Poor (w inter closure)	Important erosion and w ater flow in centreline caused by poor drainage.	Grading Dic/08 and Jan/09	N.E		
17	V_BAB		7	Good	Erosion observed in centreline		6,6	Good	
18	V_CAB		3,3	Poor	Important erosion caused by poor drainage. Winter closures. Culvert missing in a section.	Culvert repair Oct/08, grading Ene/09	7,3	Good	Erosion in centreline caused by hourse transit. Side drain required in side of the road
22	N492		6,2	Good	Lack of selected material, exposed rocks are observed.	Grading Nov/08	8,4	Very Good	Clay soil, oversized aggregate accumulated in the road sides, gravel required.
24	V_HLB	Grading Sept/08	5	Regular	Important erosion problems, how ever no w inter closures of road are observed. Some sections present oversized gravel.	Grading Nov/08	3,1	Poor	
25	V_LNJ		5,4	Regular	Some erosion problems, no w inter closures of road are observed.		7,1	Good	
27	N500		3,4	Poor	Important erosion and profile deformations in both w heelpaths caused by poor drainage. Culvert missing in km 2.2	Local grading Feb, March/09	6,7	Good	Rough surface caused by embedded oversize gravel, rutting causes irregular transverse profile.
29	V_PSA		4,9	Regular			5,4	Regular	
30	V_CHU		6,2	Good	Poor transverse profile causes erosion, good side drains.		5,3	Regular	Rough surface caused by embedded oversize gravel, rutting of 7cm in one w heelpath, side drain required.
31	V_AMI		5,4	Regular	Sections present surface deformations and erosion caused by poor drainage.		6,5	Good	Oversized gravel, irregular transverse profile. Improvement of profile and cleaning of drainage required
32	N494		8,2	Very Good	Intermunicipal road, presents bus service betw een Chudal and N60. Potholes, corrugations, oversized aggregate and lack of gravel in section w ith bus service.		6,7	Good	Gravel required. Traffic of forestry Trucks cause irregular profile. Lack of gravel causes corrugations and potholes.
33	V_LPL		5,8	Good	Poor side slope and drains. Thin silt surface produces dust problems.	Grading Oct/08	5,5	Good	
35	V_RCM		3,2	Poor	Surface deformation, erosion and w inter closures caused by poor drainage.	Grading March/09	4,8	Regular	

Table E.3.4 Chile Case Study Condition Evaluation: Earth Roads (Field 3 and 4)

Road Data		Previous Maintenance and Condition Evaluations				Previous Maintenance and Condition Evaluations						
		sep-09				sep-10		oct-11				
Section Code	Road Code	Previous Maintenance	UPCI	Condition	Comments	2010 Maint type	2010 Maint Effect	2011 Maintenance	2011 Maint type	2011 Maint Effect	UPCI	Condition
1	V_LLA	Grading and regravel in section with emergency winter closure section June, July/09; grading Aug/09 (main road?)	7,7	Very Good	Side drains only on one side of the road and uses more than half width of carriageway. Slight erosion of one wheelpath casused by water flow, poor transverse profile. First 300 m of road present important potholes (+ 1 m long), gravel required to repair.	Minimum Grading	1	1 Perfilado anual realizado por municipalidad	Minimum Grading	1	4,9	Regular
4	N496_T	Grading July/09 and previous week 28/Sept/09)	6,3	Good	Oversized gravel placed in slopes 3 years ago. Side drains only at one side. Problems with superelevation in curve, should be corrected	Minimum Grading	1	1 Perfilado anual realizado por municipalidad	Minimum Grading	1	7,1	Good
5	V_QTA	No maintenance	2	Poor	Section not evaluated as it was impassable because of severe erosion	Minimum Grading	1	1 Perfilado anual realizado por municipalidad	Minimum Grading	1	2,1	Very Poor
6	V_CU1	Local regravel july/09	6,8	Good	Good surface condition because of gravel from the river placed in slopes. Transverse erosion caused by water flow to side drains.	Minimum Grading	1	1 Perfilado anual realizado por municipalidad	Minimum Grading	1	7,6	Good
7	V_CU2	Local regraveling july/09	6,5	Good	Oversized aggregates avoid formation of mud and potholes. Important potholes observed in sections without oversized aggregates.	Minimum Grading	1	Sin mantención	No maintenance	0	6,7	Good
9	N498		7,3	Good	Four important potholes with water and some deformation of wheelpaths.	Minimum Grading	1	2 Perfilados anuales vialidad	Preventive Grading	3,5	7,7	Good
10	V_BQH	Grading 16/sept/09. Gravel and culvert placed in section with drainage and erosion problem.	4	Regular	Potholes (max 1.5 m long), irregular profile, erosion in the wheel path. No passability problems during rain.	Minimum Grading	1	1 Perfilado anual realizado por municipalidad o sin mantencion	Minimum Grading	1	4,4	Regular
11	N474	Local regravel sector los maquis june/09, grading aug/09 (main road?)	4	Regular	Important erosion,especially in wheelpaths, road closure starting at the test section. Some erosion caused by waterflow to side drains.	Minimum Grading	1	1 Perfilado anual realizado por municipalidad	Minimum Grading	1	5,4	R
12	V_BA1		N.E			Minimum Grading	1	Ripiado con bolones con fondos de pobladores	Local Regravel + Minimum Grading	2,5	4,0	R
13	V_BA2	Grading April/09 and 5/sept/09 (until municipal school)	4,3	Regular	Poor transverse profile and drainage cause rutting. Oversized aggregate added in slopes to avoid wheelpaths erosion.	Minimum Grading	1				N.E	
17	V_BAB		6,2	Good	Flat transverse profile with no side drains, cases slight erosion in the centreline.	Minimum Grading	1	Sin mantención	No maintenance	0	5,6	Very Poor
18	V_CAB		3,7	Regular	Road is impassable because of deep erosion in the wheelpath.	Minimum Grading	1	Sin mantención	No maintenance	0	5,8	Good
22	N492	Local grading April/09 (Huacalemu), grading May/09	7,2	Good	Good side slopes, slope in the centreline needs to be improved as rutting is starting to appear. Local graveling required.	Minimum Grading	1	2 perfilados anuakes, se areno y paso máquina hace 4 meses	Rehabilitation	4,5	7,1	Good
24	V_HLB		N.E								N.E	
25	V_LNJ		3,8	Poor	Thin gravel and sand placed in the section, erosion in centreline and transverse to the road. Neighbours say there is no important waterflow that could cause the road closure.	Minimum Grading	1	No se mantiene	No maintenance	0	7,6	Good
27	N500		6,4	Good	Poor drainage and profile produces water flow over road, but not winter closure. Some potholes and deformation observed in one wheelpath. Grading required.	Preventive Grading	3,5	Ripio y perfiló Claro y Vicuña recientemente.	Rehabilitation	5	8,9	Very Good
29	V_PSA		5,8	Good	Flat profile produces slight erosion, potholes and rutting.	Minimum Grading	1				N.E	
30	V_CHU	Grading April/09, 15/Sept/09 grading until Trancoyán.	5	Regular	Poor transverse profile but good side drains. Slight rutting and erosion. Embedded oversized aggregates. Grass in side ditches.	Minimum Grading	1	Ripio y perfiló Claro y Vicuña recientemente.	Rehabilitation	4,5	9,2	Very Good
31	V_AMI		4,1	Regular	Better road surface condition observed in slopes because of good gravel. Rutting and erosion repaired with gravel.	Minimum Grading	1	1 perfilado anual	Minimum Grading	1	6,3	Good
32	N494		3,3	Poor	Corrugations observed in steep slopes. Existing gravel presents oversize. Profile presents deformations and slight erosion caused by trucks traffic. Compaction, good gravel and grading required.	Minimum Grading	3,5	2 Perfilado anual realizado por municipalidad	Minimum Grading	1	6,2	Good
33	V_LPL	Regravel and grading in emergency section with erosion June/09,	6,4	Good	Side slope and ditch required on one side of the road. Recent grading eliminated erosion problem. Slight rutting observed. Loose material observed in centreline. Slopes starting to present erosion.	Minimum Grading	3,5	1 perfilado anual	Minimum Grading	1	6,7	Good
35	V_RCM		N.E								N.E	

E.4. Typical Surface Defects and Distresses observed in Paraguay Case Study

Figure E.4.1 Impassability in Road 5

Figure E.4.2 Severe Rutting in Road 2.1

Figure E.4.3 Fixed corrugations in Road 9

Figure E.4.4 Erosion in Road 11

Appendix F

Data Analysis: Development of Condition Performance Module

F.1. Unpaved Roads Condition Index Validation

Road Characteristics			**UPCI Values (1 to 10)**	
Section Code	**Road Name**	**Road Length (m)**	**Calculated**	**Observed**
1	V_LLA	550	7.7	6.5
2	N620	13900	6.2	6
3	N496_R	2000	2.8	3
4	N496_T	2800	6.3	6
6	V_CU1	400	6.8	7.5
7	V_CU2	500	6.5	5
8	N600	9700	5.7	8
9	N498	2000	7.3	6.5
10	V_BQH	850	4.0	4
11	N474	5000	4.0	3
13	V_BA2	1800	4.3	5
14	N490	4000	6.2	7
15	N480	7700	6.5	7
16	N462	3300	4.2	6
17	V_BAB	1100	6.2	6
18	V_CAB	1700	3.7	3
19	N616	3200	9.0	8
20	N486	5800	7.6	7
21	N466	11700	5.5	7
22	N492	6800	7.2	7
25	V_LNJ	1200	3.8	6.5
26	N482	11200	6.5	6
27	N500	3000	6.4	5
28	N478	5300	5.8	7
29	V_PSA	1300	5.8	6
30	V_CHU	3000	5.0	6
31	V_AMI	2000	4.1	5
32	N494	5400	3.3	6
33	V_LPL	1600	6.4	7
34	N610	10200	6.5	8
37	N60-R	15900	5.5	6.5
39	N68	11000	8.8	8

Statistical Analysis for UPCI Validation

Analysis method: t Test of comparison of means

	UPCI Calculated	*UPCI Observed*
Mean	5.88	6.11
Variance	2.23	2.03
Observations	31	31
Pearson Correlation Coefficient	0.72	
Difference between means	0	
Degrees of Freedom	30	
t observed	-1.19	
P(T<=t) two tailed test	0.24	
t critical (two tailed test)	2.04	

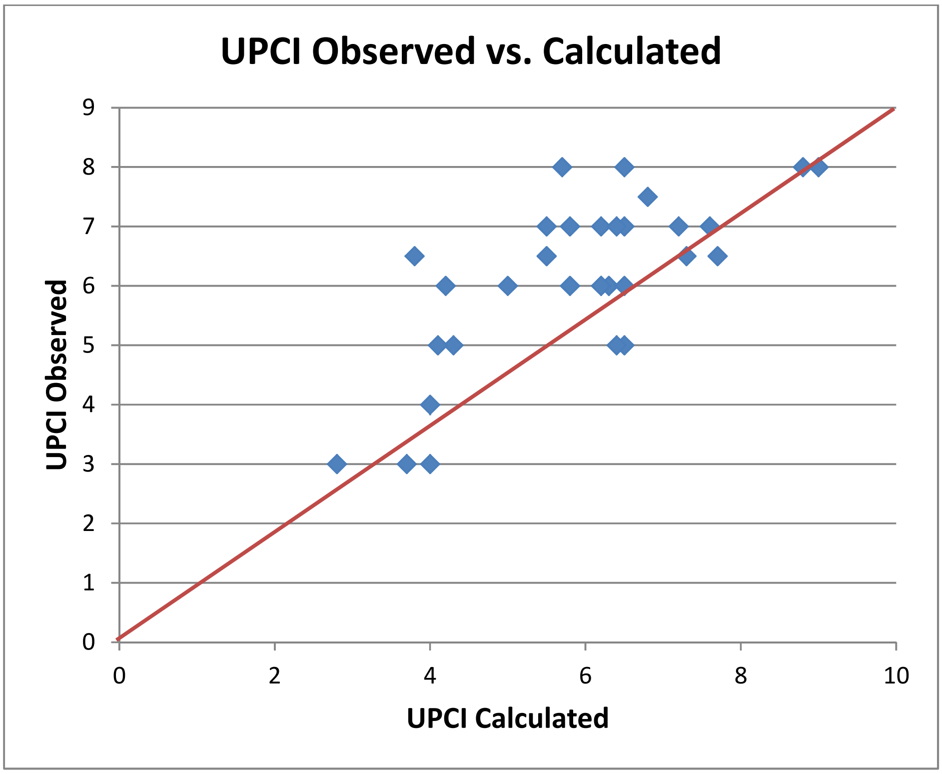
1. Null Hypothesis $H_0 : \mu_1 - \mu_2 = 0$

2. Alternative Hypothesis $H_{01} : \mu_1 - \mu_2 \neq 0$

3. Significance Level $\alpha=0.05$

4. Comparison of test statistic to critical value and decide:
The null hypothesis is rejected when $t_{critical} < t$ or when $t < - t_{critical}$
$t_{critical} = 2.04 > t = -1.19 > - t_{critical} = - 2.04$

We fail to reject the null hypothesis and therefore state that both means are equal with a confidence of 95%


UPCI Observed vs. Calculated
UPCI Observed
UPCI Calculated
0
1
2
3
4
5
6
7
8
9
0
2
4
6
8
10

F.2. Maintenance Effects on Roads Condition

F.2.1 Analysis Statistics for Gravel Roads

Summer						
Grading	**Pre Maint Dry**	**Abs Dry Incr**	**% Dry Incr**	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**
Min	6.02	2.40	34%	6.02	3.63	57%
Max	7.15	3.35	56%	6.37	3.98	66%
Mean	6.59	2.87	45%	6.20	3.80	61%
SD	0.80	0.67	16%	0.25	0.25	6%

Summer						
Local Gravel + Grading	**Pre Maint Dry**	**Abs Dry Incr**	**% Dry Incr**	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**
Min	3.50	0.83	9%	3.50	1.17	13%
Max	9.17	6.50	186%	8.83	6.50	186%
Mean	6.59	3.18	64%	6.44	3.39	68%
SD	2.03	2.07	69%	1.95	1.93	68%

Summer						
Culvert replacement and grading	**Pre Maint Dry**	**Abs Dry Incr**	**% Dry Incr**	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**
Mean (1 obs)	4.54	1.13	0.25	4.52	1.15	0.26

Winter						
Grading	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Min	2.30	2.57	74%	2.30	2.57	82%
Max	4.73	3.52	112%	4.73	3.89	112%
Mean	3.52	3.04	93%	3.52	3.23	97%
SD	1.72	0.67	26%	1.72	0.94	21%

Winter						
Local Gravel + Grading	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Min	5.33	0.06	1%	5.33	0.93	12%
Max	8.10	4.67	88%	8.10	4.67	88%
Mean	7.13	1.51	26%	7.13	2.39	38%
SD	1.23	2.13	41%	1.23	1.62	34%

Winter						
Bridge repair and grading	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Mean (1 obs)	6.91	1.34	19%	6.58	2.04	31%

Winter						
Local gravel	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Min	4.30	0.58	6%	4.30	0.71	8%
Max	9.42	3.37	78%	9.29	3.62	84%
Mean	6.86	1.98	42%	6.80	2.16	46%
SD	3.62	1.97	51%	3.53	2.06	54%

F.2.2 Analysis Statistics for Earth Roads

Summer						
1 Grading (7 obs)	**Pre Maint Dry**	**Abs Dry Incr**	**% Dry Incr**	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**
Min	2.75	1.50	28%	2.78	2.38	63%
Max	5.40	7.25	264%	5.20	7.22	260%
Mean	4.03	3.52	99%	3.94	4.33	119%
SD	1.11	1.94	78%	1.04	1.53	67%

Summer						
2 Gradings (3 obs)	**Pre Maint Dry**	**Abs Dry Incr**	**% Dry Incr**	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**
Min	3.34	2.67	73%	3.29	2.69	74%
Max	3.93	4.72	120%	3.91	4.74	136%
Mean	3.65	3.72	102%	3.61	3.96	110%
SD	0.30	1.03	26%	0.31	1.11	32%

Summer						
1 Culvert repair+1 grading	**Pre Maint Dry**	**Abs Dry Incr**	**% Dry Incr**	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**
Mean (1 obs)	3.25	6.33	195%	3.20	6.70	209%

Summer						
1 local gravel + 1 grading	**Pre Maint Dry**	**Abs Dry Incr**	**% Dry Incr**	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**
Mean (1 obs)	2.29	5.56	243%	2.27	7.38	325%

Winter						
1 Grading (2 obs)	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Min	3.91	1.45	18%	3.79	1.45	18%
Max	7.92	3.87	99%	7.92	4.11	108%
Mean	5.92	2.66	59%	5.86	2.78	63%
SD	2.84	1.71	57%	2.92	1.88	64%

Winter						
2 Gradings (3 obs)	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Min	3.67	2.69	66%	3.62	2.72	68%
Max	4.70	3.55	90%	4.70	3.65	95%
Mean	4.10	3.12	77%	4.06	3.18	79%
SD	0.53	0.43	12%	0.57	0.47	14%

Winter						
1 Culvert repair+1 grading	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Mean (1 obs)	3.91	0.64	16%	3.70	0.90	24%

Winter						
2 local gravel + 1 grading	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Mean (1 obs)	6.20	2.75	44%	6.20	2.75	44%

Winter						
1 local gravel	**Pre Maint Med**	**Abs Med Incr**	**% Med Incr**	**Pre Maint Humid**	**Abs Humid Incr**	**% Humid Incr**
Min	4.90	1.47	24%	4.80	1.50	24%
Max	6.16	3.12	64%	6.13	3.26	68%
Mean	5.53	2.30	44%	5.47	2.38	46%
SD	0.89	1.17	28%	0.94	1.24	31%

F.3 Analysis of Maintenance Effects

F.3.1 Analysis of Maintenance Effects: Gravel Roads

Dry

Maintenance	Overall Maint Abs. UPCI Incr	Application Range	
		Min	Max
Grading	2.9	6.0	7.2
Local gravel + Grading	3.2	3.5	9.2
Culvert/Bridge Repair + Grading	1.1		4.5

Mediterranean

Maintenance	Overall Maint Abs. UPCI Incr	Application Range	
		Min	Max
Grading	3.4	4.2	5.6
Local gravel + Grading	2.4	4.4	8.5
Culvert/Bridge Repair + Grading	1.2		5.7
Local Gravel	2.0	4.3	9.4

Humid

Maintenance	Overall Maint Abs. UPCI Incr	Application Range	
		Min	Max
Grading	3.2	2.3	4.7
Local gravel + Grading	2.4	5.3	8.1
Culvert/Bridge Repair + Grading	2.0		6.6
Local Gravel	2.2	4.3	9.3

F.3.2 Analysis of Maintenance Effects: Earth Roads

Dry

Maintenance	Overall Maint Abs. UPCI Incr	Application Range	
		Min	Max
Local Gravel/ Pothole Patching			
One Grading	3.5	2.75	5.40
Two Gradings	3.7	3.34	3.93
Culvert Repair + One Grading	6.3	3.25	
Local gravel + Grading	5.6	2.29	

Mediterranean

Maintenance	Overall Maint Abs. UPCI Incr	Application Range	
		Min	Max
Local Gravel/ Pothole Patching	2.3	4.90	6.16
One Grading	3.5	3.48	4.31
Two Gradings	3.5	3.48	4.31
Culvert Repair + Grading	3.7	3.56	
Local Gravel+ Grading	5.1	4.24	

Humid

Maintenance	Overall Maint Abs. UPCI Incr	Application Range	
		Min	Max
Local Gravel/ Pothole Patching	2.4	4.80	6.13
One Grading	2.8	3.79	7.92
Two Gradings	3.2	3.62	0.95
Culvert Repair + One Grading	0.9	3.70	
Local Gravel+ One Grading	2.8	6.20	

F.4. Validation of Performance Curves and Maintenance Effects on Roads Condition

F.4.1 Gravel Roads Validations

	Road Information		Traffic Data		oct-11	
N°	Code	Road length	Traffic AADT	Traffic level	UPCI Observed	UPCI Calculated
2	N620	6900	100	Moderate	8.3	8.16
3	N496_R	2000	30	Low	6.1	6.78
8	N600	9700	70	Moderate	9.5	7.43
14	N490	4000	50	Low	7.7	7.5
15	N480	7700	100	Moderate	7.1	7.83
16	N462	3300	30	Low	3.4	3.83
19	N616	3200	20	Low	8.3	6.15
20	N486	5800	40	Low	7.7	8.15
21	N466	11700	80	Moderate	9.5	8.92
26	N482	10400	60	Moderate	8.4	8.33
27	N500	3000	20	Low	8.9	8.32
28	N478	5300	80	Moderate	7.0	6.32
34	N610	10200	60	Moderate	5.0	5.5
36	N510	4900	40	Low	9.2	8
37	N60-R	15900	220	High	6.2	6.42
39	N68		100	Moderate	6.3	6

t-test for difference in means

	UPCI Observed	*UPCI Calculated*
Mean	7.41	7.10
Variance	2.90	1.78
Observations	16	16
Pearson Correlation Coefficient	0.86	
Difference between means	0	
Degrees of Freedom	15	
t observed	1.41	
P(T<=t) two tailed test	0.18	
t critical (two tailed test)	2.13	

1. Null Hypothesis $H_0 : \mu_1 - \mu_2 = 0$
2. Alternative Hypothesis $H_1 : \mu_1 - \mu_2 \neq 0$
3. Significance Level $\alpha=0.05$
4. Comparison of test statistic to critical value and decide:

The null hypothesis is rejected when $t_{critical} < t$ or when $t < - t_{critical}$

$t_{critical} = 2.13 > t = 1.41 > - t_{critical} = - 2.13$

We fail to reject the null hypothesis and therefore state that both means are equal with a confidence of 95%

F.4.2. Earth Roads Validation

	Road Information		Traffic Data		oct-11	
N°	Code	Road length	Traffic AADT	Traffic level	UPCI Observed	UPCI Calculated
1	V_LLA	550	4	Low	4.9	4.56
4	N496_T	2800	6	Low	7.1	6.99
5	V_QTA	1400	14	Low	2.1	3
6	V_CU1	400	10	Low	7.6	7.02
7	V_CU2	500	10	Low	6.7	5.51
9	N498	2000	14	Low	7.7	8.04
10	V_BQH	850	8	Low	4.4	4.4
11	N474	5000	12	Low	5.4	5.4
17	V_BAB	1100	6	Low	5.6	4.49
18	V_CAB	1700	6	Low	5.8	4.06
22	N492	6800	40	Low	7.1	7.03
25	V_LNJ	1200	16	Low	7.6	5.19
30	V_CHU	3000	30	Low	9.2	8.94
31	V_AMI	2000	6	Low	6.3	5.41
32	N494	5400	60	Moderate	6.2	7.2
33	V_LPL	1600	30	Low	6.7	5.5

t-test for difference in means

	UPCI Observed	*UPCI Calculated*
Mean	6.26	5.80
Variance	2.65	2.55
Observations	16	16
Pearson Correlation Coefficient	0.84	
Difference between means	0	
Degrees of Freedom	15	
t observed	2.03	
P(T<=t) two tailed test	0.06	
t critical (two tailed test)	2.13	

1. Null Hypothesis $H_0 : \mu_1 - \mu_2 = 0$
2. Alternative Hypothesis $H_1 : \mu_1 - \mu_2 \neq 0$
3. Significance Level $\alpha=0.05$
4. Comparison of test statistic to critical value and decide:

The null hypothesis is rejected when $t_{critical} < t$ or when $t < - t_{critical}$

$t_{critical} = 2.13 > t = 2.03 > - t_{critical} = - 2.13$

We fail to reject the null hypothesis and therefore state that both means are equal with a confidence of 95%

Appendix G

Data Analysis: Development of Network Maintenance Module

G.1 Effectiveness Calculations for Gravel Roads

Maintenance types applied in the analysis are: Minimum (Green), Routine (Purple), Rehabilitation (Blue), Reconstruction (Orange)

G.1.1 Effectiveness for GRM1 Strategy

		Dry Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Local Regravel+Min Grading. Rehab: Grading+ Gravel / Rec: Grading+ Gravel+ Culvert Replace.	0		10		10		10		10
	1	7.50	8.00	7.50	8.25	7.50	9.25	7.50	9.50
	2	6.70	7.65	6.80	8.23	7.20	9.25	7.30	9.50
	3	6.56	7.46	6.79	8.14	7.20	9.25	7.30	9.50
	4	6.47	7.32	6.76	8.03	7.20	9.25	7.30	9.50
	5	6.35	7.15	6.71	7.91	7.20	9.20	7.30	9.50
	6	6.21	6.96	6.66	7.79	7.18	9.06	7.30	9.50
	7	6.05	6.75	6.62	7.67	7.12	8.87	7.30	9.40
	8	5.87	6.52	6.57	7.54	7.05	8.67	7.26	9.21
	9	5.69	6.29	6.52	7.42	6.97	8.47	7.18	8.98
	10	5.62	6.17	6.43	7.26	6.89	8.26	7.09	8.74
	11	5.60	6.10	6.30	7.05	6.81	8.06	7.00	8.50
	12	5.59	6.04	6.12	6.80	6.72	7.85	6.90	8.25
	13	5.57	5.97	5.91	6.51	6.64	7.64	6.80	8.00
	14	5.56	5.91	5.68	6.20	6.56	7.43	6.70	7.75
	15	5.55	5.85	5.61	6.06	6.44	7.19	6.60	7.50
	16	5.54	5.79	5.58	5.95	6.24	6.87	6.50	7.25
	17	5.52	5.72	5.56	5.86	5.97	6.47	6.29	6.89
	18	5.51	5.66	5.54	5.76	5.66	6.04	5.99	6.44
	19	5.49	8.75	5.52	5.67	5.57	5.82	5.66	5.96
	20	7.00		5.50		5.53		5.56	
	Mean UPCI	6.40		6.72		7.41		7.67	
	Unit Effective.*	48.00		54.38		68.28		73.35	

*Min acceptable UPCI=4

G.1.1 Effectiveness for GRM1 Strategy (cont.)

		Mediterranean Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	**Cycle***	**UPCI Before**	**UPCI After**	**UPCI Before**	**UPCI After**	**UPCI Before**	**UPCI After**	**UPCI Before**	**UPCI After**
Prev: Local Regravel+Min Grading. Rehab: Grading+ Gravel / Rec: Grading+ Gravel+ Culvert Replace.	0		10		10		10		10
	1	6.50	7.50	6.50	8.00	6.50	9.00	6.50	9.50
	2	5.90	6.85	6.02	7.45	6.26	8.64	6.38	9.23
	3	5.75	6.65	5.89	7.24	6.18	8.43	6.32	9.02
	4	5.70	6.55	5.84	7.12	6.13	8.25	6.27	8.82
	5	5.68	6.48	5.81	7.01	6.08	8.08	6.22	8.62
	6	5.66	6.41	5.79	6.91	6.04	7.92	6.17	8.42
	7	5.65	6.35	5.77	6.82	6.00	7.75	6.12	8.22
	8	5.64	6.29	5.74	6.72	5.97	7.59	6.08	8.03
	9	5.62	6.22	5.72	6.62	5.93	7.43	6.03	7.83
	10	5.61	6.16	5.69	6.52	5.89	7.26	5.98	7.63
	11	5.60	6.10	5.67	6.42	5.85	7.10	5.94	7.44
	12	5.59	6.04	5.65	6.33	5.81	6.93	5.89	7.24
	13	5.57	5.97	5.63	6.23	5.77	6.77	5.84	7.04
	14	5.56	5.91	5.61	6.14	5.73	6.61	5.80	6.85
	15	5.55	5.85	5.59	6.04	5.69	6.44	5.75	6.65
	16	5.54	5.79	5.58	5.95	5.66	6.28	5.70	6.45
	17	5.52	5.72	5.56	5.86	5.62	6.12	5.66	6.26
	18	5.51	5.66	5.54	5.76	5.59	5.97	5.62	6.07
	19	5.47	8.75	5.52	5.67	5.56	5.81	5.58	5.88
	20	6.20		5.50		5.53		5.54	
	Mean UPCI	6.13		6.24		6.65		6.86	
	Unit Effective.*	42.55		124.72		133.08		137.29	

*Min acceptable UPCI=4

G.1.1 Effectiveness for GRM1 Strategy (cont.)

		Humid Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Local Regravel+Min Grading. Rehab: Grading+ Gravel / Rec: Grading+ Gravel+ Culvert Replace.	0		10		10		10		10
	1	5.75	6.75	5.75	7.25	5.75	8.25	5.75	8.75
	2	5.56	6.51	5.59	7.01	5.65	8.02	5.68	8.53
	3	5.54	6.44	5.57	6.92	5.63	7.88	5.66	8.36
	4	5.54	6.39	5.57	6.84	5.63	7.75	5.65	8.20
	5	5.54	6.34	5.56	6.76	5.62	7.62	5.64	8.04
	6	5.53	6.28	5.56	6.68	5.61	7.48	5.63	7.88
	7	5.53	6.23	5.55	6.60	5.60	7.35	5.63	7.73
	8	5.53	6.18	5.55	6.53	5.59	7.22	5.62	7.57
	9	5.53	6.13	5.55	6.45	5.59	7.09	5.61	7.41
	10	5.52	6.07	5.54	6.37	5.58	6.95	5.60	7.25
	11	5.52	6.02	5.54	6.29	5.57	6.82	5.59	7.09
	12	5.52	5.97	5.53	6.21	5.56	6.69	5.58	6.93
	13	5.51	5.91	5.53	6.13	5.56	6.56	5.57	6.77
	14	5.51	5.86	5.52	6.05	5.55	6.42	5.56	6.61
	15	5.51	5.81	5.52	5.97	5.54	6.29	5.55	6.45
	16	5.50	8.75	5.51	5.89	5.53	6.16	5.54	6.29
	17	5.68	6.68	5.51	5.81	5.52	6.02	5.53	6.13
	18	5.55	6.50	5.50	8.75	5.52	5.89	5.52	5.97
	19	5.54	6.44	5.68	7.18	5.51	5.76	5.51	5.81
	20	5.54		5.58		5.50		5.50	
	Mean UPCI	6.06		6.17		6.35		6.49	
	Unit Effective.*	41.11		123.45		126.91		129.85	

G.1.2 Effectiveness for GRM2 Strategy

		Dry Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Routine Grading. Rehab: Grading+ Gravel. Rec: Grading+Regravel+ Culvert Replace.	0		10		10		10		10
	1	7.50	8.00	7.50	8.25	7.50	9.25	7.50	9.50
	2	6.70	7.65	6.80	8.25	7.20	9.25	7.30	9.50
	3	6.56	7.46	6.80	8.25	7.20	9.25	7.30	9.50
	4	6.47	7.32	6.80	8.25	7.20	9.25	7.30	9.50
	5	6.35	7.15	6.80	8.25	7.20	9.25	7.30	9.50
	6	6.21	6.96	6.80	8.25	7.20	9.25	7.30	9.50
	7	6.05	6.75	6.80	8.25	7.20	9.25	7.30	9.50
	8	5.87	6.52	6.80	8.25	7.20	9.25	7.30	9.50
	9	5.69	6.29	6.80	8.25	7.20	9.25	7.30	9.50
	10	5.62	6.17	6.80	8.18	7.20	9.13	7.30	9.50
	11	5.60	6.10	6.77	8.02	7.15	8.90	7.30	9.30
	12	5.59	6.04	6.71	7.83	7.06	8.64	7.22	9.02
	13	5.57	5.97	6.63	7.63	6.95	8.35	7.11	8.71
	14	5.56	5.91	6.55	7.43	6.84	8.07	6.98	8.38
	15	5.55	5.85	6.44	7.19	6.73	7.78	6.85	8.05
	16	5.54	5.79	6.24	6.87	6.61	7.49	6.72	7.72
	17	5.52	5.72	5.97	6.47	6.49	7.19	6.59	7.39
	18	5.51	5.66	5.66	6.04	6.24	6.77	6.41	7.01
	19	5.49	8.75	5.57	5.82	5.89	6.24	6.09	6.49
	20	7.00		5.53		5.61		5.66	
	Mean UPCI	6.40		7.16		7.74		7.93	
	Unit Effective.*	48.00		63.26		74.83		78.60	

*Min acceptable UPCI=4

G.1.2 Effectiveness for GRM2 Strategy (cont.)

Maintenance	Cycle*	Mediterranean Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
		UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Routine Grading. Rehab: Grading+ Gravel. Rec: Grading+Regravel+ Culvert Replace.	0		10		10		10		10
	1	6.50	7.50	6.50	8.25	6.50	9.25	6.50	9.50
	2	5.90	6.85	6.08	8.25	6.32	9.25	6.38	9.50
	3	5.75	6.65	6.08	8.25	6.32	9.25	6.38	9.50
	4	5.70	6.55	6.08	8.21	6.32	9.25	6.38	9.50
	5	5.68	6.48	6.07	8.07	6.32	9.12	6.38	9.50
	6	5.66	6.41	6.04	7.92	6.29	8.92	6.38	9.38
	7	5.65	6.35	6.00	7.75	6.24	8.69	6.35	9.15
	8	5.64	6.29	5.97	7.59	6.19	8.46	6.30	8.90
	9	5.62	6.22	5.93	7.43	6.13	8.23	6.24	8.64
	10	5.61	6.16	5.89	7.26	6.08	8.00	6.18	8.38
	11	5.60	6.10	5.85	7.10	6.02	7.77	6.11	8.11
	12	5.59	6.04	5.81	6.93	5.97	7.55	6.05	7.85
	13	5.57	5.97	5.77	6.77	5.92	7.32	5.99	7.59
	14	5.56	5.91	5.73	6.61	5.86	7.09	5.93	7.33
	15	5.55	5.85	5.69	6.44	5.81	6.86	5.86	7.06
	16	5.54	5.79	5.66	6.28	5.75	6.63	5.80	6.80
	17	5.52	5.72	5.62	6.12	5.70	6.40	5.74	6.54
	18	5.51	5.66	5.59	5.97	5.65	6.17	5.68	6.28
	19	5.47	8.75	5.56	5.81	5.60	5.95	5.62	6.02
	20	6.20		5.53		5.56		5.57	
	Mean UPCI	6.13		6.61		7.02		7.18	
	Unit Effective.*	42.55		132.23		140.35		143.67	

*Min acceptable UPCI=4

G.1.2 Effectiveness for GRM2 Strategy (cont.)

		Humid Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Routine Grading. Rehab: Grading+ Gravel. Rec: Grading+Regravel+ Culvert Replace.	0		10		10		10		10
	1	5.75	6.75	5.75	8.25	5.75	9.25	5.75	9.50
	2	5.56	6.51	5.65	8.02	5.71	9.03	5.72	9.50
	3	5.54	6.44	5.63	7.88	5.69	8.84	5.72	9.32
	4	5.54	6.39	5.63	7.75	5.68	8.66	5.71	9.11
	5	5.54	6.34	5.62	7.62	5.67	8.47	5.70	8.90
	6	5.53	6.28	5.61	7.48	5.66	8.29	5.69	8.69
	7	5.53	6.23	5.60	7.35	5.65	8.10	5.67	8.47
	8	5.53	6.18	5.59	7.22	5.64	7.91	5.66	8.26
	9	5.53	6.13	5.59	7.09	5.63	7.73	5.65	8.05
	10	5.52	6.07	5.58	6.95	5.62	7.54	5.64	7.84
	11	5.52	6.02	5.57	6.82	5.61	7.36	5.62	7.62
	12	5.52	5.97	5.56	6.69	5.59	7.17	5.61	7.41
	13	5.51	5.91	5.56	6.56	5.58	6.98	5.60	7.20
	14	5.51	5.86	5.55	6.42	5.57	6.80	5.59	6.99
	15	5.51	5.81	5.54	6.29	5.56	6.61	5.57	6.77
	16	5.50	8.75	5.53	6.16	5.55	6.43	5.56	6.56
	17	5.68	6.68	5.52	6.02	5.54	6.24	5.55	6.35
	18	5.55	6.50	5.52	5.89	5.53	6.05	5.54	6.14
	19	5.54	6.44	5.51	5.76	5.52	5.87	5.52	5.92
	20	5.54		5.50		5.51		5.51	
	Mean UPCI	6.06		6.35		6.64		6.78	
	Unit Effective.*	41.11		126.91		132.79		135.57	

*Min acceptable UPCI=4

G.2 Effectiveness Calculations for Earth Roads

Maintenance types applied in the analysis are: Minimum (Green), Routine (Purple), Rehabilitation (Blue), Reconstruction (Orange)

G.2.1 Effectiveness for ERM1 Strategy

		Dry Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Local Regravel+Min Grading. Rehab: Grading+ Gravel / Rec: Grading+ Gravel+ Culvert Replace.	0		10		10		10		10
	1	7.50	8.00	7.50	8.25	7.50	9.25	7.50	9.50
	2	6.70	7.65	6.80	8.23	7.20	9.25	7.30	9.50
	3	6.56	7.46	6.79	8.14	7.20	9.25	7.30	9.50
	4	6.40	7.25	6.76	8.03	7.20	9.25	7.30	9.50
	5	5.86	6.66	6.71	7.91	7.20	9.20	7.30	9.50
	6	4.35	7.85	6.66	7.79	7.18	9.06	7.30	9.50
	7	6.64	7.64	6.62	7.67	7.12	8.87	7.30	9.40
	8	6.56	7.51	6.57	7.54	7.05	8.67	7.26	9.21
	9	6.50	7.40	6.52	7.42	6.97	8.47	7.18	8.98
	10	6.25	7.10	6.29	7.11	6.89	8.26	7.09	8.74
	11	5.48	8.75	5.51	6.26	6.81	8.06	7.00	8.50
	12	7.00	8.00	3.94	8.94	6.72	7.85	6.90	8.25
	13	6.70	7.65	7.08	8.25	6.64	7.64	6.80	8.00
	14	6.56	7.46	6.80	8.23	6.56	7.43	6.70	7.75
	15	6.40	7.25	6.79	8.14	6.32	7.07	6.60	7.50
	16	5.86	6.66	6.76	8.03	5.41	9.50	6.50	7.25
	17	4.35	7.85	6.71	7.91	7.30	9.25	5.86	6.46
	18	6.64	7.64	6.66	7.79	7.20	9.25	3.95	10.00
	19	6.56	7.51	6.62	7.67	7.20	9.25	7.50	9.50
	20	6.50		6.57		7.20		7.30	
	Mean UPCI	6.97		7.25		7.84		7.86	
	Unit Effective.*	59.30		64.97		76.84		77.24	

*Min acceptable UPCI=4

G.2.1 Effectiveness for ERM1 Strategy (cont.)

		Mediterranean Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Local Regravel+Min Grading. Rehab: Grading+ Gravel / Rec: Grading+ Gravel+ Culvert Replace.	0		10		10		10		10
	1	7.50	8.00	7.50	8.25	7.50	9.25	7.50	9.50
	2	4.66	8.16	5.02	8.52	6.44	8.81	6.79	9.50
	3	4.89	8.39	5.39	8.75	5.81	8.06	6.79	9.49
	4	5.21	8.71	5.73	7.23	4.75	9.25	6.78	9.33
	5	5.67	6.67	3.94	8.94	6.43	8.93	6.54	8.94
	6	3.93	8.93	6.00	7.50	5.98	8.35	6.00	8.25
	7	5.98	6.98	3.95	8.95	5.16	9.50	5.01	9.75
	8	3.94	8.94	6.01	7.51	6.79	9.25	7.15	9.50
	9	5.99	6.99	3.96	8.96	6.44	8.81	6.79	9.50
	10	3.94	8.94	6.03	7.53	5.81	8.06	6.79	9.49
	11	5.99	6.99	3.99	8.99	4.75	9.25	6.78	9.33
	12	3.94	8.94	6.06	7.56	6.43	8.93	6.54	8.94
	13	5.99	6.99	4.04	7.54	5.98	8.35	6.00	8.25
	14	3.94	8.94	4.01	7.51	5.16	9.50	5.01	9.75
	15	5.99	6.99	3.96	8.96	6.79	9.25	7.15	9.50
	16	3.94	8.94	6.02	7.52	6.44	8.81	6.79	9.50
	17	5.99	6.99	3.98	8.98	5.81	8.06	6.79	9.49
	18	3.94	8.94	6.06	7.56	4.75	9.25	6.78	9.33
	19	5.99	6.99	4.03	7.53	6.43	8.93	6.54	8.94
	20	3.94		3.99		5.98		6.00	
	Mean UPCI	6.57		6.60		7.45		7.92	
	Unit Effective.*	51.36		131.97		149.09		158.39	

*Min acceptable UPCI=4

G.2.1 Effectiveness for ERM1 Strategy (cont.)

		Humid Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Local Regravel+Min Grading. Rehab: Grading+ Gravel / Rec: Grading+ Gravel+ Culvert Replace.	0		10		10		10		10
	1	7.50	8.00	7.50	8.25	7.50	9.25	7.50	9.50
	2	4.60	8.10	4.96	8.46	6.41	8.79	6.78	9.50
	3	4.74	8.24	5.27	8.75	5.74	7.99	6.78	9.48
	4	4.96	8.46	5.69	7.19	4.59	9.09	6.74	9.29
	5	5.26	8.75	3.86	8.86	6.18	8.68	6.47	8.87
	6	5.69	6.69	5.84	7.34	5.58	7.96	5.86	8.11
	7	3.83	8.83	3.87	8.87	4.54	9.04	4.76	9.75
	8	5.80	6.80	5.86	7.36	6.11	8.61	7.14	9.50
	9	3.83	8.83	3.87	8.87	5.48	9.50	6.78	9.50
	10	5.81	6.81	5.86	7.36	6.78	9.25	6.78	9.48
	11	3.84	8.84	3.87	8.87	6.41	8.79	6.74	9.29
	12	5.81	6.81	5.86	7.36	5.74	7.99	6.47	8.87
	13	3.84	8.84	3.87	8.87	4.59	9.09	5.86	8.11
	14	5.81	6.81	5.86	7.36	6.18	8.68	4.76	9.75
	15	3.84	8.84	3.87	8.87	5.58	7.96	7.14	9.50
	16	5.81	6.81	5.86	7.36	4.54	9.04	6.78	9.50
	17	3.84	8.84	3.87	8.87	6.11	8.61	6.78	9.48
	18	5.81	6.81	5.86	7.36	5.48	9.50	6.74	9.29
	19	3.84	8.84	3.87	8.87	6.78	9.25	6.47	8.87
	20	5.81		5.86		6.41		5.86	
	Mean UPCI	6.53		6.66		7.34		7.87	
	Unit Effective.*	50.60		133.12		146.88		157.38	

*Min acceptable UPCI=4

G.2.2 Effectiveness for ERM2 Strategy

		Dry Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Routine Grading. Rehab: Grading+ Gravel. Rec: Grading+Regravel+ Culvert Replace.	0		10		10		10		10
	1	7.50	8.00	7.50	8.25	7.50	9.25	7.50	9.50
	2	6.70	7.65	6.80	8.25	7.20	9.25	7.30	9.50
	3	6.56	7.46	6.80	8.25	7.20	9.25	7.30	9.50
	4	6.40	7.25	6.80	8.25	7.20	9.25	7.30	9.50
	5	5.86	6.66	6.80	8.25	7.20	9.25	7.30	9.50
	6	4.35	7.85	6.80	8.25	7.20	9.25	7.30	9.50
	7	6.64	7.64	6.80	8.25	7.20	9.25	7.30	9.50
	8	6.56	7.51	6.80	8.25	7.20	9.25	7.30	9.50
	9	6.50	7.40	6.80	8.25	7.20	9.25	7.30	9.50
	10	6.25	7.10	6.80	8.18	7.20	9.13	7.30	9.50
	11	5.48	8.75	6.77	8.02	7.15	8.90	7.30	9.30
	12	7.00	8.00	6.71	7.83	7.06	8.64	7.22	9.02
	13	6.70	7.65	6.63	7.63	6.95	8.35	7.11	8.71
	14	6.56	7.46	6.55	7.43	6.84	8.07	6.98	8.38
	15	6.40	7.25	6.32	7.07	6.73	7.78	6.85	8.05
	16	5.86	6.66	5.39	8.75	6.61	7.49	6.72	7.72
	17	4.35	7.85	7.00	8.25	6.46	7.16	6.59	7.39
	18	6.64	7.64	6.80	8.25	5.64	6.17	6.22	6.82
	19	6.56	7.51	6.80	8.25	3.93	9.75	4.75	9.75
	20	6.50		6.80		7.40		7.40	
	Mean UPCI	6.97		7.46		7.79		8.01	
	Unit Effective.*	59.30		69.19		75.88		80.24	

*Min acceptable UPCI=4

G.2.2 Effectiveness for ERM2 Strategy (cont.)

		Mediterranean Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Routine Grading. Rehab: Grading+ Gravel. Rec: Grading+Regravel+ Culvert Replace.	0		10		10		10		10
	1	7.50	8.00	7.50	8.25	7.50	9.25	7.50	9.50
	2	4.66	8.16	5.02	8.52	6.44	9.25	6.79	9.50
	3	4.89	8.39	5.39	8.75	6.44	9.25	6.79	9.50
	4	5.21	8.71	5.73	8.23	6.44	9.25	6.79	9.50
	5	5.67	6.67	4.98	8.48	6.44	9.24	6.79	9.50
	6	3.93	8.93	5.34	8.75	6.41	9.04	6.79	9.50
	7	5.98	6.98	5.73	8.23	6.13	8.58	6.79	9.50
	8	3.94	8.94	4.98	8.48	5.49	9.50	6.79	9.39
	9	5.99	6.99	5.34	8.75	6.79	9.25	6.63	9.03
	10	3.94	8.94	5.73	8.23	6.44	9.25	6.13	8.33
	11	5.99	6.99	4.98	8.48	6.44	9.25	5.13	9.75
	12	3.94	8.94	5.34	8.75	6.44	9.25	7.15	9.50
	13	5.99	6.99	5.73	8.23	6.44	9.24	6.79	9.50
	14	3.94	8.94	4.98	8.48	6.41	9.04	6.79	9.50
	15	5.99	6.99	5.34	8.75	6.13	8.58	6.79	9.50
	16	3.94	8.94	5.73	8.23	5.49	9.50	6.79	9.50
	17	5.99	6.99	4.98	8.48	6.79	9.25	6.79	9.50
	18	3.94	8.94	5.34	8.75	6.44	9.25	6.79	9.50
	19	5.99	6.99	5.73	8.23	6.44	9.25	6.79	9.39
	20	3.94		4.98		6.44		6.63	
	Mean UPCI	6.57		7.00		7.81		8.08	
	Unit Effective.*	51.36		139.93		156.21		161.56	

*Min acceptable UPCI=4

G.2.2 Effectiveness for ERM2 Strategy (cont.)

		Humid Climate							
		Min Budget		Low Budget		Med. Budget		High Budget	
Maintenance	Cycle*	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After	UPCI Before	UPCI After
Prev: Routine Grading. Rehab: Grading+ Gravel. Rec: Grading+Regravel+ Culvert Replace.	0		10		10		10		10
	1	7.50	8.00	7.50	8.25	7.50	9.25	7.50	9.50
	2	4.60	8.10	4.96	8.46	6.41	9.25	6.78	9.50
	3	4.74	8.24	5.27	8.75	6.41	9.25	6.78	9.50
	4	4.96	8.46	5.69	8.19	6.41	9.25	6.78	9.50
	5	5.26	8.75	4.87	8.37	6.41	9.21	6.78	9.50
	6	5.69	6.69	5.14	8.64	6.36	8.98	6.78	9.50
	7	3.83	8.83	5.53	8.03	6.03	8.48	6.78	9.50
	8	5.80	6.80	4.64	8.14	5.29	9.50	6.78	9.38
	9	3.83	8.83	4.80	8.30	6.78	9.25	6.59	8.99
	10	5.81	6.81	5.04	8.54	6.41	9.25	6.04	8.24
	11	3.84	8.84	5.38	8.75	6.41	9.25	4.95	9.75
	12	5.81	6.81	5.69	8.19	6.41	9.25	7.14	9.50
	13	3.84	8.84	4.87	8.37	6.41	9.21	6.78	9.50
	14	5.81	6.81	5.14	8.64	6.36	8.98	6.78	9.50
	15	3.84	8.84	5.53	8.03	6.03	8.48	6.78	9.50
	16	5.81	6.81	4.64	8.14	5.29	9.50	6.78	9.50
	17	3.84	8.84	4.80	8.30	6.78	9.25	6.78	9.50
	18	5.81	6.81	5.04	8.54	6.41	9.25	6.78	9.50
	19	3.84	8.84	5.38	8.75	6.41	9.25	6.78	9.38
	20	5.81		5.69		6.41		6.59	
	Mean UPCI	6.53		6.87		7.78		8.06	
	Unit Effective.*	50.60		137.48		155.51		161.20	

*Min acceptable UPCI=4

G.3 Cost Effectiveness Analysis for Gravel Roads

G.3.1 Cost Effectiveness Analysis for Strategy GRM1

			Dry Climate				Mediterranean Climate				Humid Climate			
Maint	Traffic	Cycle*	Min Budget	Low Budget	Med. Budget	High Budget	Min Budget	Low Budget	Med. Budget	High Budget	Min Budget	Low Budget	Med. Budget	High Budget
1 Local Gravel per cycle	Low Traffic (<50 AADT)	Mean UPCI	6.40	6.72	7.41	7.67	6.13	6.24	6.65	6.86	6.06	6.17	6.35	6.49
		AADT	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14
		Effectiveness	1638.61	1856.39	2330.90	2504.14	1452.55	4257.83	4543.12	4686.75	1403.42	4214.34	4332.67	4432.94
		PWC CAD$	1556.15	2202.74	3406.45	5994.15	1556.15	2202.74	3406.45	5994.15	1603.21	2202.74	3406.45	5994.15
		EUSC**	77.81	110.14	170.32	299.71	77.81	110.14	170.32	299.71	80.16	110.14	170.32	299.71
		E/C***	1.05	0.84	0.68	0.42	0.93	1.93	1.33	0.78	0.88	1.91	1.27	0.74
		Unit E/C***	0.031	0.025	0.020	0.012	0.027	0.057	0.039	0.023	0.026	0.056	0.037	0.022
3 Local Gravel per cycle	Mod. Traffic (50-100 AADT)	Mean UPCI	6.40	6.72	7.41	7.67	6.13	6.24	6.65	6.86	6.06	6.17	6.35	6.49
		AADT	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28
		Effectiveness	3277.21	3712.78	4661.80	5008.29	2905.10	8515.67	9086.25	9373.49	2806.85	8428.69	8665.34	8865.88
		PWC CAD$	4480.02	6608.21	10219.35	17982.44	4480.02	6608.21	10219.35	17982.44	4597.66	6608.21	10219.35	17982.44
		EUSC**	224.00	330.41	510.97	899.12	224.00	330.41	510.97	899.12	229.88	330.41	510.97	899.12
		E/C***	0.73	0.56	0.46	0.28	0.65	1.29	0.89	0.52	0.61	1.28	0.85	0.49
		Unit E/C***	0.011	0.008	0.007	0.004	0.009	0.019	0.013	0.008	0.009	0.019	0.012	0.007
6 Local Gravel per cycle	High Traffic (>100 AADT)	Mean UPCI	6.40	6.72	7.41	7.67	6.13	6.24	6.65	6.86	6.06	6.17	6.35	6.49
		AADT	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55
		Effectiveness	6554.43	7425.56	9323.61	10016.57	5810.21	17031.33	18172.49	18746.98	5613.70	16857.37	17330.67	17731.77
		PWC CAD$	7403.90	11013.69	17032.25	29970.73	7403.90	11013.69	17032.25	29970.73	7592.12	11013.69	17032.25	29970.73
		EUSC**	370.19	550.68	851.61	1498.54	370.19	550.68	851.61	1498.54	379.61	550.68	851.61	1498.54
		E/C***	0.89	0.67	0.55	0.33	0.78	1.55	1.07	0.63	0.74	1.53	1.02	0.59
		Unit E/C***	0.006	0.005	0.004	0.002	0.006	0.011	0.008	0.005	0.005	0.011	0.007	0.004

*Min acceptable UPCI=4

**EUSC: Equivalent Uniform Semi-Annual Costs per km

***E/C: Cost Effectiveness per km = Unit Effectiveness*Average AADT/PWC

****Unit E/C: Cost Effectiveness per km per veh= E/C / AADT

G.3.2 Cost Effectiveness Analysis for Strategy GRM2

			Dry Climate				Mediterranean Climate				Humid Climate			
Maint	**Traffic**	**Cycle***	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**
1 Prev. Grading per cycle	**Low Traffic (<50 AADT)**	**Mean UPCI**	6.40	7.16	7.74	7.93	6.13	6.61	7.02	7.18	6.06	6.35	6.64	6.78
		AADT	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14
		Effectiveness	1638.61	2159.52	2554.53	2683.40	1452.55	4514.23	4791.44	4904.72	1403.42	4332.67	4533.22	4628.29
		PWC CAD$	1556.15	2358.59	3537.89	7075.77	1556.15	2358.59	3537.89	7075.77	1603.21	2358.59	3537.89	7075.77
		EUSC**	77.81	117.93	176.89	353.79	77.81	117.93	176.89	353.79	80.16	117.93	176.89	353.79
		E/C***	1.05	0.92	0.72	0.38	0.93	1.91	1.35	0.69	0.88	1.84	1.28	0.65
		Unit E/C***	0.031	0.027	0.021	0.011	0.027	0.056	0.040	0.020	0.026	0.054	0.038	0.019
3 Prev. Grading per cycle	**Mod. Traffic (50-100 AADT)**	**Mean UPCI**	6.40	7.16	7.74	7.93	6.13	6.61	7.02	7.18	6.06	6.35	6.64	6.78
		AADT	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28
		Effectiveness	3277.21	4319.04	5109.06	5366.80	2905.10	9028.46	9582.88	9809.44	2806.85	8665.34	9066.43	9256.59
		PWC CAD$	4480.02	7075.77	10613.66	21227.31	4480.02	7075.77	10613.66	21227.31	4597.66	7075.77	10613.66	21227.31
		EUSC**	224.00	353.79	530.68	1061.37	224.00	353.79	530.68	1061.37	229.88	353.79	530.68	1061.37
		E/C***	0.73	0.61	0.48	0.25	0.65	1.28	0.90	0.46	0.61	1.22	0.85	0.44
		Unit E/C***	0.011	0.009	0.007	0.004	0.009	0.019	0.013	0.007	0.009	0.018	0.013	0.006
6 Prev. Grading per cycle	**High Traffic (>100 AADT)**	**Mean UPCI**	6.40	7.16	7.74	7.93	6.13	6.61	7.02	7.18	6.06	6.35	6.64	6.78
		AADT	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55
		Effectiveness	6554.43	8638.07	10218.13	10733.60	5810.21	18056.92	19165.75	19618.89	5613.70	17330.67	18132.86	18513.17
		PWC CAD$	7403.90	11792.95	17689.43	35378.85	7403.90	11792.95	17689.43	35378.85	7592.12	11792.95	17689.43	35378.85
		EUSC**	370.19	589.65	884.47	1768.94	370.19	589.65	884.47	1768.94	379.61	589.65	884.47	1768.94
		E/C***	0.89	0.73	0.58	0.30	0.78	1.53	1.08	0.55	0.74	1.47	1.03	0.52
		Unit E/C***	0.006	0.005	0.004	0.002	0.006	0.011	0.008	0.004	0.005	0.011	0.008	0.004

*Min acceptable UPCI=4

**EUSC: Equivalent Uniform Semi-Annual Costs per km

***E/C: Cost Effectiveness per km = Unit Effectiveness*Average AADT/PWC

****Unit E/C: Cost Effectiveness per km per veh= E/C / AADT

G.4 Cost Effectiveness Analysis for Earth Roads

G.4.1 Cost Effectiveness Analysis for Strategy ERM1

			Dry Climate				Mediterranean Climate				Humid Climate			
Maint	**Traffic**	**Cycle***	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**
1 Local Gravel per cycle	Low Traffic (<50 AADT)	Mean UPCI	6.97	7.25	7.84	7.86	6.57	6.60	7.45	7.92	6.53	6.66	7.34	7.87
		AADT	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14
		Effectiveness	2024.57	2217.90	2623.37	2636.96	1753.33	4505.43	5089.87	5407.21	1727.27	4544.53	5014.44	5372.75
		PWC CAD$	829.54	1385.23	1772.46	3475.60	3101.37	3211.10	2135.76	3302.26	3118.31	3561.16	2214.87	3302.26
		EUSC**	41.48	69.26	88.62	173.78	155.07	160.56	106.79	165.11	155.92	178.06	110.74	165.11
		E/C***	2.44	1.60	1.48	0.76	0.57	1.40	2.38	1.64	0.55	1.28	2.26	1.63
		Unit E/C***	0.071	0.047	0.043	0.022	0.017	0.041	0.070	0.048	0.016	0.037	0.066	0.048
3 Local Gravel per cycle	Mod. Traffic (50-100 AADT)	Mean UPCI	6.97	7.25	7.84	7.86	6.57	6.60	7.45	7.92	6.53	6.66	7.34	7.87
		AADT	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28
		Effectiveness	4049.13	4435.79	5246.73	5273.92	3506.67	9010.87	10179.74	10814.42	3454.53	9089.05	10028.87	10745.50
		PWC CAD$	2990.59	4818.87	6951.38	12213.58	6841.27	7636.00	7677.98	12598.66	6968.01	8070.46	7836.19	12598.66
		EUSC**	149.53	240.94	347.57	610.68	342.06	381.80	383.90	629.93	348.40	403.52	391.81	629.93
		E/C***	1.35	0.92	0.75	0.43	0.51	1.18	1.33	0.86	0.50	1.13	1.28	0.85
		Unit E/C***	0.020	0.013	0.011	0.006	0.008	0.017	0.019	0.013	0.007	0.016	0.019	0.012
6 Local Gravel per cycle	High Traffic (>100 AADT)	Mean UPCI	6.97	7.25	7.84	7.86	6.57	6.60	7.45	7.92	6.53	6.66	7.34	7.87
		AADT	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55
		Effectiveness	8098.27	8871.58	10493.46	10547.84	7013.34	18021.74	20359.47	21628.84	6909.07	18178.11	20057.74	21491.01
		PWC CAD$	4977.27	7153.95	10634.78	19024.18	10406.30	11849.53	12814.59	19813.54	10823.45	11957.46	13289.23	19813.54
		EUSC**	248.86	357.70	531.74	951.21	520.32	592.48	640.73	990.68	541.17	597.87	664.46	990.68
		E/C***	1.63	1.24	0.99	0.55	0.67	1.52	1.59	1.09	0.64	1.52	1.51	1.08
		Unit E/C***	0.012	0.009	0.007	0.004	0.005	0.011	0.012	0.008	0.005	0.011	0.011	0.008

*Min acceptable UPCI=4

**EUSC: Equivalent Uniform Semi-Annual Costs per km

***E/C: Cost Effectiveness per km = Unit Effectiveness*Average AADT/PWC

****Unit E/C: Cost Effectiveness per km per veh= E/C / AADT

Note: Unviable cases in red

G.4.2 Cost Effectiveness Analysis for Strategy ERM2

			Dry Climate				Mediterranean Climate				Humid Climate			
Maint	**Traffic**	**Cycle***	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**	**Min Budget**	**Low Budget**	**Med. Budget**	**High Budget**
1 Prev. Grading per cycle	Low Traffic (<50 AADT)	Mean UPCI	6.97	7.46	7.79	8.01	6.57	7.00	7.81	8.08	6.53	6.87	7.78	8.06
		AADT	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14	34.14
		Effectiveness	2024.57	2362.09	2590.33	2739.32	1753.33	4776.86	5332.65	5515.41	1727.27	4693.27	5309.01	5503.15
		PWC CAD$	829.54	1220.90	2062.66	3626.65	3101.37	1823.96	1926.61	3659.37	3118.31	1910.05	1926.61	3659.37
		EUSC**	41.48	61.04	103.13	181.33	155.07	91.20	96.33	182.97	155.92	95.50	96.33	182.97
		E/C***	2.44	1.93	1.26	0.76	0.57	2.62	2.77	1.51	0.55	2.46	2.76	1.50
		Unit E/C***	0.071	0.057	0.037	0.022	0.017	0.077	0.081	0.044	0.016	0.072	0.081	0.044
3 Prev. Grading per cycle	Mod. Traffic (50-100 AADT)	Mean UPCI	6.97	7.46	7.79	8.01	6.57	7.00	7.81	8.08	6.53	6.87	7.78	8.06
		AADT	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28	68.28
		Effectiveness	4049.13	4724.19	5180.67	5478.65	3506.67	9553.72	10665.29	11030.82	3454.53	9386.54	10618.02	11006.31
		PWC CAD$	2990.59	3662.70	5836.17	10879.95	6841.27	5471.87	5779.83	10978.10	6968.01	5730.14	5964.46	10978.10
		EUSC**	149.53	183.13	291.81	544.00	342.06	273.59	288.99	548.91	348.40	286.51	298.22	548.91
		E/C***	1.35	1.29	0.89	0.50	0.51	1.75	1.85	1.00	0.50	1.64	1.78	1.00
		Unit E/C***	0.020	0.019	0.013	0.007	0.008	0.026	0.027	0.015	0.007	0.024	0.026	0.015
6 Prev. Grading per cycle	High Traffic (>100 AADT)	Mean UPCI	6.97	7.46	7.79	8.01	6.57	7.00	7.81	8.08	6.53	6.87	7.78	8.06
		AADT	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55	136.55
		Effectiveness	8098.27	9448.38	10361.34	10957.29	7013.34	19107.43	21330.59	22061.65	6909.07	18773.07	21236.04	22012.62
		PWC CAD$	4977.27	7325.39	11203.26	21759.91	10406.30	10943.73	11559.66	22604.19	10823.45	11460.28	11559.66	21956.20
		EUSC**	248.86	366.27	560.16	1088.00	520.32	547.19	577.98	1130.21	541.17	573.01	577.98	1097.81
		E/C***	1.63	1.29	0.92	0.50	0.67	1.75	1.85	0.98	0.64	1.64	1.84	1.00
		Unit E/C***	0.012	0.009	0.007	0.004	0.005	0.013	0.014	0.007	0.005	0.012	0.013	0.007

*Min acceptable UPCI=4

**EUSC: Equivalent Uniform Semi-Annual Costs per km

***E/C: Cost Effectiveness per km = Unit Effectiveness*Average AADT/PWC

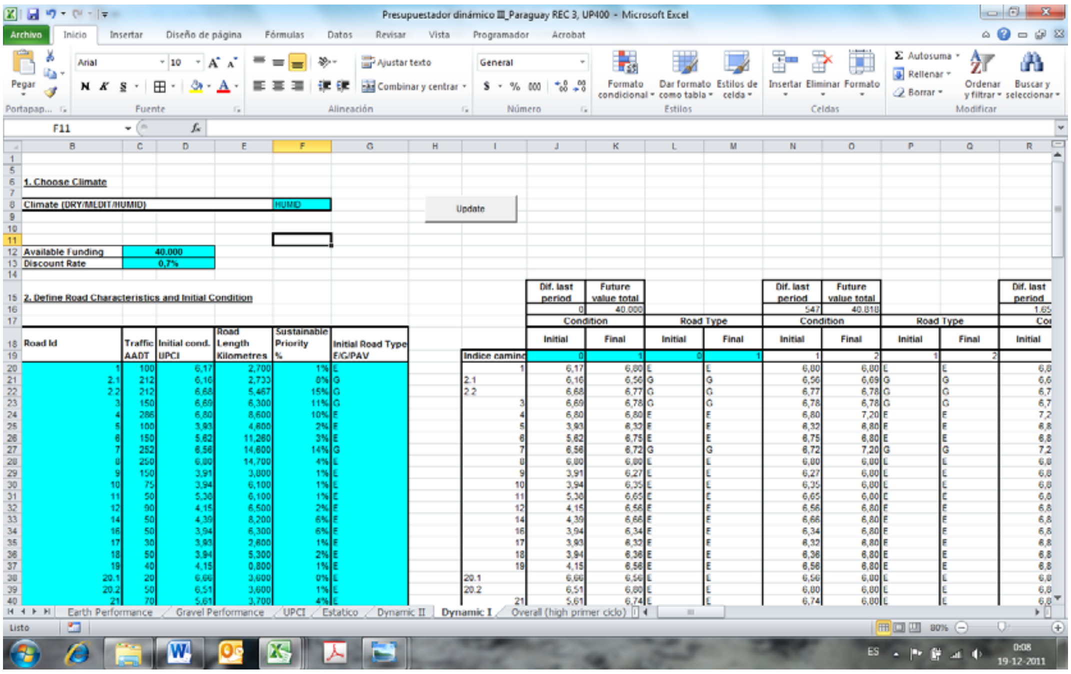
****Unit E/C: Cost Effectiveness per km per veh= E/C / AADT

Note: Unviable cases in red

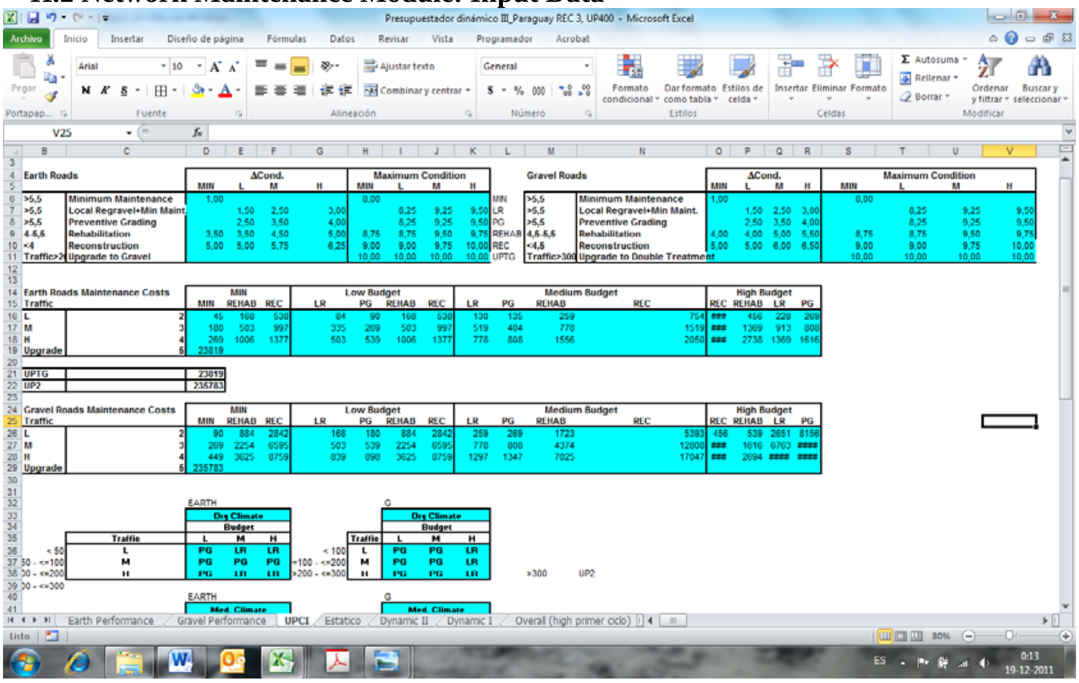
Appendix H

Computer Tool Overview

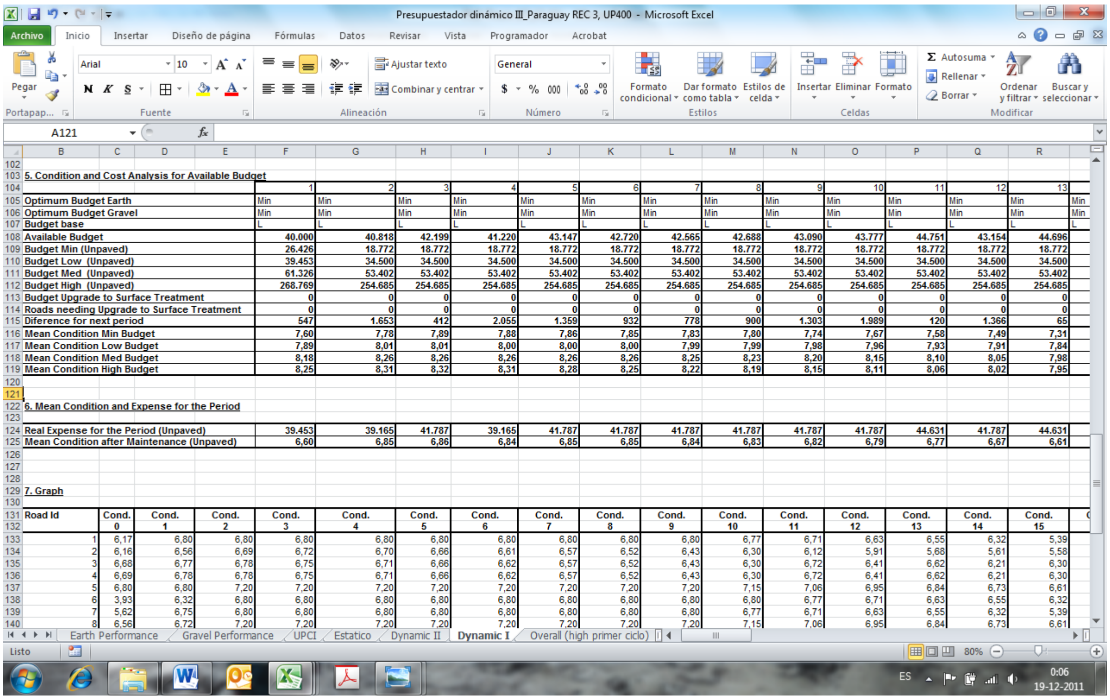
H.1 Input Data: Climate selection, available Funding, Discount Rate, Roads Characteristics



H.2 Network Maintenance Module: Input Data



H.3 Network Analysis Interface: Condition and Cost Analysis per Cycle



5. Condition and Cost Analysis for Available Budget

	1	2	3	4	5	6	7	8	9	10	11	12	13
Optimum Budget Earth	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min
Optimum Budget Gravel	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min	Min
Budget base	L	L	L	L	L	L	L	L	L	L	L	L	L
Available Budget	40.000	40.818	42.199	41.220	43.147	42.720	42.565	42.688	43.090	43.777	44.751	43.154	44.696
Budget Min (Unpaved)	26.426	18.772	18.772	18.772	18.772	18.772	18.772	18.772	18.772	18.772	18.772	18.772	18.772
Budget Low (Unpaved)	39.453	34.500	34.500	34.500	34.500	34.500	34.500	34.500	34.500	34.500	34.500	34.500	34.500
Budget Med (Unpaved)	61.326	53.402	53.402	53.402	53.402	53.402	53.402	53.402	53.402	53.402	53.402	53.402	53.402
Budget High (Unpaved)	268.769	254.685	254.685	254.685	254.685	254.685	254.685	254.685	254.685	254.685	254.685	254.685	254.685
Budget Upgrade to Surface Treatment	0	0	0	0	0	0	0	0	0	0	0	0	0
Roads needing Upgrade to Surface Treatment	0	0	0	0	0	0	0	0	0	0	0	0	0
Diference for next period	547	1.653	412	2.055	1.359	932	778	900	1.303	1.989	120	1.366	65
Mean Condition Min Budget	7,60	7,78	7,89	7,88	7,86	7,85	7,83	7,80	7,74	7,67	7,58	7,49	7,31
Mean Condition Low Budget	7,89	8,01	8,01	8,00	8,00	8,00	7,99	7,99	7,98	7,96	7,93	7,91	7,84
Mean Condition Med Budget	8,18	8,26	8,26	8,26	8,26	8,26	8,25	8,23	8,20	8,15	8,10	8,05	7,98
Mean Condition High Budget	8,25	8,31	8,32	8,31	8,28	8,25	8,22	8,19	8,15	8,11	8,06	8,02	7,95

6. Mean Condition and Expense for the Period

Real Expense for the Period (Unpaved)	39.453	39.165	41.787	39.165	41.787	41.787	41.787	41.787	41.787	41.787	44.631	41.787	44.631
Mean Condition after Maintenance (Unpaved)	6,60	6,85	6,86	6,84	6,85	6,85	6,84	6,83	6,82	6,79	6,77	6,67	6,61

7. Graph

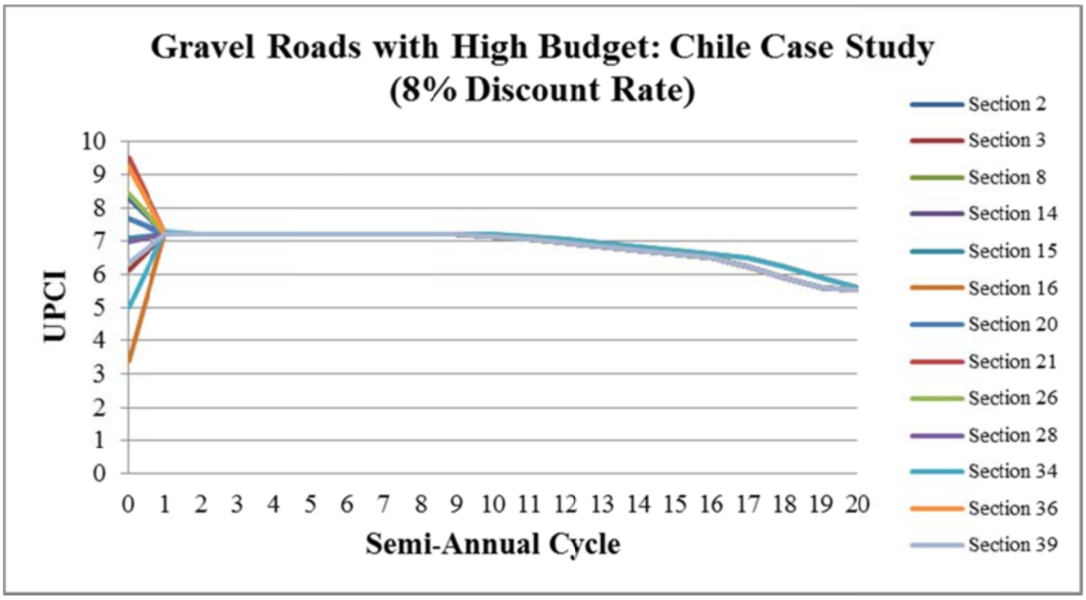
Road Id	Cond. 0	Cond. 1	Cond. 2	Cond. 3	Cond. 4	Cond. 5	Cond. 6	Cond. 7	Cond. 8	Cond. 9	Cond. 10	Cond. 11	Cond. 12	Cond. 13	Cond. 14	Cond. 15
1	6,17	6,80	6,80	6,80	6,80	6,80	6,80	6,80	6,80	6,80	6,77	6,71	6,63	6,55	6,32	5,39
2	6,16	6,56	6,69	6,72	6,70	6,66	6,61	6,57	6,52	6,43	6,30	6,12	5,91	5,68	5,61	5,58
3	6,68	6,77	6,78	6,75	6,71	6,66	6,62	6,57	6,52	6,43	6,30	6,72	6,41	6,62	6,21	6,30
4	6,69	6,78	6,78	6,75	6,71	6,66	6,62	6,57	6,52	6,43	6,30	6,72	6,41	6,62	6,21	6,30
5	6,80	6,80	7,20	7,20	7,20	7,20	7,20	7,20	7,20	7,20	7,15	7,06	6,95	6,84	6,73	6,61
6	3,93	6,32	6,80	6,80	6,80	6,80	6,80	6,80	6,80	6,80	6,80	6,77	6,71	6,63	6,55	6,32
7	5,62	6,75	6,80	6,80	6,80	6,80	6,80	6,80	6,80	6,80	6,77	6,71	6,63	6,55	6,32	5,39
8	6,56	6,72	7,20	7,20	7,20	7,20	7,20	7,20	7,20	7,20	7,15	7,06	6,95	6,84	6,73	6,61

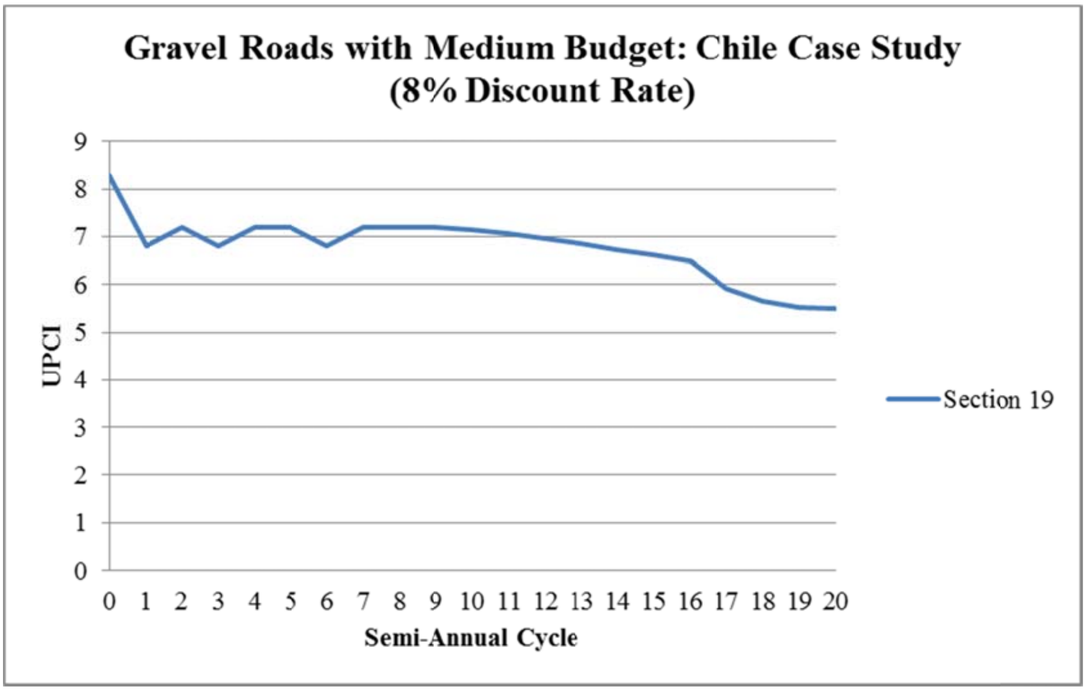
Appendix I

Application and Validation of the Management System

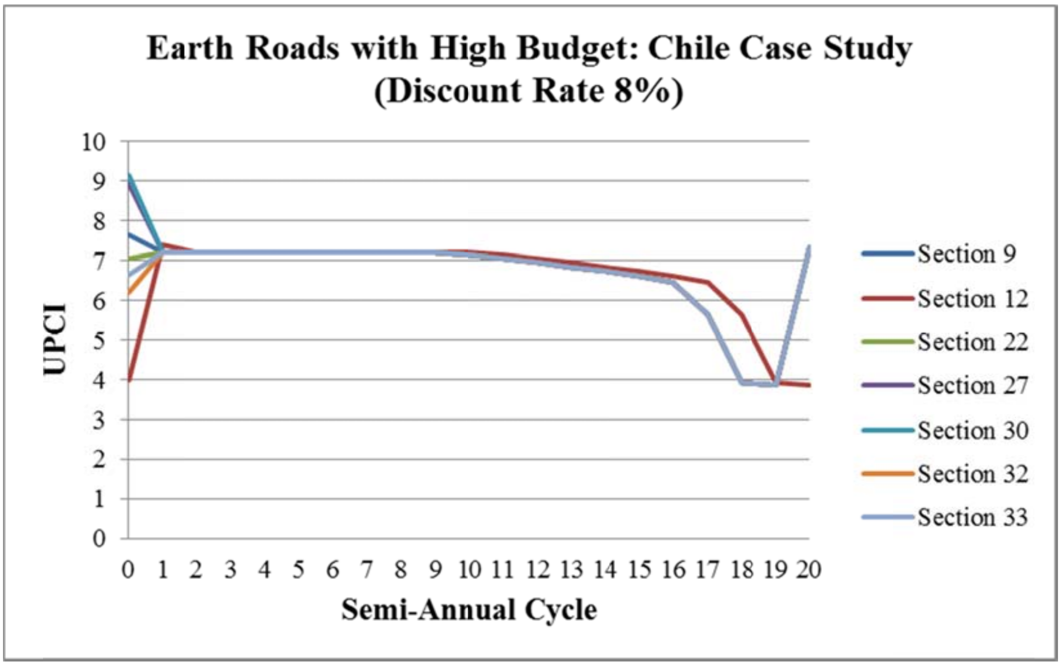
I.1 Chile Case Study

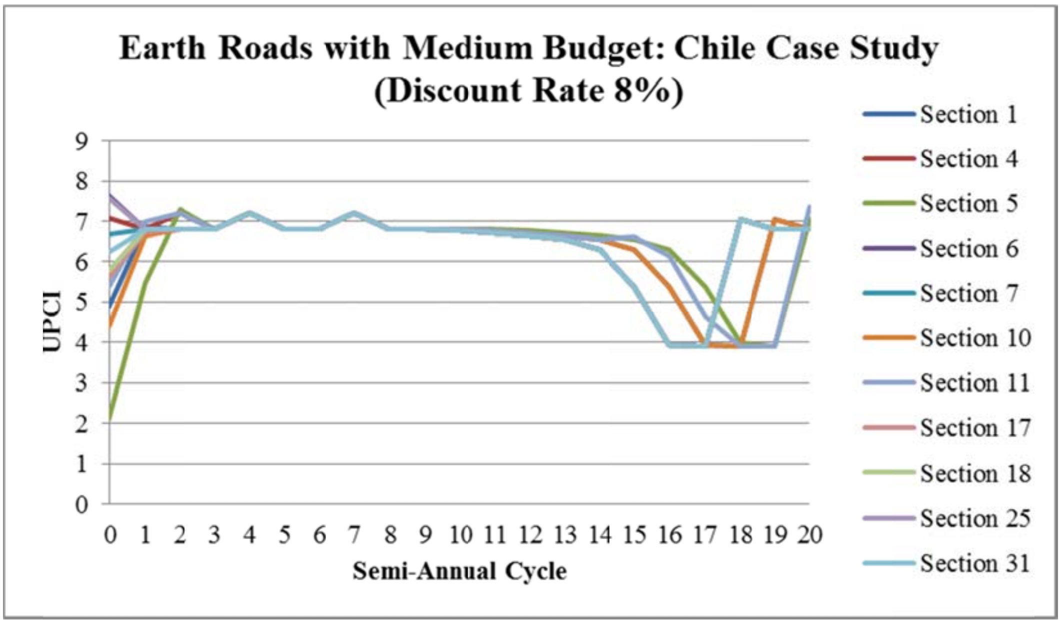
I.1.1 Gravel Roads Condition per Road: Chile Case Study





I.1.2 Earth Roads Condition per Road: Chile Case Study





I.1.3 Condition Data Life Cycle Analysis: Chile Case Study

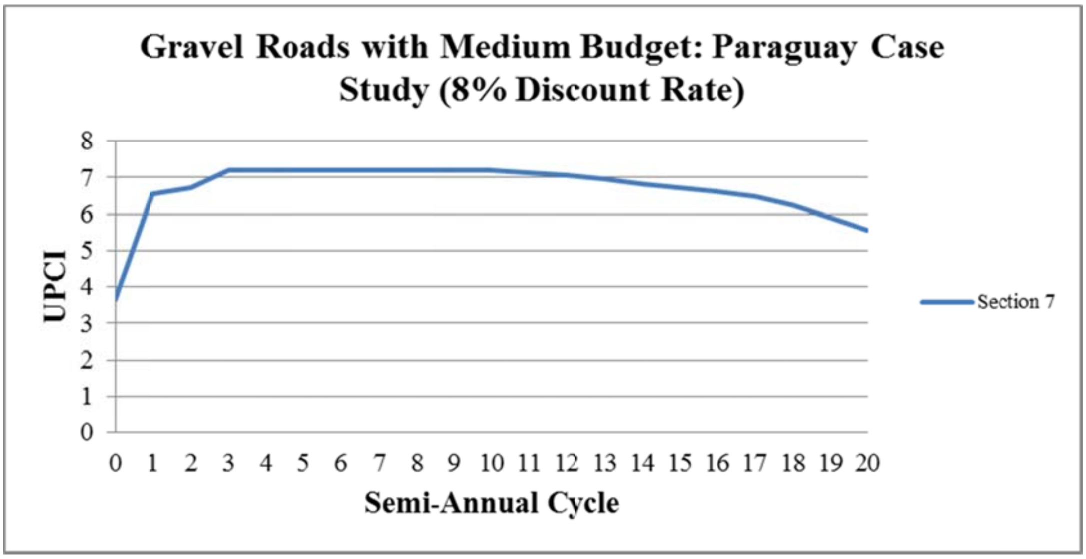
Road Id	Initial Road Type	Final Road Type	Priority Rank	Cycle 0	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Cycle 11	Cycle 12	Cycle 13	Cycle 14	Cycle 15	Cycle 16	Cycle 17	Cycle 18	Cycle 19	Cycle 20
1	E	E	33	4.9	6.9	6.8	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8
2	G	G	5	8.3	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
3	G	G	19	6.1	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
4	E	E	24	7.1	6.8	7.2	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8	6.8
5	E	E	23	2.1	5.5	7.3	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	4.0	3.9	7.1
6	E	E	30	7.6	6.8	6.8	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8	6.8
7	E	E	27	6.7	6.8	6.8	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8	6.8
8	G	G	3	9.5	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
9	E	E	18	7.7	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	5.6	3.9	3.9	7.3
10	E	E	32	4.4	6.7	6.8	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8
11	E	E	22	5.4	7.0	7.2	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.8	6.7	6.6	6.6	6.6	6.1	4.6	3.9	3.9	7.4
12	E	E	20	4.0	7.4	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	5.6	3.9	3.9
14	G	G	15	7.7	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
15	G	G	2	7.1	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
16	G	G	17	3.4	7.3	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6
17	E	E	28	5.6	6.8	6.8	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8	6.8
18	E	E	26	5.8	6.8	6.8	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8	6.8
19	G	G	21	8.3	6.8	7.2	6.8	7.2	7.2	6.8	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	5.9	5.7	5.5	5.5
20	G	G	12	7.7	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
21	G	G	4	9.5	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
22	E	E	8	7.1	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	5.6	3.9	3.9	7.3
25	E	E	29	7.6	6.8	6.8	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8	6.8
26	G	G	10	8.4	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
27	E	E	16	8.9	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	5.6	3.9	3.9	7.3
28	G	G	6	7.0	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
30	E	E	13	9.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	5.6	3.9	3.9	7.3
31	E	E	25	6.3	6.8	6.8	6.8	7.2	6.8	6.8	7.2	6.8	6.8	6.8	6.7	6.6	6.6	6.3	5.4	3.9	3.9	7.1	6.8	6.8
32	E	E	9	6.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	5.6	3.9	3.9	7.3
33	E	E	14	6.7	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	5.6	3.9	3.9	7.3
34	G	G	7	5.0	7.3	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6
36	G	G	11	9.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5
37	G	PAV	37	6.2	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
38	G	PAV	36	5.9	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
39	G	G	1	6.3	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.1	7.0	6.8	6.7	6.6	6.5	6.2	5.9	5.6	5.5

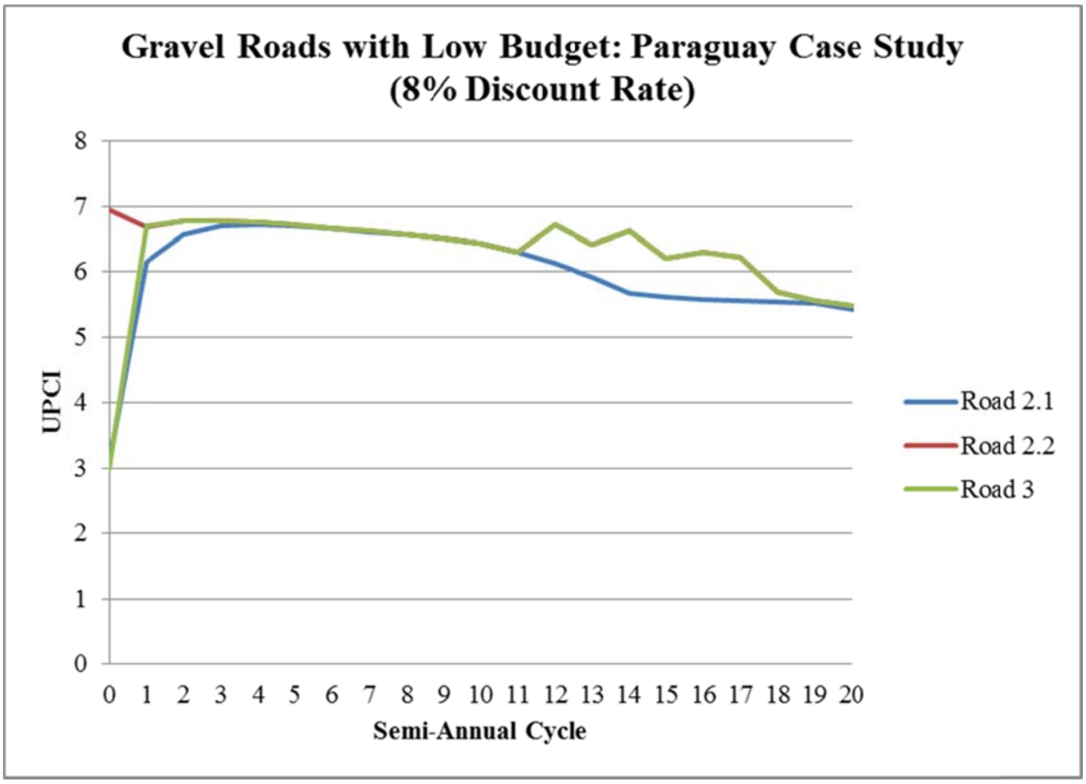
I.1.4 Sustainable Network Prioritization: Chile Case Study

Road Id	Priority Rank	AADT	Initial UPCI	Kilometres	%	Initial Road Type
1	33	4	4.9	0.55	0.1%	E
2	5	100	8.3	13.9	3.3%	G
3	19	30	6.1	2	0.7%	G
4	24	6	7.1	2.8	0.4%	E
5	23	14	2.1	1.4	0.5%	E
6	30	10	7.6	0.4	0.3%	E
7	27	10	6.7	0.5	0.5%	E
8	3	70	9.5	9.7	8.7%	G
9	18	14	7.7	2	1.2%	E
10	32	8	4.4	0.85	0.2%	E
11	22	12	5.4	5	0.3%	E
12	20	30	4.0	1.5	0.6%	E
14	15	50	7.7	4	1.2%	G
15	2	100	7.1	7.7	10.0%	G
16	17	30	3.4	3.3	0.6%	G
17	28	6	5.6	1.1	0.3%	E
18	26	6	5.8	1.7	0.2%	E
19	21	20	8.3	3.2	0.6%	G
20	12	40	7.7	5.8	1.2%	G
21	4	80	9.5	11.7	5.0%	G
22	8	40	7.1	6.8	1.6%	E
25	29	16	7.6	1.2	0.1%	E
26	10	60	8.4	11.2	1.9%	G
27	16	20	8.9	3	0.8%	E
28	6	80	7.0	5.3	6.2%	G
30	13	30	9.2	3	1.9%	E
31	25	6	6.3	2	0.3%	E
32	9	60	6.2	5.4	3.1%	E
33	14	30	6.7	1.6	1.2%	E
34	7	60	5.0	10.2	4.0%	G
36	11	40	9.2	4.9	1.5%	G
37	37	220	6.2	15.9	15.5%	G
38	36	260	5.9	15.9	15.5%	G
39	1	100	6.3	11	10.5%	G

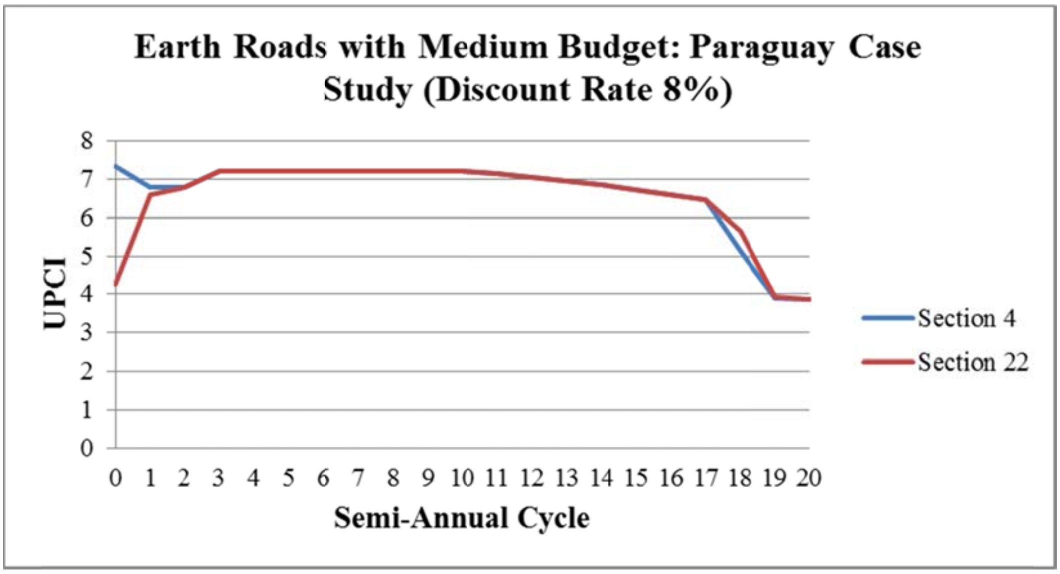
I.2 Paraguay Case Study

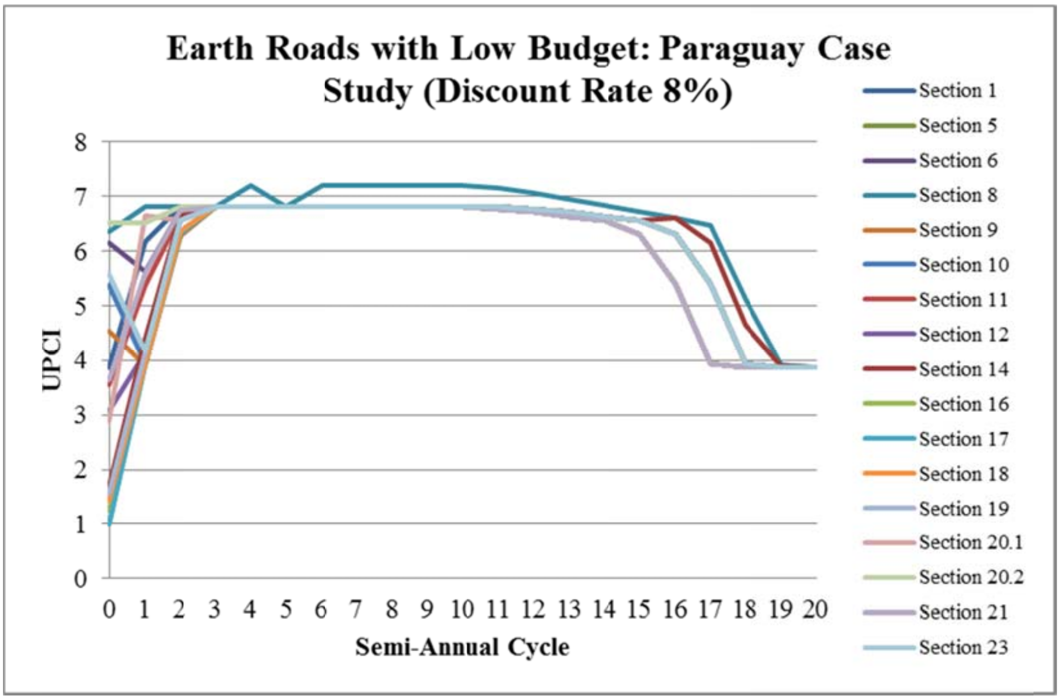
I.2.1 Gravel Roads Condition per Road: Paraguay Case Study





I.2.2 Earth Roads Condition per Road: Paraguay Case Study





I.2.3 Condition Data Life Cycle Analysis: Paraguay Case Study

Road Id	Initial Road Type	Final Road Type	Priority Rank	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.	Cond.
	E/G/PAV	E/G/PAV		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	E	E	20	3.87	6.17	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87	3.87
2.1	G	G	12	3.09	6.16	6.56	6.69	6.72	6.70	6.66	6.61	6.57	6.52	6.43	6.30	6.12	5.91	5.68	5.61	5.58	5.56	5.54	5.52	5.43	5.19
2.2	G	G	6	6.95	6.68	6.77	6.78	6.75	6.71	6.66	6.62	6.57	6.52	6.43	6.30	6.72	6.41	6.62	6.21	6.30	6.23	5.69	5.55	5.47	5.29
3	G	G	5	2.98	6.69	6.78	6.78	6.75	6.71	6.66	6.62	6.57	6.52	6.43	6.30	6.72	6.41	6.62	6.21	6.30	6.23	5.69	5.55	5.47	5.29
4	E	E	3	7.35	6.80	6.80	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.15	7.06	6.95	6.84	6.73	6.61	6.46	5.13	3.91	3.86	3.86
5	E	E	16	1.00	3.93	6.32	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87
6	E	E	9	6.16	5.62	6.75	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87	3.87
7	G	G	1	3.64	6.56	6.72	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.15	7.06	6.95	6.84	6.73	6.61	6.49	6.24	5.89	5.57	5.47
8	E	E	4	6.36	6.80	6.80	6.80	7.20	6.80	7.20	7.20	7.20	7.20	7.20	7.15	7.06	6.95	6.84	6.73	6.61	6.46	5.13	3.91	3.86	3.86
9	E	E	18	4.54	3.91	6.27	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87
10	E	E	14	5.37	3.94	6.35	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87
11	E	E	15	3.56	5.38	6.65	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87	3.87
12	E	E	10	3.08	4.15	6.56	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87
14	E	E	7	1.68	4.39	6.66	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.61	6.15	4.64	3.90	3.87	3.87
16	E	E	8	1.25	3.94	6.34	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87
17	E	E	21	1.00	3.93	6.32	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87
18	E	E	13	1.43	3.94	6.36	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87
19	E	E	23	1.58	4.15	6.56	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87
20.1	E	E	23	2.90	6.66	6.56	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87	3.87
20.2	E	E	19	6.52	6.51	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87	3.87
21	E	E	11	3.65	5.61	6.74	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87	3.87
22	E	E	2	4.27	6.61	6.80	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.15	7.06	6.95	6.84	6.73	6.61	6.46	5.64	3.93	3.86	3.86
23	E	E	17	5.58	4.16	6.56	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.77	6.71	6.63	6.55	6.32	5.39	3.93	3.88	3.87	3.87

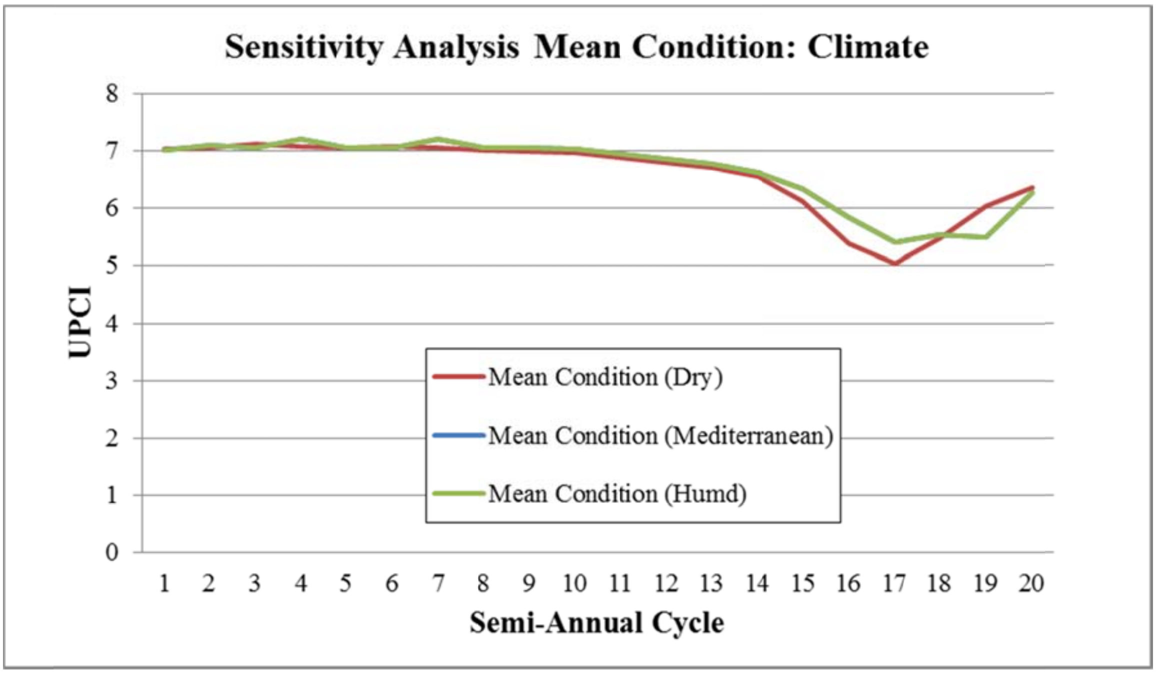
I.2.4 Sustainable Network Prioritization: Paraguay Case Study

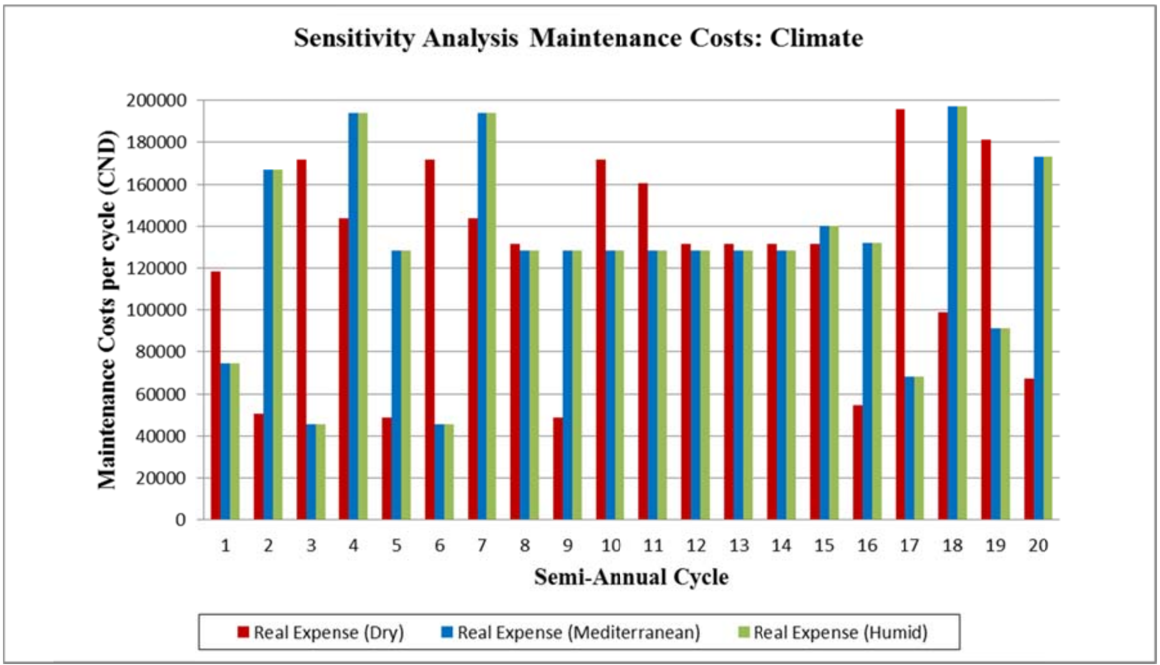
Road Id	Priority Rank	AADT	Initial UPCI	Kilometres	%	Initial Road Type
1	20	100	3,87	2,70	1%	E
2.1	12	212	3,086	2,73	8%	G
2.2	6	212	6,95	5,47	15%	G
3	5	150	2,983	6,30	11%	G
4	3	286	7,345	8,60	10%	E
5	16	100	1	4,60	2%	E
6	9	150	6,155	11,26	3%	E
7	1	252	3,64	14,60	14%	G
8	4	250	6,355	14,70	4%	E
9	18	150	4,54	3,80	1%	E
10	14	75	5,365	6,10	1%	E
11	15	50	3,56	6,10	1%	E
12	10	90	3,08	6,50	2%	E
14	7	50	1,675	8,20	6%	E
16	8	50	1,25	6,30	6%	E
17	21	30	1	2,60	1%	E
18	13	50	1,43	5,30	2%	E
19	23	40	1,58	0,80	1%	E
20.1	23	20	2,9	3,60	0%	E
20.2	19	50	6,52	3,60	1%	E
21	11	70	3,65	3,70	4%	E
22	2	83	4,265	11,00	8%	E
23	17	60	5,5815625	3,10	1%	E

Appendix J

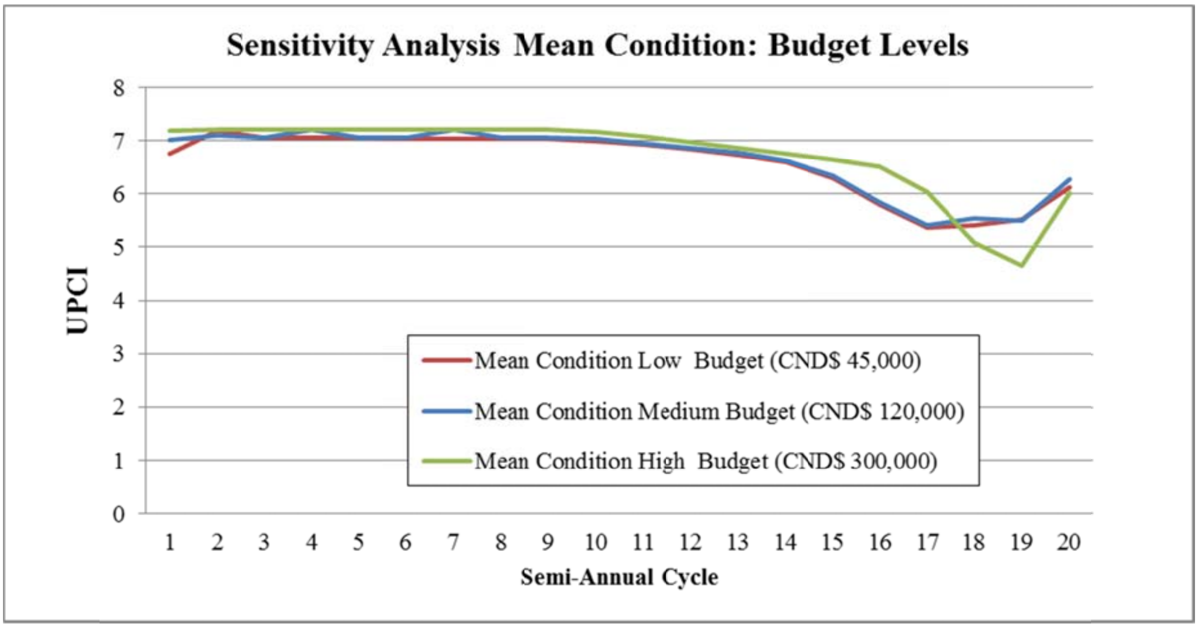
Sensitivity Analysis of the Management System

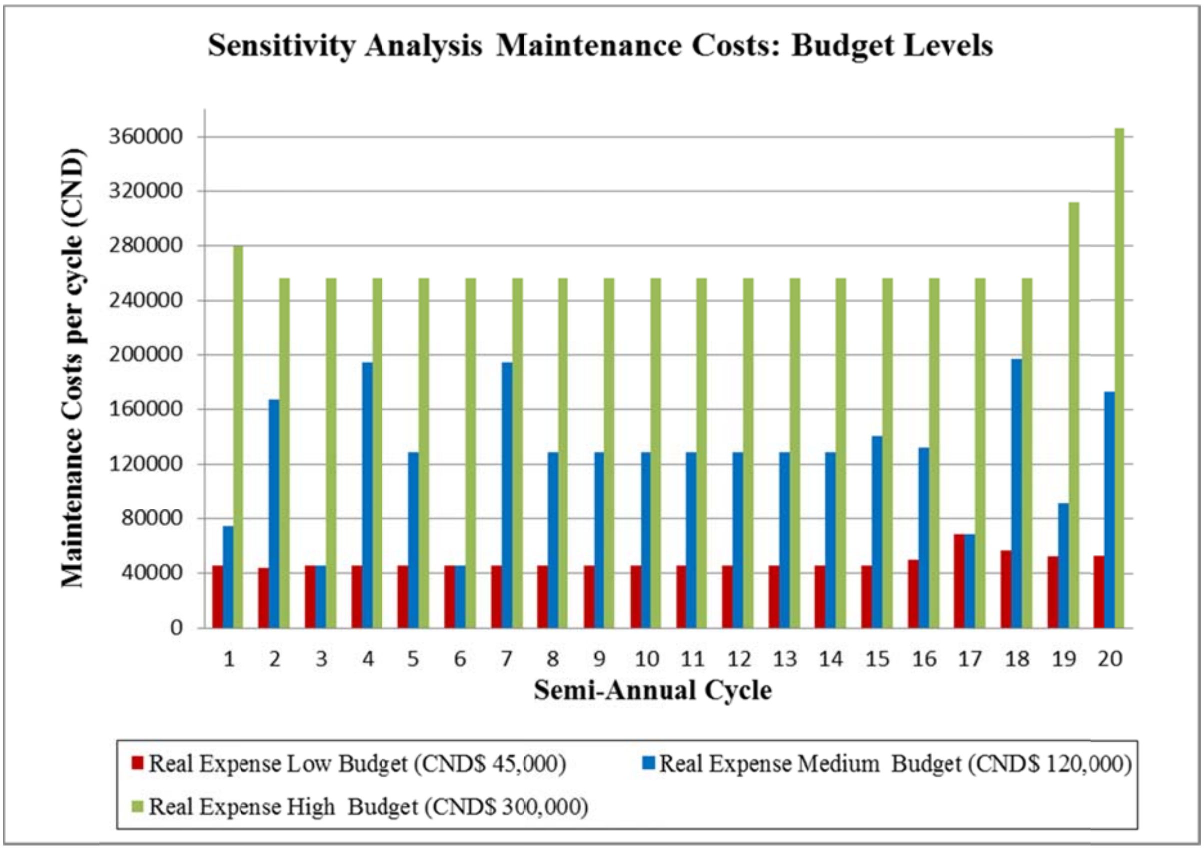
I.1 Sensitivity Analysis: Climate





I.2 Sensitivity Analysis: Budget





I.3 Sensitivity Analysis: Discount Rate