Sustainable Tactical Planning for Road Infrastructure Management

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This is to certify that the thesis prepared

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

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ABSTRACT

Pavement management systems are commonly employed by departments of transportation and municipalities to preserve and maintain roads at good levels of condition. There are many treatments applicable at different stages during the lifecycle of a pavement; their allocation normally follows principles of cost and effectiveness, failing to consider measures of environmental impact. Another problem lies in the disconnection between strategic decision making support tools and tactical and operational planning. This thesis aims to propose an extension of classical performance-based optimization to incorporate the environmental impact of maintenance and rehabilitation treatments in order to choose more sustainable, yet cost-effective actions. A three step process is proposed to achieve optimal condition levels with minimum environmental impact and cost. A case study of a dataset from Alberta highways is used to demonstrate the procedure. International Roughness Index remains at about same levels while achieving 19% energy reduction and 24% reductions in gas emissions while using same levels of budget and planning horizon. Additionally, this research proposes the use of commercial software to coordinate actions in order to reallocate treatments at adjacent segments during a close window of time by advancing or deferring such treatments in order to minimize disruptions to the public. A corridor based on a buffer of road assets along Route 1 in New Brunswick is used to illustrate the method. Five clusters of assets to be treated at years 2, 3, 5, 7, 10 were found. Degree of optimality for bridges remain very close to optimal at 91%, followed by pavements at 83%, chip sealed roads suffer the most from reallocation of treatments at 66% optimality.

DEDICATION

To
Golnaz, Mum and Dad

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I am deeply indebted to my supervisor Dr. Luis Amador for his advice, support, encouragement and friendship during my graduate studies at Concordia University. I wish all the best to him and his family. I would like to express my appreciation to my committee members, Professor Fariborz Haghighat, Professor Lan Lin and Professor Navneet Vidyarthi.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
DOT	Department of Transportation
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GHG	Greenhouse Gas
GWP	Global Warming Potential
IRI	International Roughness Index
LCA	Life Cycle Analysis
LEED	Leadership in Energy and Environmental Design
M&R	Maintenance and Rehabilitation
NCHRP	National Cooperative Highway Research Program
NRC	National Research Council Canada
TRB	Transportation Research Board
VOC	Vehicle Operating Cost

CHAPTER 1
INTRODUCTION

1.1 Background

Tactical planning refers to the ability to identify groups of actions for a short period of time, normally 4 or 5 years. Tactical plans play a major role in road infrastructure management systems because they serve as a connection between longer term analysis and operational programs of works. The precise knowledge of which assets to intervene, what treatments to apply and the timing for that is not a simple task as it requires the identification of all possible combinations of applicable treatments across time for a network of roads, their main effects and cost. Such analysis is in most cases supported by an optimization algorithm and in immature systems done on an annual basis by senior engineers using subjective criteria.

It has been a common practice to address the problem of road infrastructure management by looking at results from optimization tools, despite the fact that such results provide a schedule of generic actions scattered across time and space with no regards to the impact to users (disruptions), the environmental footprint or conflicting with actions scheduled at other infrastructure systems.

Several classical approaches fall short on many desirable features for sustainable tactical planning integrated with strategic plans. Linear integer programming models were developed based on lifecycle cost of historical condition data. Heuristic methods differ on linear integer programming only in the way in which they solve the problem, which is supported by a simulation algorithm, however such methods also lack of coordination or environmental considerations besides that their solution is approximate. Some cost benefit decision support tools do account for environmental impact by looking at emissions generated by road users (vehicles) however they do not consider emissions generated by maintenance and rehabilitation treatments in such a way that less polluting alternatives are selected

Presently, environmental considerations are becoming popular on the determination of the impact that human activities have on the environment. Several methods have been developed to measure energy consumption and greenhouse gas (GHG) emissions from dissimilar activities related to civil works. However, these methods have not been added to strategic or tactical planning of maintenance and rehabilitation works for civil infrastructure. Therefore, there is a need to expand decision making tools to encourage environmentally friendly rehabilitation and maintenance works for road infrastructure management. At present, infrastructure agencies (in both developed and developing countries) are predominantly using either linear programming or heuristic methods. In general, most of models used in current practice lack a mechanism to account for environmental footprint.

1.2 Problem Statement

The various approaches currently used for road infrastructure management do not explicitly consider means to produce sustainable tactical plans, and therefore decision support tools remain at the strategic level. Specific problems associated with such current practices of management models include: (1) the inability to transfer optimal schedule of actions from long term analysis into shorter periods of time by considering deferral or advancement of actions given their time or space adjacency. In addition compatibility of treatments for different assets and other operational considerations should also be included when coordinating intervention works, (2) analysis pay too much attention to economic criteria for optimizing resources and ignore the environmental impact of maintenance and rehabilitation such that those treatments with lower GHG emissions and energy use are given preference, and (3) the analysis should be able to conduct a trade-off between asset condition, environmental impact and overall cost. Therefore, there is a need to develop sustainable tactical plans capable of balancing resource allocation, minimize environmental footprint and achieve coordinated actions that minimize disruptions to the public.

1.3 Research Objective

1.3.1 Overall Goal

The overall goal of this research is to develop a procedure for obtaining sustainable tactical plans for road management systems.

1.3.2 Research Tasks

Two tasks were identified to address the main goal of this research:

Task 1

The motivation of this task is to address the very common need to take into consideration the environmental impact of maintenance and rehabilitation of road infrastructure during the selection of optimal timing and type of treatments. This task will apply classical linear integer programming to consider GHG emissions and energy consumption, and will deal with conflictive objectives pursuing a trade off analysis between economic cost, environmental impact and asset condition.

- To account for the environmental impact of maintenance and rehabilitation practices;
- To conduct a trade off analysis to find optimal levels of expenditure and selection of treatments to achieve sustainable maintenance and rehabilitation practices.

Task 2

This task is motivated by the need in the industry to develop an approach capable of extracting tactical plans by reallocating results from strategic analysis produced by optimization algorithms:

- To develop an approach capable of coordinating the allocation of treatments for maintenance and rehabilitation of networks of road infrastructure. It was important to verify that such approach is capable of taking into consideration spatial and temporal adjacency for deferring or advancing the allocation of compatible treatments.

1.4 Scope and Limitations

The scope of this research is limited to applications in road asset management. Only provincial road networks are considered, networks of urban residential roads are excluded. Coordination is conducted for corridors and no zonal considerations (as those probably recommended for urban zones) are employed. The case studies are all taken from asphalt concrete pavements, chip-seal roads and bridges. The research methodology uses case studies to demonstrate the applicability in practice. The data required for the case studies was provided by the New Brunswick Department of Transportation (NBDOT), and the 7th International Conference on Managing Pavement Assets which uses a dataset from Alberta Transportation.

1.5 Research Significance

This research makes the following contributions:

1. It presents an approach capable of translating strategic plans into tactical plans by coordinating actions across time and space for a road corridor.
2. It incorporates environmental considerations in the selection of maintenance and rehabilitation for road infrastructure, and pursues a more balanced solution with less environmental impact, similar cost and asset condition than the original solution.
3. The overall research will enhance the cost-effectiveness of management systems to better allocate scarce public funds. More sustainable tactical plans are expected.

1.6 Organization of the Thesis

This thesis is presented in five chapters as follows. Chapter 1 defines the problem and presents the objectives of the research and structure of the thesis. Chapter 2 contains a review of the state of the practice in road infrastructure management and sustainability: classical planning and management methods are criticized for the lack of environmental impact considerations and their limitations to produce tactical plans are highlighted. Chapter 3 presents the methodology employed to obtain sustainable coordinated tactical plans. Chapter 4 presents the work covered under Task 1. This chapter is devoted to incorporate environmental considerations in a road management system. The chapter demonstrates how GHGs emission and energy consumption can be used to select more environmentally friendly treatments.

In Chapter 5 the work under Task 2 of the research is presented. A case study illustrates the development of coordinated tactical plans from long term strategic analysis for a road corridor. Chapter 6 presents the conclusions and lessons learnt from the modeling experience and, make recommendations for future research.

The work described in Chapters 4, and 5 have been written as self contained papers and as such, each chapter has its own abstract and references. These chapters have been submitted for publication in the following journals:

Chapter 4: Faghih-Imani, S.A. and Amador-Jimenez, L. 2012. "*Incorporating environmental impact into performance based optimization sustainability in*". Journal of Civil Engineering and Environmental Systems (Taylor and Francis). Submitted.

Chapter 5: Faghih-Imani, S.A. and Amador-Jimenez, L. 2012. "*From Strategic Optimization to Tactical Plans: Coordinating Treatments on Road Infrastructure*". 92nd Annual Meeting of the Transportation Research Board of the National Academies and Transportation Research Record, Journal of the Transportation Research Board. Submitted.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The goal of this chapter is to establish the need for a better method for developing sustainable management system including coordinated tactical planning and considerations of environmental impact.

The chapter is divided in three major sections: 1) the first one (Section 2.2.1) provides review of state of the practice in road infrastructure management; reviewing background, criticizing current decision support models and establishing the need of a better approach. A brief introduction of the software suite *REMSOFT woodstock* is presented at the end of the first section, summarizing its advantages and limitations for the modeling of sustainable tactical plans.

2) Next part (Section 2.2.2) presents coordination of maintenance and rehabilitation (M&R) programs in the asset management, reviews the efforts in this area and magnifies the benefits that governments would gain from coordination of actions. 3) Part three (Section 2.2.3) focuses on road infrastructure works particularly on M&R actions with an eye on sustainability from environmental standpoint. This part discusses and reviews the fundamentals of GHG emissions and energy consumption of maintenance and rehabilitation for road infrastructure.

2.2 Road Infrastructure Management Systems

2.2.1 Overview of Road Infrastructure Asset Management

Road infrastructures are vital to have a productive and competitive economy (Amador and Willis 2012). The increase in demands and decrease in financial and human resources make the management of deteriorating infrastructure a complex and daunting task for governments and agencies. However, they are still responsible for providing sustainable networks of assets capable of delivering acceptable level of services to their people. Public and private agencies around the world, faced with these problems, have gradually realized the benefits of implementing infrastructure management systems. Infrastructure Assets are defined as fixed systems (or networks) that provide a specific level of service to help communities while the whole system needs to be maintained constantly by continuing replacement and refurbishment of its components (NAMS 2006).

Communities depend on various infrastructures to adequately support travel and lifestyle namely business and commerce, transport system, energy supply systems, water and disposal systems, recreational, health and educational systems. While taking the most of benefits and reducing the expenditures, it is critical to keep infrastructure assets in appropriate condition to support economic and social development. The failure in one component can lead to disruption not only in that particular system but also in other networks. No one can neglect the important role of infrastructures in a country. In fact, only countries that manage to invest heavily in infrastructure have attained and can sustain global leadership. In United States, about 24 percent of the country’s major roads are in poor to mediocre condition and 25.4 percent of bridges are structurally poor and deficient (ULI 2008). Thus, in 2007 a national commission recommended increasing annual funding on transport infrastructure in about 280% from 2008 to 2020 (from about $86 billion in 2008 to $241 billion by 2020) in order to involve maintenance and capital needs (ULI 2008).

Infrastructure asset management is a process and decision making framework that considers a diverse range of assets and covers the whole service life of an asset from both engineering and economics standpoints (Vanier and Rahman 2004). It tries to bring a systematic process of operating, maintaining, upgrading, and expanding physical assets cost-effectively; a logical approach to handle well-defined objectives for both short and long term planning (FHWA 1999, AASHTO 2010).

Historically, infrastructure asset management has evolved from pavement management systems. As most of the infrastructure systems reached maturity and the demands started to rapidly increase in the mid-1960s, a global effort was made through the entire world to develop a systematic approach in managing pavement infrastructures. The process started with the development of pavement management systems. A pavement management system refers to an inclusive collaboration among all the main phase of pavement works including planning, designing, constructing, maintaining rehabilitating, monitoring and evaluating pavement conditions (Haas *et al.* 1994). The evolution of management systems continued with bridge management systems and integrated infrastructure management systems, and has finally advanced into asset management (Hudson *et al.* 1997, NCHRP 2002, see Krugler *et al.* 2006 for a comprehensive review of asset management literature).

Resource allocation throughout the whole life of infrastructures has a significant role in asset management. Keeping the level of service in a proper form, the emphasis of infrastructure investment has shifted in the past 30 years toward maintenance and rehabilitation (M&R) rather than new construction (McNeil 2008). This gradually tendency for moving from new construction to maintenance and rehabilitation had some reasons. First, there were enough constructed infrastructures like road and water networks and there was no need to build a new one. Also, those constructed infrastructures were deteriorating and must have been maintained and rehabilitated to be capable of delivering acceptable level of service. Therefore, it has been rational shift in investments towards M&R programs by governments.

Insufficient resources and financial limitations lead to development of various methods to find the best way of resource allocation across assets. Worst first, life cycle cost analysis, optimization methods such as linear programming (most formal optimization methods), non-linear programming, integer programming or heuristic methods are some examples of different techniques and decision making approaches which are currently using in transportation asset management state of practice. Many studies and works have been done during past decades to provide analytical tools that help to find out the best optimum solution for allocating funds across competing alternatives (NCHRP 2005). These include scheduling of maintenance and rehabilitation (M&R) projects as well. PONTIS for bridge management system and PAVER, HDM4, HERS-ST for road management system are the examples of software which are built up based on these concepts aimed to help planning process.

Transportation asset management state of practice lies on trade-off optimization for selecting the optimal set of action among competing alternatives to maintain, rehabilitate and upgrade infrastructure assets (NCHRP 2005). Consequently, one can identify the appropriate treatments for each asset at proposed year. It must be mentioned that treatment availability depends on asset type. For example, for pavements there are often several treatment options at different stages of the lifespan while for water networks usually there are few choices. The performance and effectiveness of treatments are shown in Figure (2.1):

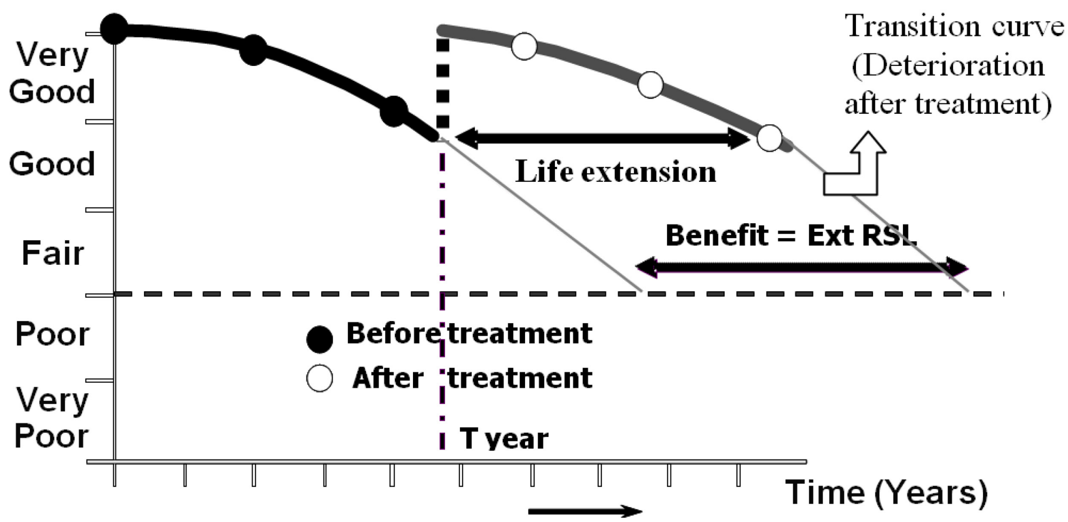


Figure 2. 1 Asset Performance and Treatment Effectiveness

Linear optimization has been used to find the optimal path of assets, treatments and time to fully take advantage of cost-effectiveness of individual treatments associated with individual asset elements and benefits of advancing or deferring a certain treatment. It seeks an allocation that minimizes costs (or maximizes the benefits, or any other measures of return on investment) over the whole network of assets in the long run. Thus, it would answer the optimal solution for the question of "What treatments?" on "What asset?" in "What year?"

New methods in optimization help asset management decision makers to program and plan M&R works. In 1979, Friesz and Fernandez developed one of the first M&R optimization models, proposed for transportation infrastructure. Fwa *et al.* (1998) developed a scheduling methodology for M&R activities of a road network over a multiple-period planning horizon to minimize traffic delays using a genetic algorithm. Hajdin and Lindenmann (2007) employed branch-and-bound method for finding the optimum work zone for M&R works considering both budget and distance constraints. Durango-Cohen and Sarutipand (2009) presented a quadratic programming framework to find an optimal M&R program for multi-facility transportation systems. The development and implementation of network-level optimization model for pavement M&R have been provided by de la Garza *et al.* (2011) and Gao *et al.* (2012) while a project-level optimal framework has been offered by Irfan *et al.* (2012).

One of the recent commercial software applied in the field of asset management is *Woodstock Remsoft* (Feunekes *et al.* 2011). The software has been originally developed for forestry spatial planning and harvest scheduling. It is able to model linear binary programming including goal and weighted objective programming. It formulates the long-term planning optimization problem as a standard linear programming problem, generates LP matrices and uses a commercial LP solver (*e.g.*, MOSEK, LPABO) to solve the problem. The capability of object oriented built-in commands and GIS interface makes this software a unique choice; flexible to adapt to a range of spatial planning and scheduling problems. These capabilities to solve spatial problems attracted New Brunswick department of transportation (NBDoT) in their exploration of the market, officially adopting this software for its asset management program back in 2006. Major disadvantages of this software came from the fact that modeling commands and modules are written in terms of forestry management.

2.2.2 Coordination of Activities

As discussed before, there have been many efforts concerned only with the mathematical formulation of optimization methods in long-term (strategic planning). Re-expressing strategic analysis into tactical plans represents a less explored field. Raw results from any long term analysis are actions randomly scattered across space and time that do not reflect any measures of coordination or efficiency.

If strategic analysis results were to be implemented in the manner in which they had come from the lifecycle optimization, it would signify many small contracts which would translate into constant disruption of services for the users and higher cost for the governments. Also, uncoordinated actions between different systems may produce utility cuts or premature damages to recently rehabilitated assets. Coordination of actions in management system is not a new topic and has been implemented in health systems for administration coordination (Hartley *et al.* 2008) or industrial engineering for harmonizing work in scale of a factory (Dekker and Wildeman 1997).

It is in the best interest of municipalities to prepare medium range tactical plans that rearrange investments across different types of infrastructure, achieving minimal service disruptions and closure of roads. In addition, the problem becomes more sensitive in small municipalities as they suffer from a lack of specialized contractors and they traditionally pay premiums relative to the degree of isolation in the form of distance from a major urban centre. Still, they're responsible for delivering adequate level of services in order to foster economic development and encourage population growth (Amador and Magnuson 2011).

Coordinating infrastructure works have many benefits such as reducing project costs, reducing disruption and social costs, increasing sensitivity of infrastructure managers to consider other infrastructure areas and so on while the limitation and possible consequences associated with coordination are economic life lost due to premature replacements, increasing administrative costs, opposition from external (private) utilities and etc. A comprehensive study has been done by National Research Council of Canada (NRC 2003) to conduct a review of various practices that municipalities across Canada use and to show the position of coordination among infrastructure programs. This study mentioned that the development of multiyear plans is an important key to effective coordination of different programs. One year horizons coordinate the upcoming construction season, but do not offer enough lead time for effective long-term coordination. However, the outside utility companies unable to plan for more than a one or two year horizon. This difference in approach is a significant obstacle in an effective coordination and lead to opposition from external utility companies. It seems everybody can handle to manage on a 3-5 years horizon for coordination. This time horizon is usually assigned to tactical planning in hierarchal planning.

Hierarchical planning represents an approach and concept towards the organization, planning and scheduling of activities which has been existed both in theory and practice for decade. It simplifies complex planning problems that have many different objectives covering different scales by breaking the planning problem into three broad planning levels namely *strategic planning*, *tactical planning* and *operational planning and scheduling*. (Miller 2002, Hans *et al.* 2007) Strategic planning decisions are concerned with long-term large-scale resource allocation (typically 20 years or more). Consequently, strategic planning decisions normally have the higher degree of risk and uncertainty joined with them than lower levels decisions. Tactical planning represents a second or intermediate level of decision making which order activities over middle-scale space and time frames. At this level, the decision making process must focus on how strategic plans would be implemented successfully. Tactical plans are shorter and smaller than strategic plans and vary from 3-5 years typically based on political periods. Operational planning and scheduling represent the lowest level of hierarchy planning approach detailing exactly how each activity will be performed. Operational plans usually allocate resources and schedule works for upcoming year based on decisions made at tactical level. In general, hierarchy planning reduces the complexity of decision making process by distributing the objectives over three different levels and manages uncertainty and risk by dividing time horizons. It is reasonable to coordinate program of works within tactical planning.

NRC study (2003) suggests various ways to coordinate infrastructure works while presents nothing about mathematical frameworks. These ways include corridor upgrades or restrictive practices. Corridor upgrade is relatively common approach between governments. Two different methods are in practice currently. One method is identifying proper corridor (*i.e.* street program) at first, then other related assets such as water, sewer, and drainage is considered to upgrade as many elements as possible. Other method starts with a program (like water program) and then overall corridor is upgraded during that program and opportunity is given to repave the entire roadway when the underground utility is complete. Another approach in upgrading is to look for an appropriate zone in a neighbourhood and find places and assets that need improvements. This approach is called zonal upgrading.

On the other hand, many municipalities use restrictive practices to support coordination and reduce disruption. These are some rules such as all the excavators need to get a permit from government before any excavation, or no-cut rule which is limited any excavation for a certain period of time after a pavement overlays unless emergency situation . Pavement degradation fees are established because no matter how well a utility cut is repaired, it has significant effect on life of pavement. Many believe corridor upgrading is the best way as it maximizes the coordination benefits and minimizes disruption and user costs. However, concerns about life lost of assets may induce the idea that benefits of corridor upgrading are not sufficient to cover lost life and other costs. Considering this issue, a trade-off analysis between the benefits of corridor upgrading which are reducing the user and social costs and disruption in the network, and the lost due to remaining life of premature assets must be done to evaluate and justify corridor upgrading.

As mentioned above, governments are going to understand the benefits of coordination of works in infrastructure management. They try to use different methods to gain these benefits. However, the lack of a mathematical framework is really sensed to produce coordinated programs of works derived from strategic analysis. Such a framework would reduce disruption to a minimum and still be able to deliver infrastructure in good level of service.

Almost in all of new discussions for improvement of infrastructure management systems, one part is specified to coordination of actions. For example, Halfawy (2008) mentioned three main requirements to facilitate improvement of infrastructure management: 1) efficient coordination and information flow between inter-dependent processes, 2) efficient integration and management of infrastructure lifecycle data within and across assets in a way that maximizes the reuse and sharing of data, 3) Integration of models and software applications. It is identified that to maximize economic and social benefits, coordination on a national and local level along with changes in legislation (if necessary) is really crucial. In addition, this study suggests that the advanced ICT solutions might help and improve current practices. Coordination of plans at asset level for different infrastructures based on optimization results is the last step of a four-step asset management planning tool suggested by Hafskjold (2010). Water and road network systems are the two of most interdependent infrastructure assets. Nafi and Kleiner (2009), Kleiner *et al.* (2010) examined the position of coordination of actions in the planning of adjacent water and road systems. On the other hand, Li *et al.* (2011) introduced a new grouping model useful for coordination of pipeline and road programs. Although these studies have mentioned coordination in their efforts, there is paucity of literature providing a complete and practical framework for coordination of M&R actions.

Planning tools applied to manage public infrastructure used by national, regional and local governments, are based on long term strategic analysis that employ economic and engineering principles to allocate treatments during assets' lifespan to achieve a desired level of service. Levels of service are traditionally expressed through condition of the asset across time, and rarely expanded to incorporate other measures like safety, mobility, risk and or accessibility. Typical analyses seek to minimize expenditure while achieving target levels of service. The problem lies in the inability of such planning systems to prepare coordinated programs of works, in which activities happening on a group of assets at different moments on time can be advanced or deferred to be merged into one package of works. The goal of coordination is to find the optimal time and space, where well coordinated plans are executed with the best possible total result for the invested resources as well as minimum disruption and costs for users.

2.2.3 Environmental Impact

As discussed before, asset management evaluates potential transportation projects, programs, and strategic plans from a mixture of engineering and economic standpoint. However, only cost-effectiveness criteria are no longer sufficient for a sustainable transportation infrastructure as the focus of asset management has recently evolved towards achieving a sustainable system. A sustainable system defines with three main elements: economic and social development and environmental protection (Jeon and Amekudzi 2005). Clearly, cost-effective scheduling of maintenance and rehabilitation results in improvements of the economic component of the system but ignores other two aspects.

The effects of transportation projects on the environment can be lasting and substantial and usually significantly related to the quality of life (Flintsch 2008). For example, construction, maintenance and rehabilitation of pavement infrastructure need obtaining, processing, and manufacturing, transporting and placing construction materials. Transportation infrastructures such as pavements need a large amount of energy and emit considerable amount of GHGs throughout their entire life cycle for every step of production and acquisition of materials and in the process of construction, maintenance and rehabilitation (Santero and Horvath 2009). Moreover, the operation of a highway adds significant amounts of GHG emissions and energy consumption from its users; passenger cars, trucks and buses (Inamura 1999).

Transportation sector is almost responsible for 27% of all of the GHG emissions in the United State. In this sector, the share of the on-road transportation is near 85% and is the most rapidly increasing source of emissions (EPA 2009). From 8 to 14% of road sector's emissions are coming from non-operational components such as construction and rehabilitation actions (Chester and Horvath 2009). Approximately the amount of energy used by about 50 average American households in one year is needed for making one lane of road, one mile long (Muench *et al.* 2011).

Such significant environmental impact of pavements in addition to the vastly different techniques of construction, maintenance and rehabilitation during the design life of pavements has led to attempts to include the environmental impact in life cycle analysis (LCA). On the other hand, the important role of environmental impact of pavements and the vastly different techniques of construction, maintenance and rehabilitation during design life of pavements has resulted in creating the concept of the rating systems such as Greenroads to assess roadway sustainability by ranking, scoring and comparing different road projects on their overall performance towards sustainability (Muench *et al.* 2011). The same concept exists for buildings through the Leadership in Energy and Environmental Design (LEED) system. LEED was developed with the objective of minimizing environmental impacts throughout the process of design and construction of buildings. Other current models for assessing sustainability are GreenLITES, STEED, I-LAST, STARS and STEM (Samberg *et al.* 2011).

Various studies have looked at the life cycle environmental impact of different types of pavement and compared them with each other. For example, Horvath and Hendrickson (1998) studied and compared two common pavement material, asphalt and concrete, and suggested that asphalt pavement is better choice from sustainability point of view. Uzarowski and Moore (2008) examined the sustainability of perpetual pavements using a real case study and found out that perpetual pavement is not only a cost effective alternative but also has a significantly lower environmental impact compared to the same strength conventional pavement. Recent researches focused on life-cycle analysis and assessment of pavement roads. Employing a hybrid life cycle assessment, Cass and Mukherjee (2011) quantified the life-cycle emissions associated with different pavement designs and emphasized on construction and rehabilitation operations phase to capture its impact on environment. Furthermore, Mithraratne and Vale (2012) investigated process of maintenance and rehabilitation for sealed and unsealed pavements and concluded that from environmental standpoint, sealed pavements have more advantages although need higher expenditures.

Some studies consider traffic congestion and delays caused by construction site during M&R program of pavement. Zhang *et al.* Study in 2010 not only captured the environmental impact of pavement material, construction, maintenance and preservation and end of life phase, but also considered the effect of construction-related traffic congestion. Huang *et al.* (2009) used a micro-simulation model to assess the construction-related traffic congestion and employed the result of this micro-simulation to a traffic emissions model and found out that the additional fuel consumption and emissions by the traffic during the roadwork were substantial. On the contrary, Lepert and Brillet (2009) analyzed the trade-off between an increase in GHG emissions during road works and the reduction in emissions from traffic once the works are completed since generally road works are in the way of improving traffic related issues. They showed that when road works had been introduced to correct longitudinal profiles, rather than texture, the emissions benefit had been significant.

Efforts that examined the interactions between pavement and vehicles (roughness and deflection) demonstrated influence of pavement smoothness on fuel consumption was significant (Akbarian and Ulm 2012). Therefore, recent attempts try to optimize fuel consumption by maintaining smooth pavements throughout the life cycle. The desire to have a smooth pavement increases the need for maintenance activities over the life cycle and consequently magnifies the environmental impact from materials, transportation, onsite equipment, and traffic delay components. However, the environmental benefits from reduced fuel consumption as a result of smooth pavement are large enough to justify the focus on pavement smoothness (Santero and Horvath 2009).

Besides, pavement roughness directly influence on vehicle operating costs (VOC) including fuel consumption, vehicle repairs and maintenance and damage to goods. Some recent studies have attempted to quantify these impacts (Zaabar 2010). Smooth pavements can reduce vehicle fuel consumption. The smoother pavement is, the less rolling resistance pavement has. Consequently, the fuel consumption and GHGs emissions drop in a considerable amount. It is calculated that a decrease in pavement roughness by 3 m/km will result in a 1% to 2% decrease in the fuel consumption (TRB 2006). This may look a small reduction but considering the entire road network and vehicle fleet, a significant amount of energy would be saved. Moreover, it is observed that for highway sections with high traffic volumes the energy and GHG savings gained by reduction in rolling resistance can be significantly larger than the energy use and GHG emissions from material production and construction. The focus of many transportation policies has been shifted to reduce transportation sector's energy consumption and GHG emissions. It has been proved that savings from smoother pavements can be larger than those from other strategies to decrease environmental impacts of road transportation sector improvements in fuel consumption of future vehicles (Wang *et al.* 2012).

Historical attempts to consider environmental impact in pavement management system can be found in HERS-ST (FHWA 2007), PaLATE (Cross *et al.* 2011) or Zhang *et al.* (2010) study. However, some of the efforts have been Life-Cycle Cost-Benefit

Analysis which monetizes indicators associated with conflicting objectives to achieve a common unit of comparison, losing sight on the corresponding performance of each objective across time. On the other hands, many models have concentrated only on environmental impacts from vehicles and neglected maintenance and rehabilitation effects.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter presents the methodology employed to obtain sustainable tactical plans. The chapter is divided in two sections; the first section explains the method used to incorporate environmental impact of maintenance and rehabilitation works of road infrastructure into performance-based optimization. The second section presents the method used to translate results from long term (strategic) analysis into tactical plans; specifically this section follows a heuristic method for coordinating the allocation of maintenance and rehabilitation.

3.2 Incorporating Gas Emissions and Energy Usage in Performance-Based Optimization

The incorporation of environmental impact of maintenance and rehabilitation treatments of pavements into performance-based optimization requires the measurement of the environmental footprint of each type of treatment. An extensive literature review identified other studies that had determined indicators of gas emissions and energy consumption considering extraction of materials, manufacturing of asphalt mixes, and transportation to final place of application and placing. For instance for GHG emissions, the most common indicator is CO_2 equivalent (CO_{2e}). On Kyoto agreement, various greenhouse gases have been mentioned harmful to the environment. However, studies showed that CO_2 is the most important contributing factor. Therefore, it is rational that other gases are converted to an equivalent amount of CO_2 which is indicated as CO_{2e} (CO_2 equivalent). The conversion is based on Greenhouse Warming Potential (GWP) of every greenhouse gas. CO_{2e} describes the amount of CO_2 that would have the same global warming potential as a given mixture and amount of GHGs measured over a specified timescale (generally, 100 years). According to Bilal and Chappat (2003) the main GHGs in road construction process are Carbon Dioxide CO_2, Nitrous Oxide (N_2O) and Methane (CH_4). The GWP of N_2O is 310 and that of CH_4 is 21. It means that one kg of N_2O has as much effect as 310 kg of CO_2 (EPA 2009).

Environmental impact of each type of treatment should be considered in the optimization algorithm similarly to economic cost; aiming to reduce such an indicator while at the same time aiming to maximize asset condition. This is possible by using a three-step trade-off process as proposed in this research: the first step seeks to find the minimum budget required to have non declining level of condition across time. The second step maximizes condition and is constrained by the budget determined on step 1. Finally a third step seeks to minimize energy use and GHG emissions while keeping condition and budget at the same levels of the two previous steps (Figure 3.1).

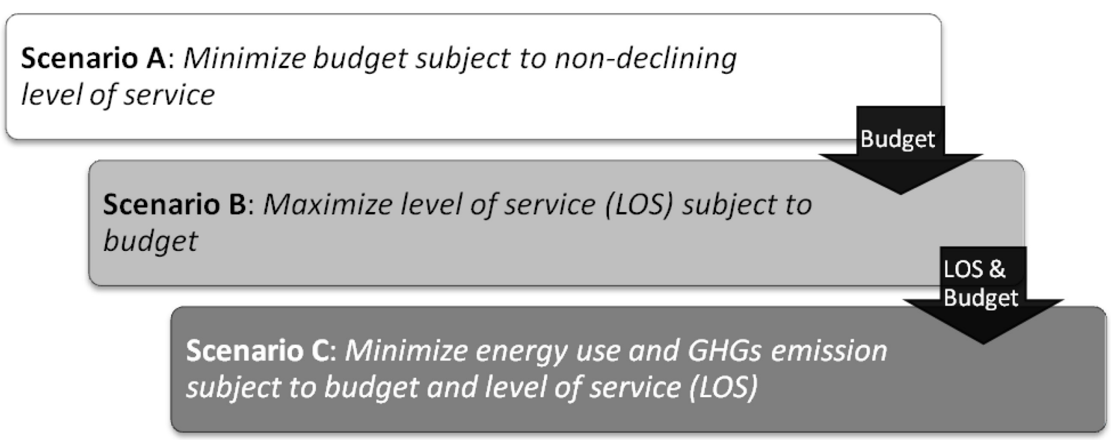


Figure 3. 1 Summary of Scenarios

The three-fold process previously described requires to extent traditional mathematical formulation of objectives and constraints, presented in the following section.

3.2.1 Mathematical Formulation

Mathematical formulations for optimizing decisions in a network of spatially distributed assets can be found elsewhere (Watanatada *et al*. (1987), Li *et al.* (1998) and Vitale *et al.* (1996)). A typical optimization process attempts to achieve the objectives while subject to constraints. In the field of transportation, road management applies optimization tools to maximize the aggregated network level of service (Equation 1) subject to a given budget per planning period (B_t). There are other traditional constraints reflecting logical constraints such as upper and lower bounds for the level of service indicator (traditionally asset condition), the limitation that every asset can receive no more than one treatment per year and in some circumstances the preclusion of assets to be treated in a certain period of time, immediately after receiving a specialized intervention. However, such traditional formulation refers only to an economic perspective failing to consider environmental aspects (energy usage and GHG emissions) of pavement treatments allocated during.

It should be noted that the binary variable x carries three sub-indices that represent time (t), asset (i) and treatment (j). Solutions for this optimization will enumerate chains of variables $x_{i,t,j}$ that represent sets of assets at different periods of time receiving those treatments that produce the most cost effective solution in terms of the objectives (traditionally related to level of service or cost).

$$MAXIMIZE\ \ \mathrm{Z} = \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t} \tag{1}$$

$$\text{Subject to}: \sum_{i=1}^{\mathrm{N}}\sum_{t=1}^{T}\sum_{j=1}^{J} C_{t,j} x_{i,t,j} L_i \leq B_t \tag{2}$$

$$Q_L \le Q_{i,t} \le Q_U \tag{3}$$

$$\sum_{j \in J_{t,i}} x_{i,t,j} \le 1 \quad \text{\{for all times, } t \text{ and for each asset } i \text{ ….\}} \tag{4}$$

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

$Q_{i,t}$ = level of service of asset i on time t,

L_i = Length (size) of the asset (segment) i

$C_{t,j}$ = Monetary Cost of treatment j on time t

Q_U, Q_L= Upper and lower bound for level of service indicator

B_t= Planning budget on time t

Typically, a total enumeration process (Watanatada *et al*. 1987) complement this mathematical formulation with arcs connecting paths and nodes recording levels of service (per treatment option) and associated cost when a particular treatment (or none) is selected. This enumeration process maps expected consequences of applying each available treatment at each segment of road at every time step during the length of the analysis. It generates chains of alternative decision variables; one of these chains is the optimal set of actions regarding to particular objectives and constraints which the software would select (Figure 3.2). Integer linear programming (as herein suggested) or a heuristic method such as an evolutionary algorithm may be used to obtain a solution (although approximate).

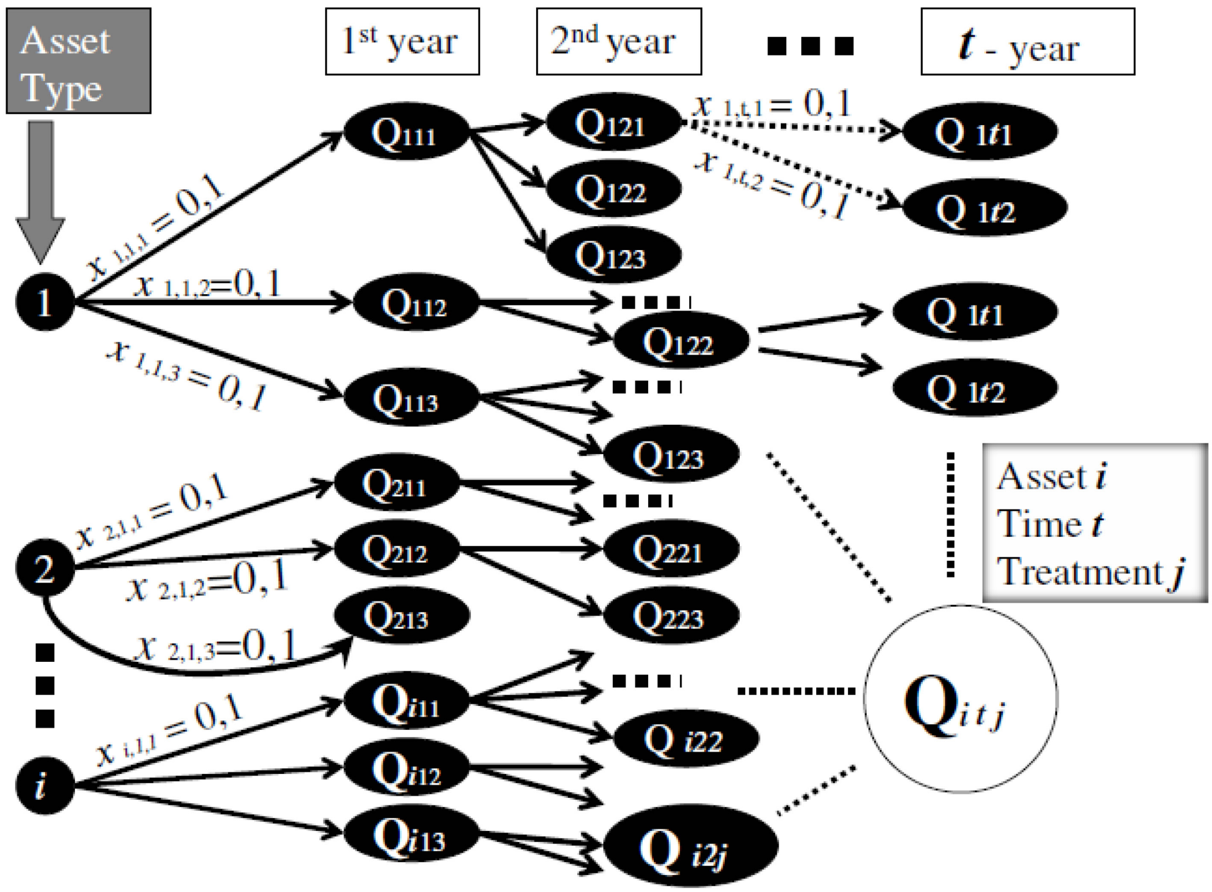


Figure 3. 2 Total Enumeration Process

In this thesis, assets consisted of pavement segments. The international roughness index (IRI) was used as indicator of level of service (*i.e.*, condition). Lower values of IRI indicate smoother roads therefore in better condition. Consequently, to maximize level of service, the optimization algorithm should seek to minimize IRI. On the other hand, vehicle operating costs (VOC) can be incorporated into the analysis as indicator of user costs. As illustrated in Figure 3.1, the first step of the process aims to find the necessary budget to keep condition of pavements at an appropriate level of condition. This step can be synthesized by equations 5 and 6:

$$MINIMIZE\ \ Z = \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} C_{t,j}x_{i,t,j}L_i + \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} VOC_{i,t,j}x_{i,t,j}L_i \tag{5}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t} \geq \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t-1} \tag{6}$$

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

$Q_{i,t}$ = level of service of asset i on time t,

L_i = Length (size) of the asset (segment) i

$C_{t,j}$ = Monetary Cost of treatment j on time t

$VOC_{i,t,j}$= Vehicle Operating Cost on time t, for segment i, after receiving treatment j, and depends on traffic flow and segments condition (IRI)

The constraint that condition in each year must be better than the one during the previous year leads to a non decreasing level of service (condition). Because of the increasing nature of IRI for deteriorating roads, it is expected to be a non increasing function. The second step is proposed to find maximum pavement condition subject to a constant budget. This step can be formulated by the following equations:

$$MAXIMIZE\ \ Z = \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t} \tag{7}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} C_{t,j}x_{i,t,j}L_i \leq B_t \tag{8}$$

These two scenarios are typically found on pavement management systems (Watanatada *et al*. 1987, Li *et al.* 1998 and Vitale *et al.* 1996). The first step estimated annual budget and then by fixing such a budget the model attempted to reach the maximum possible level of service. These steps can satisfy economic aspect of sustainability but still environmental aspects are out of the analysis. A third step will be used to incorporate such environmental impacts of pavement treatments. The objective is identification of a set of maintenance and rehabilitation treatments that minimizes energy consumption and GHG emissions during the lifecycle of the network subject to budget and level of service constraints from previous steps. This last step can be represented by the following equations:

$$MINIMIZE\ \ Z = \alpha\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} E_{t,j}x_{i,t,j}L_i + \beta\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} G_{t,j}x_{i,t,j}L_i \tag{9}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} C_{t,j}x_{i,t,j}L_i \le B_t \tag{10}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t} \ge Q_t \tag{11}$$

Where: $E_{t,j}$ is energy use of treatment *j* on time *t*,

$G_{t,j}$ is GHG emissions of treatment *j* on time *t*

α and β are used to capture the difference in the dimension of energy and GHG.

Incorporation of environmental footprint of pavement treatments can produce a more sustainable management system. This approach provides decision makers with two different schedules of actions, both achieving appropriate level of service (condition) and spending the same annual budget. However, there are substantial differences between these two plans regarding to environmental impact; being that the second one has the minimum energy consumption and GHG emissions.

3.2 Coordinating the Allocation of Maintenance and Rehabilitation

3.2.1 Classical Mathematical Formulation

Solutions of classical strategic analysis from the previous section, will generate chains of binary variables $x_{t,i,j}$ (time t, asset i and treatment j) that represent sets of assets at different periods of time receiving treatments, in a nutshell, getting the most cost-effective solution in terms of the objectives (traditionally related to level of service or cost). However, these results represent actions randomly scattered across space and time, lacking measures of coordination or operational efficiency. This means that no considerations have been given to operational limitations such as maximum amount of projects happening in parallel, contractor's maximum operational capacity (financial, labor and/or equipment), or the clustering of investments to minimize disruptions to the public or to avoid utility cuts.

3.2.2 Coordination of M&R Activities

As seen before, the mathematical formulation of constraints from traditional strategic planning (supported by long term optimization) does not consider operational or tactical aspects, such as proximity in time and space of allocated investments to maintain and rehabilitate road assets. An optimal program of works, for such strategic optimization, contains a long term allocation of treatments happening at different points of time and all over the network, as predefined by Equations *1* and *2*. Incorporation of all the spatial and temporal aspects (space and time adjacencies) of the problem can create a model too complex to be solved by exact methods of linear integer programming. The complexity of such a model comes from the high degree of spatial sense of the problem if adjacencies are incorporated, in addition to an already huge combinatorial enumeration process; containing a large number of assets in the network, long term horizons and dozens of possible treatments.

The use of a hierarchical approach to overcome such a problem in stages and at increasing levels of spatial resolution, has been proposed elsewhere and will be followed in this research (Feunekes *et al.* 2011). Hierarchical planning represents an approach towards the organization, planning and scheduling of activities which has been existed both in theory and practice for decade. It simplifies complex planning problems that have many different objectives covering different scales by breaking the planning problem into three broad planning levels namely strategic planning, tactical planning and operational planning and scheduling.

The idea behind this hierarchical approach is that strategic planning results can be a base for tactical and operational planning. A heuristic approach can search for possible candidates of assets compatible to be merged together. Heuristic methods are approximate algorithms which help to solve complex problems. Approximate methods are good alternatives when a large scale optimization or complex problem with many data needs to be solved and exact methods cannot be used to solve them within an acceptable amount of time (Talbi 2009).

Results from the optimization model (strategic analysis) include the optimal schedule i.e., what assets to fix and when to fix, throughout the planning horizon. In order to coordinate activities, adjacent assets receiving treatments within a given time window should be clustered. Two main criteria must be defined, spatial constraints and temporal constraints. The spatial constraint identify segments to be grouped together if they are within specific distance (adjacent distance); while time proximity (temporal distance) dictates the number of periods of time that a treatment can be deferred or advanced from its original scheduling. These constraints ascertain possible assets to be cluster together. For example, as illustrated in Figure 3.3, within the prescribed adjacent distance, segment 4 and 10 are originally receiving treatments 2 and 3 (respectively) on year 1, while segment 9 is receiving treatment 3 on year 2, and segment 12 is receiving treatment 1 on year 3. Assuming temporal distance is set to two years, these four segments will be grouped together, creating a new group of asset segments (group 1).

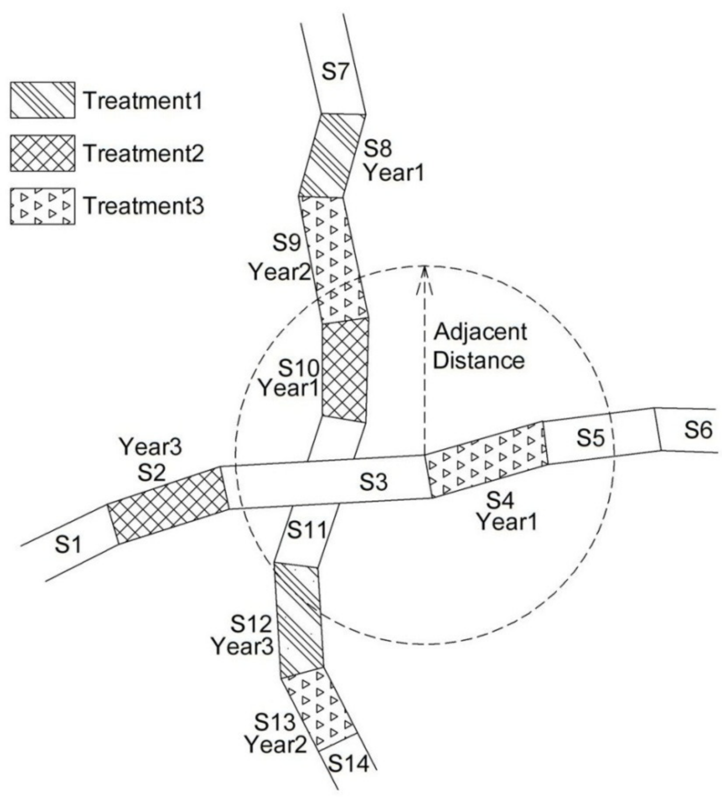


Figure 3. 3 Spatial and Temporal Constraints

Figure 3.4 illustrates the concepts of time and space openings. Recalling from the previous example, segments 4, 9, 10 and 12 were assigned into group 1, similarly group 2 could have been formed by joining segments 16 and 17. These two groups can now be joined if they are within a distance called space opening which indicates willingness of accepting spatial separation between two groups scheduled on the same year if by operational standards make more sense to assign them to the same contractor or undertake both projects (groups) at the same time. An extension to this concept is that of time opening, in which two groups spatially within an acceptable space opening but separated in time (scheduled at different periods) can be joined for similar reasons as the above noted. This results in a second temporal movement (advance or deferral) of the assets in one of the groups to match the other. It should be noted that by coordinating actions and clustering asset segments, the tactical plan is stepping farther from the optimal set of actions, but potentially lowering the impact to the user and agency cost. The degree of optimality can be determined by comparing coordinated and optimal set of actions. The desired degree should be justified by a trade off analysis between benefits of coordination and detriment of receding from optimal solution.

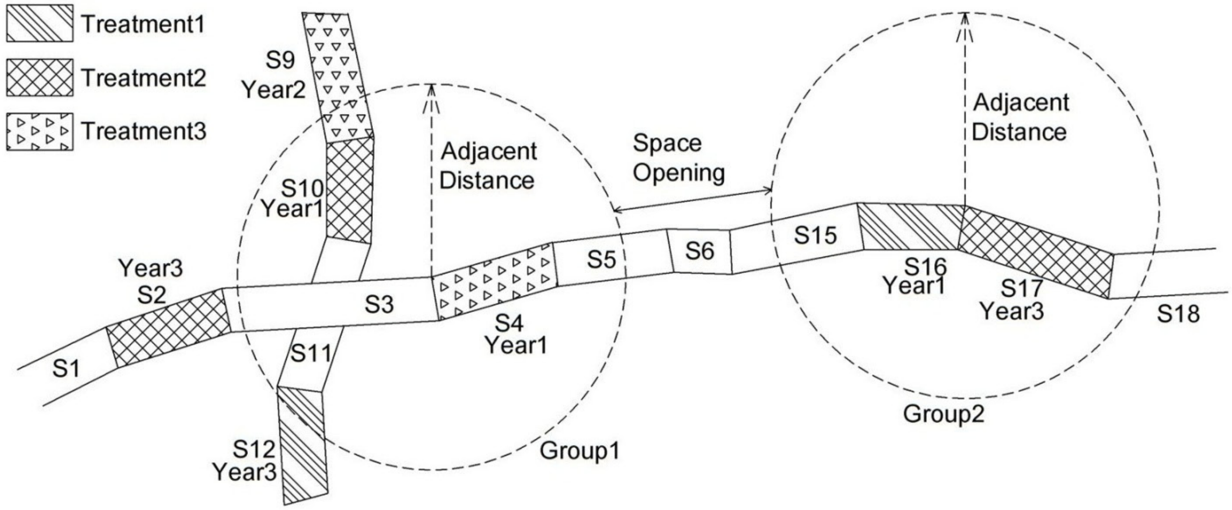


Figure 3. 4 Spatial and Temporal Openings

Spatial and temporal constraints are not the only criteria which must be taken into account for developing coordinated tactical plans. It is clear that not all of M&R actions can be performed at the same time. The compatibility of actions must be evaluated before considering them in a coordination process. This consideration depends on agencies' decision, resources, contractor's specialization, compatibility of machinery, time required per task, etc. In the case study presented in Chapter 5, all the M&R actions of roads and bridges are assumed compatible with each other, simply for the purpose of having a richer scheduling to illustrate the process.

Practical establishment of coordination parameters must come from a consultation process at the local transportation agency and preferable to be established as a policy to standardize the criteria across contracts (for maintenance and rehabilitation). Values for spatial adjacency can be guided by mean segment size and buffer distance from the centerline of major routes. Time proximity should be guided by maximum advisable treatment frequency; for example, crack sealing can be performed annually while bridge rehabilitations more often than 5 years apart are undesirable because of large social cost of the disruptions.

3.3 Summary of the Approach

The overall approach suggested in this research to develop sustainable tactical plans for maintenance and rehabilitation of pavements is as follows:

- Quantify environmental impact of treatments
  - Indicator for GHG emissions
  - Indicator for Energy consumption
- Conduct a strategic analysis using heuristic or linear integer programming optimization
  - Minimize gas emissions and energy consumption
  - Minimize VOC
  - Minimize agency cost
  - Maximize Condition
- Obtain optimal scheduling of treatments for the entire road network or municipal region for the planning horizon
  - Allocation of treatments across assets (or segment) and time
- Establish spatial and temporal coordination criteria, in specific
  - Adjacent distance = Assets within "Adjacent distance" of each other have the possibility of being merged in a block
  - Time adjacency = Allow actions to be deferred/advanced in the period of "Time adjacency"

    - Space Opening = dictates the maximum distance between groups of assets to be merged into one group
    - Time Opening = allow groups of assets within space opening but at different periods (but within "Time Opening") to be merged into one group
- Develop a coordinated tactical program of work for the network

Two case studies independently illustrate the incorporation of environmental impact into performance-based optimization for strategic planning only and then the coordination of treatments from strategic analysis to obtain tactical planning.

CHAPTER 4
INCORPORATING ENVIRONMENTAL IMPACT INTO PERFORMANCE-BASED OPTIMIZATION FOR SUSTAINABLE PAVEMENT MANAGEMENT

Abstract: Transportation asset management systems are concerned with the daunting task of maintenance and upgrade of infrastructures while restricted by annual budgets. However, the consideration of environmental impacts is normally left out of the analysis. This paper incorporates environmental impacts of maintenance and rehabilitation of pavements into the strategic planning. It explicitly considers greenhouse gas (GHG) emissions and energy usage from such activities and conducts a performance-based optimization. It follows a three-step tradeoff process: finding minimum requirement of annual budget, maximizing condition and reducing environmental impacts. The results show that considering environmental impacts in the strategic planning returns a substantial gain in energy savings and GHG emissions reduction although a small sacrifice in pavement performance is required. It reduces energy usage and GHG emissions by 19 percent and 24 percent, respectively, while pavement condition drops slightly to 98.5 percent of optimal solution.

CE Database subject headings: Strategic analysis, linear programming, integer optimization, maintenance and rehabilitation, environmental impact, user cost, asset condition.

4.1 Introduction

Environmental considerations must be used to choose environmentally friendly maintenance and rehabilitation (M&R) treatments for road infrastructure management. This chapter expands traditional linear integer programming optimization used as decision support tool to account for gas emissions and energy consumption of M&R treatments. Such elements serve as the basis to guide the selection of M&R actions that consider environmental impact. A case study of Alberta based on the ICMPA7 conference dataset with pavements for a small network of roads is used to demonstrate the suggested approach to incorporate environmental considerations and conduct trade off analysis between asset condition, environmental impact, user cost and agency cost.

4.1.1 Transportation Asset Management

Modern societies rely on various types of infrastructure to adequately support living environment (*i.e.*, energy, water, recreation, health and education) and socio-economic activities (*i.e.*, flows of passengers and commodities). No one can neglect the important role of infrastructure in a country. In fact, only countries that manage to consistently invest in infrastructure have attained and can sustain economic and human development (Amador and Willis 2012). Sustaining public infrastructure at adequate levels of service is a daunting task limited by scarcity on public funds and sometime inadequate management practices (Watanatada *et al.* 1987). Allowing a network to fail not only provokes disruptions and losses but may even result in further repercussions on other systems (NAMS 2006). Governments around the world had implemented systems to manage their networks of physical assets. Infrastructure Management has evolved over the last three decades to become a mature practice (Haas 2001). Asset Management is a process and decision making framework that strives to extend the service life of a diverse range of assets employing engineering and economic principles (Vanier and Rahman 2004). Relatively difficult to capture, user costs must be considered in Asset Management in addition to the agencies' costs (Delwar and Papagiannakis 2001). User Costs for a road network are typically comprised of vehicle operating cost (VOC), travel time delay, safety, comfort and convenience. VOC are related to fuel and oil consumption, tire wear, repair and maintenance, and depreciation (Bennett and Greenwood 2003).

The focus of asset management has recently evolved towards achieving a sustainable system. A sustainable system consists of three main parts: economic and social development and environmental protection (Jeon and Amekudzi 2005). Transportation managers had traditionally focused only on the economic aspect of sustainability; using optimization methods to take full advantage of individual treatments, associated with individual asset elements and benefits of advancing or deferring a certain treatment, seeking an allocation that minimizes costs (or maximize benefits) while constrained by good levels of service (or budget) over the whole network of assets in the long run.

4.1.2 Environmental Impact

Cost-effective scheduling of maintenance and rehabilitation results in improvements of the economic component of the system but ignores environmental protection and social development. Transportation infrastructures such as pavements need a significant amount of energy and emits considerable amount of green house gases (GHGs) in production and acquisition of materials and in the process of construction, maintenance and rehabilitation throughout their entire life cycle (Santero and Horvath 2009). Moreover, the operation of a highway adds significant amounts of GHG emissions and energy consumption from its users; passenger cars, trucks and buses (Inamura 1999).

Construction, maintenance and rehabilitation of pavement infrastructure need obtaining, processing, manufacturing, transporting and placing construction materials. At each step energy is consumed and GHGs are produced. Energy consumption is positively correlated with GHG emissions. The on-road motorized vehicles were responsible for 23% of all GHG emissions in 2007 in USA (EPA 2009). From 8 to 14% of this emissions came from non-operational components such as construction and rehabilitation (Chester and Horvath 2009). Approximately the amount of energy used by about 50 average American households in one year is needed for making one lane of road, one mile long (Muench *et al.* 2011).

Such significant environmental impact of pavements in addition to the vastly different techniques of construction, maintenance and rehabilitation during the design life of pavements has led to attempts to include the environmental impact in life cycle analysis (LCA) and rating systems such as Greenroads to assess roadway sustainability by ranking, scoring and comparing different road projects on their overall sustainable performance (Muench *et al.* 2011). The same concept exists for buildings through the Leadership in Energy and Environmental Design (LEED) system. LEED was developed with the objective of minimizing environmental impacts throughout the process of design and construction of buildings. Other current models for assessing sustainability are GreenLITES, STEED, I-LAST, STARS and STEM (Samberg *et al.* 2011).

Various studies have looked at the life cycle environmental impact of different types of pavement and compared them with each other (Horvath and Hendrickson 1998, and Uzarowski and Moore 2008). Recent researches focused on life-cycle analysis and assessment of pavement roads (Cass and Mukherjee 2011, and Mithraratne and Vale 2012). Some studies consider traffic congestion and delays caused by construction site during M&R program of pavement (For example, Zhang *et al.* 2010, Huang *et al*. 2009 and Lepert and Brillet 2009). Considering the interactions between pavement and vehicles (roughness and deflection) and the effect of it on fuel consumption (Akbarian and Ulm 2012), have resulted in attempts to optimize fuel consumption by maintaining smooth pavements throughout the life cycle. This may increase frequency of maintenance activities over the life cycle and consequently aggravate the environmental impact from materials, transportation, onsite equipment, and traffic delay components. However, the environmental benefits from reduced fuel consumption are large enough to justify the focus on pavement smoothness (Santero and Horvath 2009). Recent efforts have attempted to quantify the impact of pavement roughness on vehicle operating costs including fuel consumption, vehicle repairs and maintenance and damage to goods (Zaabar 2010). One of the benefits of improving pavement roughness is a reduction in rolling resistance and consequently a reduction in vehicle fuel consumption and GHGs emissions. A decrease in pavement roughness by 3 m/km will result in a 1% to 2% decrease in the fuel consumption (TRB 2006). Considering the entire road network and vehicle fleet, this small reduction may result in a significant amount. For highway sections with high traffic volumes the energy and GHG savings gained by reduced rolling resistance can be significantly larger than the energy use and GHG emissions from material production and construction. These savings can be larger than those from other strategies to reduce highway transportation energy use and emissions, such as projected improvements in fuel consumption of future vehicles (Wang *et al.* 2012).

Historical attempts to consider environmental impact in pavement management can be found in HERS-ST (FHWA 2007), PaLATE (Cross *et al.* 2011) or Zhang *et al.* (2010) study. However, such models incorporate gas emissions from vehicles forgetting about maintenance and rehabilitation activities, besides they are based on Life-Cycle Cost-Benefit Analysis which monetizes indicators associated with conflicting objectives to achieve a common unit of comparison, losing sight on the corresponding performance of each objective across time.

This paper uses Performance-based optimization (NAMS 2006), retaining objective's indicators in their original units and proposes a three-stage optimization process that achieves better results than traditional life cycle optimization. Its goal is to find out the optimal set of treatments for a planning horizon to minimize expenditures as well as environmental impacts such as energy usage and GHG emissions while trying to achieve as high level of service (pavement condition) as possible.

4.2. Objective

The objective of this paper is to incorporate the environmental impact of Maintenance and rehabilitation into pavement management.

4.3. Methodology

A three-step trade off process was applied: the first step seeks to find the minimum budget requirement to have non declining levels of service. The second step maximized condition constrained by such a budget. Finally concluding with a third step that minimized energy use and GHG emissions while keeping condition and budget at the same level of the previous steps (Figure 4.1).

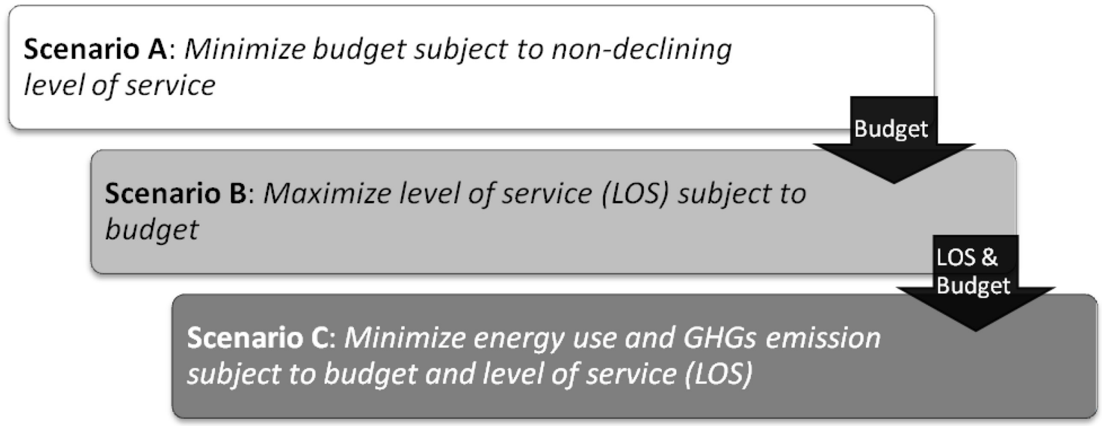


Figure 4. 1 Summary of Scenarios

4.3.1 Mathematical Formulation

Mathematical formulations for optimizing decisions in a network of spatially distributed assets can be found at Watanatada *et al*. (1987), Li *et al.* (1998) and Vitale *et al.* (1996). A typical application of the optimization process seeks to maximize the aggregated network level of service (Equation 1) subject to a given budget per planning period (B_t). Other traditional constraints represent logical conditions such as upper and lower bounds for the level of service indicator, the limitation that every asset can receive no more than one treatment per year and in some circumstances the preclusion of assets to be treated in a certain period of time immediately after receiving a specialized intervention. However, in such traditional formulation, no considerations have been given to Environmental Impact (energy usage and GHG emissions) of pavement treatment.

Equation 1 shows the traditional formulation employed in strategic analysis for pavement management. It should be noted that the binary variable x carries three sub-indices that represent time (t), asset (i) and treatment (j). Solutions for this optimization will produce chains of variables $x_{i,t,j}$ that represent sets of assets at different periods of time receiving those treatments that produce the most cost effective solution in terms of the objectives (traditionally related to level of service or cost).

$$MAXIMIZE\ \ Z = \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t} \tag{1}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} C_{t,j} x_{i,t,j} L_i \leq B_t \tag{2}$$

$$Q_L \leq Q_{i,t} \leq Q_U \tag{3}$$

$$\sum_{j \in J_{t,i}} x_{t,i,j} \leq 1 \quad \text{\{for all times, t and for each asset i ….\}} \tag{4}$$

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

$Q_{i,t}$ = level of service of asset i on time t,

L_i = Length (size) of the asset (segment) i

$C_{t,j}$ = Monetary Cost of treatment j on time t

Q_U, Q_L= Upper and lower bound for level of service indicator

B_t= Planning budget on time t

This mathematical formulation is complemented with a total enumeration process (Watanatada *et al*. 1987) with arcs connecting paths and nodes recording levels of service (per treatment option) and associated cost in the event that a particular treatment (or none) is selected. This enumeration process maps expected consequences of applying each available treatment at each segment of road at every time step during the length of the analysis. It produces chains of alternative decision variables from which the software selects the optimal in terms of the particular objectives and constraints (Figure 4.2). Integer linear programming (as herein suggested) or a heuristic method such as an evolutionary algorithm may be used to obtain a solution (although approximate).

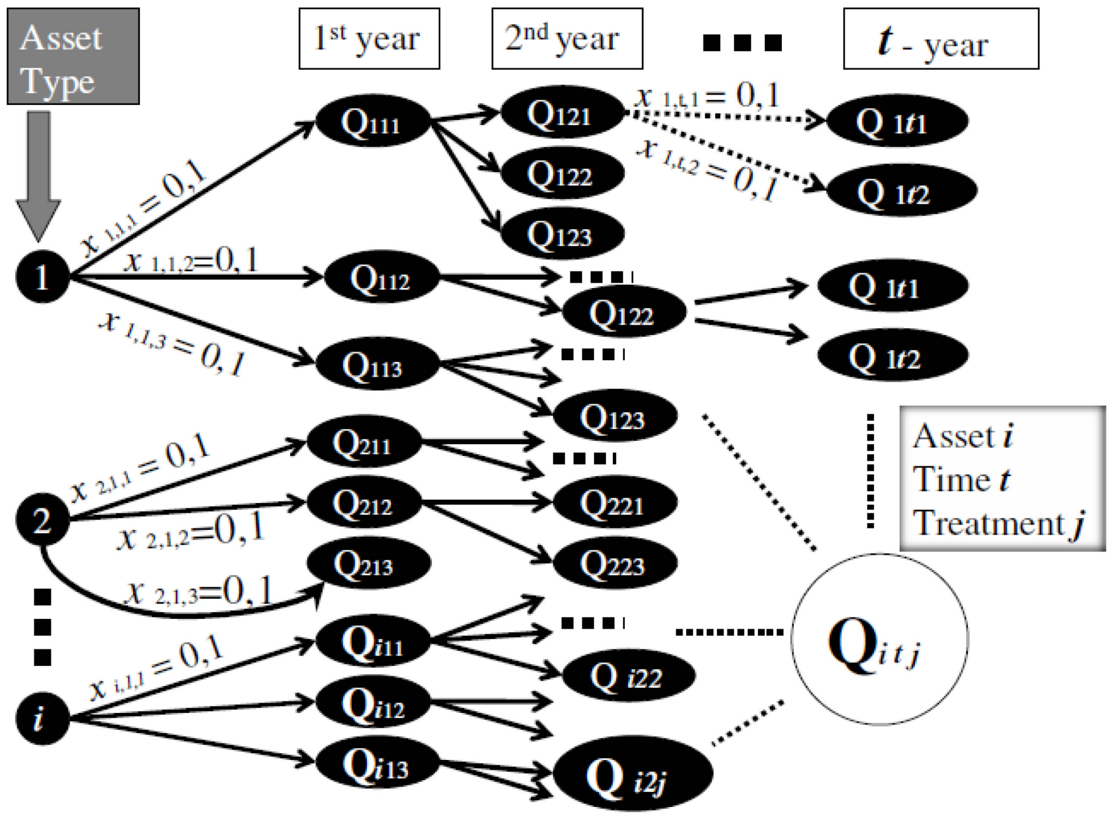


Figure 4. 2 Total Enumeration Process

In this paper, assets consisted of pavement segments, the international roughness index (IRI) was used as indicator of level of service (*i.e.*, condition). Vehicle operating costs (VOC) were incorporated in the analysis by correlating to IRI; the relationships given at the Alberta Challenge (ICMPA7 2007) were used. Three steps were defined. Each step had a specific purpose. Step A was intended to find the required budget to keep condition of pavement constant. This step can be synthesized by equations 5 and 6:

$$MINIMIZE\ \ Z = \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} C_{t,j} x_{i,t,j} L_i + \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} VOC_{i,t,j} x_{i,t,j} L_i \tag{5}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t} \geq \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t-1} \tag{6}$$

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

$Q_{i,t}$ = level of service of asset i on time t,

L_i = Length (size) of the asset (segment) i

$C_{t,j}$ = Monetary Cost of treatment j on time t

$VOC_{i,t,j}$= Vehicle Operating Cost on time t, for segment i, after receiving treatment j, and depends on traffic flow and segments condition (IRI)

The constraint that condition in each year must be better than the one during the previous year leads to a non decreasing performance (condition). Because IRI was the indicator of condition, it is expected to be a non increasing function. The second step seeks maximum pavement condition subject to a constant budget. This second step can be formulated by the following equations:

$$MAXIMIZE\ \ Z = \sum_{i=1}^{N}\sum_{t=1}^{T} L_i Q_{i,t} \tag{7}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J} C_{t,j} x_{i,t,j} L_i \leq B_t \tag{8}$$

These two scenarios are typically found on pavement management systems (Watanatada *et al*. 1987, Li *et al.* 1998 and Vitale *et al.* 1996). The first step estimated annual budget and then by fixing such a budget the model attempted to reach the maximum possible level of service. Environmental Impacts of pavement treatments were considered in third step focused on minimizing energy use and GHG emissions during the procedure of maintenance and rehabilitation of pavement networks and subject to budget and level of service of the previous steps. This last step can be represented by following equations:

$$MINIMIZE\ Z = \alpha\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J}E_{t,j}x_{i,t,j}L_i + \beta\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J}G_{t,j}x_{i,t,j}L_i \tag{9}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{J}C_{t,j}x_{i,t,j}L_i \le B_t \tag{10}$$

$$\text{Subject to}: \sum_{i=1}^{N}\sum_{t=1}^{T}L_iQ_{i,t} \ge Q_t \tag{11}$$

Where: $E_{t,j}$ is energy use of treatment *j* on time *t*,

$G_{t,j}$ is GHG emissions of treatment *j* on time *t*

α and β are used to capture the difference in the dimension of energy and GHG.

Decision makers can compare the last two scenarios to plan a set of actions that reach an appropriate level of service (condition) subject to a constant budget while minimizing the energy use and GHG emissions. A more sustainable pavement management system is expected by incorporating the environmental impact of pavement treatments as explained before.

4.3.2 Case Study

The data for this case study came from TRB's The 7th International Conference on Managing Pavement Assets (ICMPA7 2007). In 2007, a synthetic database for a pavement network and other assets such as bridges, culverts, and signs were given as “challenge” for institutional participants of the conference to demonstrate organizational decision making system’s ability. The pavement network was comprised of 1293 road sections spanning 3240 km, covering two road classes, and varying in traffic use, surface age, and condition. The rural roads spanned most traffic and condition categories. Inter-urban roads were represented on the medium to very highly trafficked roads (ICMPA7 2007). All pavement sections were located within the same climatic region with consistent sub-soil conditions. Each section had a defined length, width, number of lanes, AADT, soil type, year of construction, base thickness, base material type, most recent treatment, and surface thickness. The relation between surface smoothness (IRI) and vehicle operating cost (VOC) was given in term of reference of challenge (ICMPA7 2007).

For a pavement segment, there are several stages at which energy is consumed and GHGs are generated. From the extraction of raw material to the end of pavement’s service life, all the stages and components must be taken into account. Energy is used and GHGs are produced at every step of the process, manufacture, transport and placement of construction materials for the purpose of maintenance, rehabilitation or construction. In order to determine the overall energy usage and GHG emissions for every treatment one must disaggregate the treatment into its basic components. Then, the amount of energy usage and GHG emission can be incorporated to the process of decision making to find out a more sustainable set of treatments that yet maximizes total network condition and minimizes total cost. In 2003, Bilal and Chappat calculated the amount of energy usage and GHG emissions of all the phases and stages of production, extraction, manufacture, transport and placement required for a common pavement. It must be mentioned that their works are based on some assumptions. For example, energy consumed and GHG emissions from transport of material at each steps was calculated based on IVL (The Swedish Environmental Research Institute) data. For one kilometre transport of one ton of material by lorry 0.9 MJ energy is used and 0.06 kg CO2 is generated. The average distance between different stages of road construction process was considered as: 300 km between the refinery for bitumen production and the mixing plant, 150 km between the cement works and the manufacturing plant, 500 km between the steel factory and the installation site, 75 km between the aggregate quarry and the manufacturing site, and finally 20 km between the manufacturing site and the construction site.

Chehovits and Galehouse (2010) presented a complete research of energy usage and GHG emissions of various pavement maintenance and rehabilitation works. These various techniques also provide differing amounts of pavement design lives and life extensions. For each pavement treatment, the life extension can be compared to the required energy and GHG emissions to determine an annualized energy use and GHG emissions level. The normalization is accomplished by dividing unit area energy and GHG data of pavement treatment by the life extensions of each of them in order to produce annualized results.

Table 4. 1 Annualized Total Energy Use and GHG Emissions of Pavement Treatment

Treatment	**Details**	**Life Extension (years)**	**Energy Use per Year (MJ/m^2)**	**GHG Emissions per Year (kg/m^2)**
Reconstruction	100mm HMA over 150mm Aggregate Base	As New	9.9	0.7
Major Rehab WMA	100mm Overlay	15	9.2	0.8
Hot in Place Recycling	Thickness 5cm 50/50 Recycle/new	5-10	6.5-13	0.5-1.0
Chip Seal	Emulsion 2.0L/m^2 Aggregate 21kg/m^2	3-6	1.5-3	0.08-0.10
Micro-surfacing	Type III, 12% Emulsion, 13kg/m^2	3-5	1.3-2.2	0.06-0.10

The amount of energy usage and GHG emissions were calculated in Table 4.1. In addition, surface condition assessments (International Roughness Index IRI, and others), extent of distresses, and predicted trigger or needs year were specified for all sections. Every treatment was typified by a range of applicability (operational window), an expected extension in service life and cost (which were given by ICMPA7 2007). The discount rate for the analysis of investments was specified as 6%. Maintenance and rehabilitation (M&R) activities used in this paper are presented in Table 4.2. This paper uses CO2 equivalent (CO2e) as index of GHG emissions. Although there are various green house gases which are listed on the Kyoto agreement, CO2 is the most important contributing factor; thus GWP (Greenhouse Warming Potential) of all other gases should be converted to an equivalent amount of CO2 (CO2e). CO2e describes the amount of CO2 that would have the same global warming potential as a given mixture and amount of GHGs measured over a specified timescale (generally, 100 years). The main GHGs in road construction process are Carbon Dioxide (CO2), Nitrous Oxide (N2O) and Methane (CH4) (EPA 2009).

Table 4. 2 Pavement's Treatments Characteristics

Treatment	Micro-surfacing	Chip Seal	Hot in Place Recycling	Major Rehabilitation	Re-construction
Life Extension	5 years	7 years	10 years	15 years	As new
Cost	$5.25/m^2	$3.75/m^2	$9.00/m^2	$12.00/m^2	$37.50/m^2
Operational Window	IRI ≤ 1.5, rut < 12mm	IRI ≤ 1.5	1.5≤ IRI ≤1.8	1.8 ≤ IRI ≤ 2.5	Age ≥ 10 years

4.4. Analysis & Results

Three different scenarios were used in this paper and the model was analyzed for each of them. The network of pavement with required characteristics such as length and width of segments, condition of segments (*i.e.*, IRI) was given by ICMPA7 Challenge. For each treatment, the cost, the effectiveness (*i.e.*, number of years extending life of pavement), GHG emissions and energy usage was determined. Linear integer programming was used to solve the optimization equation in each scenario. The planning horizon was 18 years, common for pavement service life.

The first analysis determined the annual requirement of budget (Scenario A) and is equivalent to lifecycle cost optimization because it minimizes total cost (both agency costs and VOC) while achieving required LOS. The goal was to minimize budget while keeping levels of service as a non increasing curve for IRI. This scenario returned the need of mean annual budgets of $30 million per year. Using the result of first run (Scenario A), a constant budget of $30 million per year was used as constraint on second analysis (Scenario B) to maximize level of service (here, minimizing IRI). This scenario is usually the core of current pavement management systems. The result of this analysis was an optimal set of treatments to maximize network's level of service using the planned annually budget.

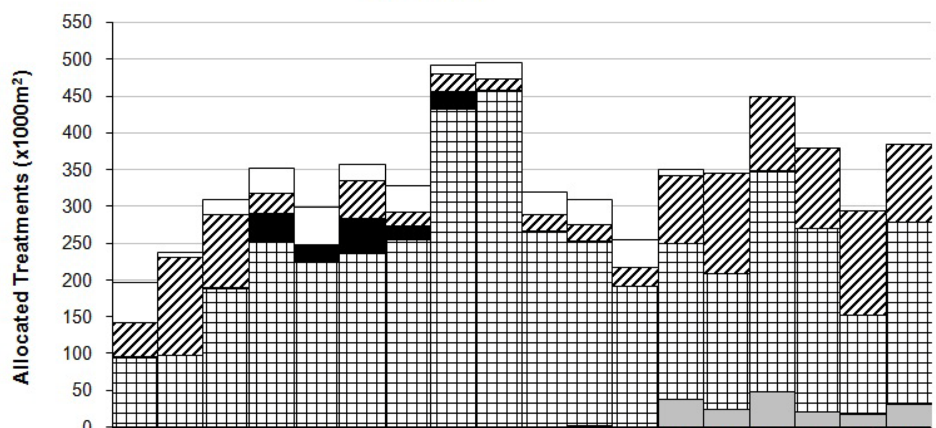
The last analysis incorporated environmental impact of each treatment. The goal of this scenario was to identify a set of treatments which could minimize the amount of GHG emissions and energy use while using the same budget and attaining almost the same condition of scenario B. Thus, scenario C was defined as minimizing energy use and GHG emissions of pavement maintenance and rehabilitation works subject to same budget of $30 million per year and almost the same network's average IRI of scenario B. Not considering the impacts of road user such as traffic delays and congestions in this scenario is a significant limitation of this study. Those impacts must be included to completely incorporate environmental impacts into management systems. Table 4.3 summarizes these three scenarios.

Table 4. 3 Definition of Scenarios and Expected Outcomes

Scenario	Objective	Constraint	Outcome
A	Minimize Cost	Non Increasing IRI	Annual Budget
B	Maximize Condition	Annual Budget from A	Network's Average IRI
C	Minimize Energy Use and GHG emission	Annual Budget from A and network's average IRI from B	Sustainable choice of treatments

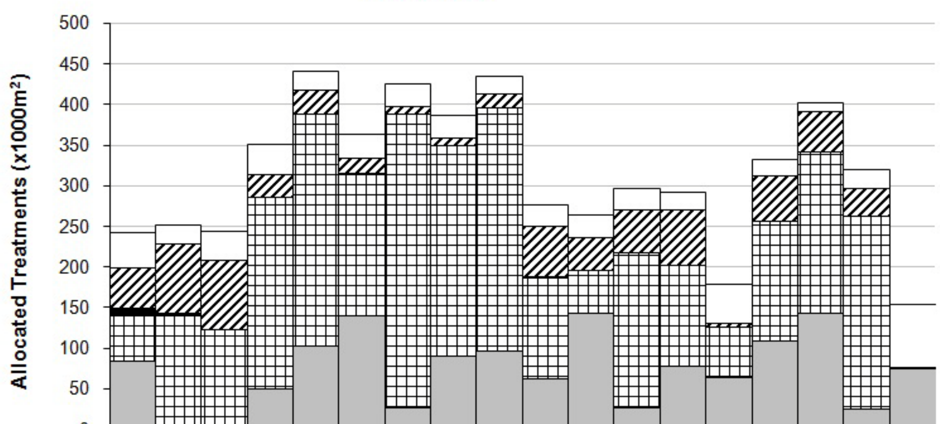
The allocation of treatments (in thousands of m^2) for scenario B and C are illustrated in Figure 4.3. This figure shows that altering the proposed type of treatments can reduce the energy use and GHG emissions while achieving the same average condition for the network of pavement. It can be observed that in a more sustainable planning (scenario C), the use of micro-surfacing is more frequent than in scenario B which suggest that this treatment produces less environmental impacts than others in addition to the advantages of its preventive maintenance nature.

Scenario B



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Reconstruction	55	7	19	35	52	22	35	12	21	31	34	38	8	0	0	0	0	0
Major Rehabilitation	45	133	100	27	2	51	19	24	16	22	22	26	92	137	101	109	142	105
Hot in place recycle	1	0	2	39	23	48	19	23	0	2	0	0	0	0	0	0	0	0
Chipseal	96	99	188	252	224	236	256	433	459	266	251	192	211	184	301	250	134	249
Microsurfacing	0	0	0	0	0	0	0	0	0	0	3	1	40	24	48	22	19	31

Scenario C



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Reconstruction	42.64	23.56	36.83	37.36	22.66	29.21	27.83	28.29	22.38	26.73	28.31	25.25	20.23	48.12	20.2	11.27	23.87	77.46
Major Rehabilitation	49.57	85.25	84.61	27.83	30.24	18.74	9.214	10.2	16.38	61.31	39.72	53.49	68.5	3.94	56.25	49.55	32.8	2
Hot in place recycle	9.67	1.2	0	0	0	0	0	0	0	1.04	0	0	0	0	0	0	0	0
Chipseal	55.61	140.5	124	236.5	284.9	176.3	361.3	257.9	299.1	125.4	53.27	191	124.7	61.75	147.8	198.9	238	0
Microsurfacing	85.25	2.06	0	50.53	103.5	140.2	27.77	91.85	97.79	62.51	143.5	27.03	78.63	65.34	109.4	143.5	26.11	75.87

Figure 4. 3 Allocation of Treatments for Scenarios B and C

Also, it can be seen that use of hot-in-place recycle and major rehabilitation treatments in scenario C decrease significantly, while the trend for chip-seal and reconstruction are approximately the same in the two scenarios. It should be noticed that mean network IRI (for the 18 years planning horizon) for scenario A maintain at initial average of network, while scenarios B and C reached similar levels (1.35 for scenario B and 1.37 for scenario C). Vehicle operating costs also considered for every scenarios as indicator of user costs. Figure 4.4 shows the network's mean IRI for every scenario and Figure 4.4 demonstrates VOC during planning horizon.

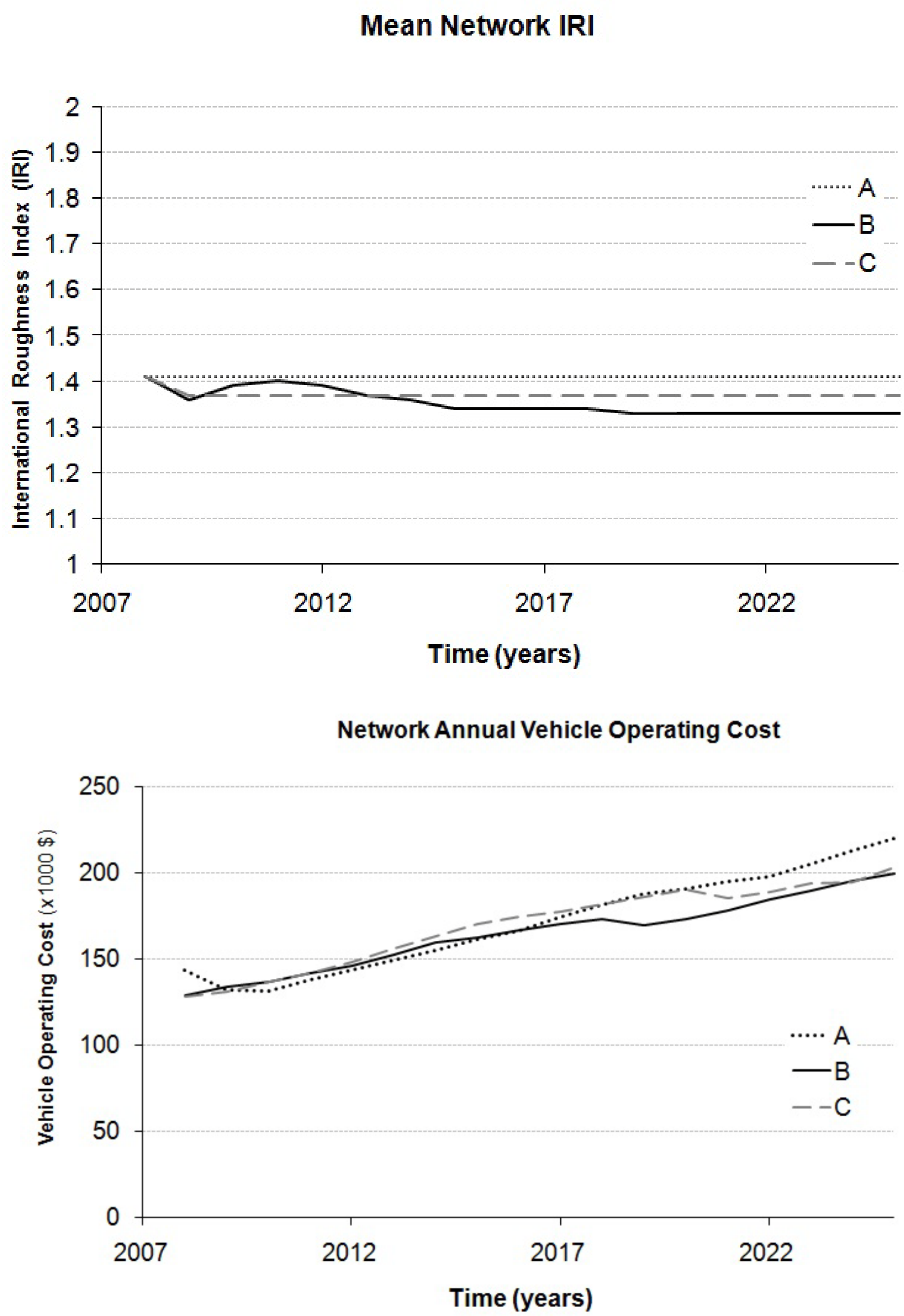


Figure 4. 4 Network Average IRI and Annual VOC for Each Scenario

As shown, the difference in condition is negligible while scenario C tries to reach minimum effects on environment and can be considered part of the tradeoff. The energy used and GHGs emitted for both scenarios are given in Figure 4.5, 4.6. The total energy used during the whole service life of 18 years for scenario B is 349,412,567 MJ while for scenario C is 280,656,642 MJ. Compared to a negligible loss in condition, nearly 69 million MJs of energy were saved at scenario C. The average annual energy usage of scenario B is 19,411,809 MJ and that of scenario C is 15,592,036MJ (19.68% less).

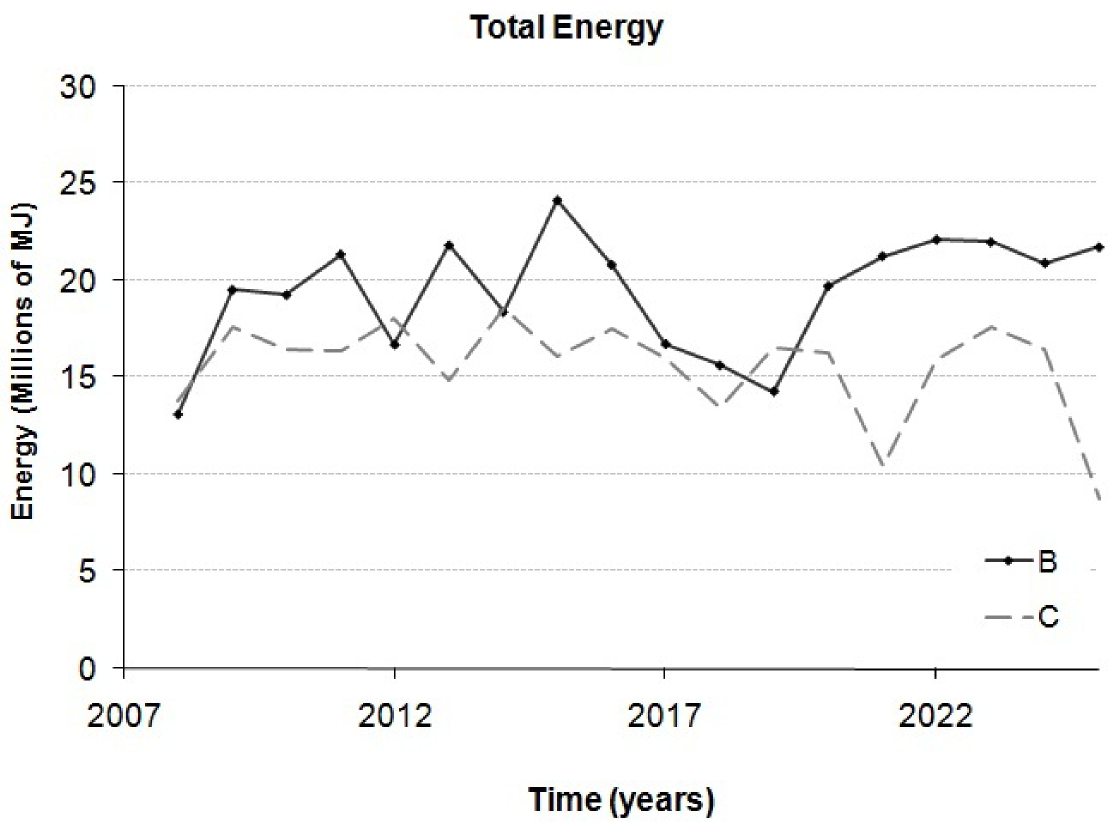


Figure 4. 5 Energy Usage of Each Scenario

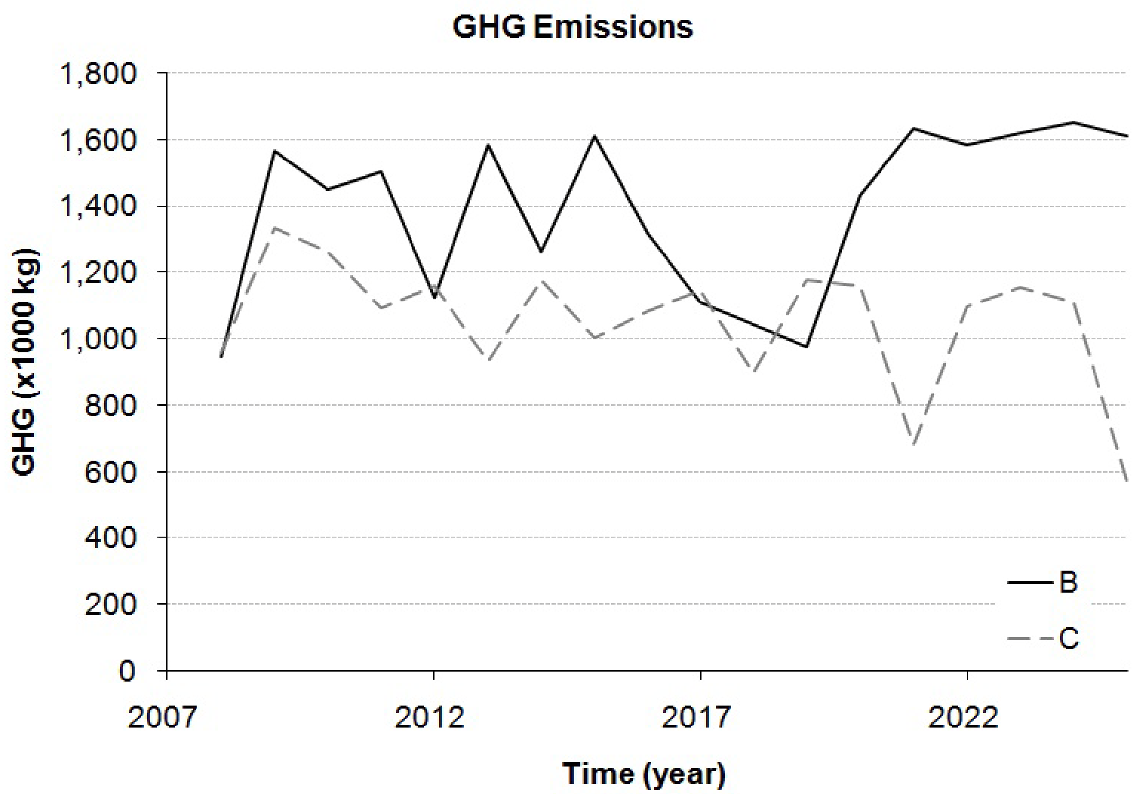


Figure 4. 6 GHG Emissions of Each Scenario

The results are almost the same for GHG emissions. The benefit of implementing scenario C is reduction of almost 6,000 tons of GHGs. Total GHGs emitted from pavement's treatments throughout 18 years of planning horizon dropped by 24.16% from 25,020,213kg for scenario B to 18,973,591kg for scenario C. Table 4.4 summarizes differences between scenarios B and C. As previously mentioned, the environmental effect of traffic is not considered in this study. However, within the goal of maintaining smooth pavement, it is expected that the reduction of rolling resistance results in less GHG emissions from vehicles.

Table 4. 4 Summary of Results with Constant Annually Budget of 30 Million Dollars

Scenario	Total Avg. network IRI	Total Energy Use (MJ)	Annual Average Energy Use (MJ)	Total GHG Emissions (kg)	Annual Average GHG Emissions (kg)
B	1.35	349,412,567	19,411,809	25,020,213	1,390,012
C	1.37	280,656,642	15,592,036	18,973,591	1,054,088
Scenario	Microsurfacing Total Area (m^2)	Chipseal Total Area (m^2)	Hot-in-place recycle Total Area (m^2)	Major Rehabilitation Total Area (m^2)	Reconstruction Total Area (m^2)
B	188,060	4,279,840	157,390	1,173,146	369,152
C	1,330,810	3,077,106	11,910	699,580	552,191

4.5. Conclusions

This paper has demonstrated an approach for the incorporation of the environmental impact of maintenance and rehabilitation activities into pavement management. This was accomplished by explicitly considering the amount of energy used and GHG emissions released for every maintenance and rehabilitation activity. This in turn was determined by accounting for the environmental impact of every process from the extraction of raw materials, the production of asphalt mixtures, the application (construction), etcetera, until the end of the service life of the pavement.

A case study was used to further illustrate the different strategies and associated impacts. A sustainable set of actions that significantly reduced the amount of energy usage and GHG emissions was identified. This was achieved while attaining similar mean network's condition (across time) as that obtained before considering the environmental footprint. Annual budget was also maintained constant. It was confirmed that Hot in Place Recycle and Major Rehabilitation are less environment friendly than Micro-surfacing, while chip seal and Reconstruction have an intermediate impact. Similar trends in energy use and GHG emissions were observed, supporting the idea that dropping energy usage also leads to achieve a reduction of GHG emissions (GHGs are not emitted unless energy is consumed).

This paper has demonstrated that the most economical strategy is not always the most sustainable. There is a short and long term tradeoff between economic and environmental considerations when managing a network of roads; today a small sacrifice in condition performance (suboptimal) may return a substantial gain in environmental impact (energy usage and GHG emissions), which would be safer for our environment and future generations.

The consideration presented in this research should not be limited to pavements; it should be extended to all kinds of physical assets and their associated M&R treatments, as well energy usage and GHGs emissions from users (*i.e.*, vehicles) must be added in order to reach truly sustainable management of infrastructure assets to support economic activities and living environments for our communities.

CHAPTER 5
FROM STRATEGIC OPTIMIZATION TO TACTICAL PLANS: COORDINATION OF TREATMENTS IN ROAD INFRASTRUCTURE

ABSTRACT

Infrastructure management is well established around the world. However, its main use is for strategic planning, typically to figure it out levels of funding required to achieve and sustain target levels of service to end users. Translating strategic planning into tactical and operational planning has not been so widely explored. Often there is a disconnection between long term analysis and annual programs of works. This paper explores the mechanisms for translating results from integer programming optimization into tactical programs of works. Space and time criteria along with treatment compatibility, are used to re-allocate treatments to minimize disruptions to users by clustering together neighbor projects to happen at the same time. A corridor of 1km wide along Route 1 in New Brunswick was used to illustrate the method. The strategic analysis consisted of 20 years of treatment allocation for pavements, chip-sealed roads and bridges. It was found that treatments for a tactical plan of 15 years were re-allocated into groups at years 2, 3, 5, 7 and 10. Clusters at years 2 and 3 were separated by a distance superior to the maximum space opening criteria specified and therefore were not clustered into one group. Coordinated program of works resulted in suboptimal plans affecting more largely chip-sealed roads (33% away from optimal) and then pavements (17% away), bridges remained less affected with values for total bridge condition much closer (9% away) to optimal uncoordinated values of such objective.

5.1 Introduction

5.1.1 Road Infrastructure Management

Infrastructure Assets are defined as fixed systems (or networks) that support economic activities and sustaining life in communities; they are vital for social and economical development of countries (Amador and Willis 2012). Infrastructure assets need to be maintained constantly by continuing refurbishment of its components or replacement (NAMS 2006).

Over the last 30 years asset management evolved to become a framework to support decision making, employing engineering and economic principles to support a systematic process of maintaining, upgrading, and operating physical assets cost-effectively (FHWA 1999, Haas and Hudson 1994, and Vanier and Rahman 2004). Resource allocation throughout the whole lifecycle of infrastructures has a significant role in Asset management. The presence of extent but aging infrastructure gradually shifted the emphasis towards preventive maintenance and rehabilitation (M&R) rather than new construction (Zimmerman and Peshkin 2004, and McNeil 2008). In fact recent global recession provided governments with the opportunity to invest in infrastructure renewal and expansion as a way to dynamist their economies in the short term and strengthen their competitiveness in the long run (Amador and Willis 2012).

Historically, scarce resources and financial limitations lead to the development of various optimization methods to find the best way of allocating resources across assets. During past decades, many researches and efforts have been assigned to provide analytical tools to assist finding the optimum solution for allocating funds across competing alternatives (trade-off) as well as scheduling maintenance and rehabilitation (M&R) projects (For example, see Friesz and Fernandez 1979, Fwa *et al.* 1998, Hajdin and Lindenmann 2007, Durango-Cohen and Sarutipand 2009, de la Garza *et al.* 2011, and Irfan *et al.* 2012).

However, these efforts were concerned with the formulation of optimization methods in long-term (strategic) trade-off. Re-expressing strategic analysis into tactical plans represents a less explored field. Raw results from any long term analysis produces actions randomly scattered across space and time that do not reflect any measures of coordination or operational efficiency, potentially producing many small contracts that would translate into constant disruption of services to the users and higher cost to the government (more bids, inspections, relocation of machinery, transporting materials, etc). Also, uncoordinated actions between different systems may result in utility cuts in the form of premature damage to recently rehabilitated assets. Therefore, it's in the best interest of departments of transportation and municipalities to prepare medium range tactical plans able to advance or defer investments across different types of adjacent infrastructure, achieving minimal service disruptions and closure of roads (NRC 2003) yet staying close enough to optimal results from strategic analysis.

5.1.2 Coordination of Investments

The idea of coordinating actions, services, or processes is not new. It has been implemented in health systems (Hartley *et al.* 2008) or industrial engineering (Dekker and Wildeman 1997). However, there are assumptions and constraints in those models which limit their applicability in transportation infrastructure. For instance, most of the coordination in health system has been done in administration and legislation procedures and, the coordination in industrial engineering has been done in small scale of a factory. Coordinating road infrastructure projects can lead to many benefits such as reducing project costs, disruption and social costs or increasing sensitivity of infrastructure managers to considerations in other infrastructure areas. The limitations and possible consequences associated with coordination are economic life lost due to premature refurbishment or replacement, increased administrative costs and opposition from external (private) utility companies (NRC 2003). Concerns about life lost of assets may induce the idea that benefits of coordination are not sufficient to cover lost life and other costs. A trade-off analysis between the profit and loss of coordination must be done to evaluate and justify coordination.

Coordination of actions has become one of the main discussions for improvement of infrastructure management systems (Halfawy 2008, Nafi and Kleiner 2009, Kleiner *et al.* 2010, Hafskjold 2010, Kachua *et al.* 2010 ,Li *et al.* 2011, Amador and Magnuson 2011, and Islam and Moselhi 2012). Governments have started to understand the need and benefits of coordination of investments in infrastructure management; a comprehensive study done by National Research Council of Canada reviewed coordination practices across cities in Canada (NRC 2003).

Current state of practice in Canada for coordinating infrastructure programs includes corridor or zonal upgrades (NRC 2003). Corridor upgrade is relatively common between governments; it looks into allocating M&R on a road corridor, involving all assets located within a specified distance, however little support tools exist to aid in this task (NRC 2003). Another approach is zonal upgrading; to look into a zone in a neighborhood instead of a corridor and find assets in need of improvements. Many municipalities use restrictive practices to reduce disruption but not necessarily coordinate: rules such as all the excavators need to get a permit from the government before any excavation, or no-cut rule limiting any excavation for a certain period of time after overlaying a pavement have been observed in Canada. Some municipalities and infrastructure managers are ready to start coordinating actions, while most of them are somewhere between building up data bases and applying long term planning tools (NRC 2003).

5.1.3 Hierarchical Planning for Infrastructure Management

Development of a one step model able to perform a strategic analysis with coordination of actions is rather difficult because of the need to incorporate all the spatial and temporal aspects of the problem. Such a model would have been too complex to solve by exact methods (linear programming) regarding to highly spatial sense of the problem, considering the huge number of combinatorial possibilities from assets in the network, long term horizons and spatio-temporal constraints. The use of a hierarchical approach to break the planning process into stages and at increasing levels of details in spatial resolution has been recently proposed (Feunekes *et al.* 2011). Hierarchical planning represents an approach and concept towards the organization, planning and scheduling of activities which has been existed both in theory and practice for decades. It simplifies complex planning problems that have many different objectives covering different scales by breaking the planning problem into three broad planning levels namely strategic planning, tactical planning and operational planning and scheduling (Miller 2002, and Hans *et al.* 2007).

Strategic Planning decisions are concerned with long-term large-scale resource allocation (typically 10 years or more). Consequently, strategic planning decisions normally have the higher degree of risk and uncertainty joined with them than lower levels decisions. Tactical planning represents a second or intermediate level of decision making which order activities over middle-scale space and time frames. At this level, the decision making process must focus on how strategic plans would be implemented successfully. Tactical plans are shorter and smaller than strategic plans and vary from 3-5 years typically, unfortunately normally following political periods. Operational planning and scheduling represent the lowest level of hierarchy planning approach detailing exactly how each activity will be performed. Operational plans usually allocate resources and schedule works for upcoming year based on decisions made at tactical level. In general, hierarchy planning reduces the complexity of decision making process by distributing the objectives over three different levels and manages uncertainty and risk by dividing time horizons.

This paper proposes the application of hierarchical planning to translate strategic plans into tactical plans leaving the door open for further deploy additional considerations to obtain operational programs or works. In this paper, an optimization model seeks to find the optimal long term strategic planning. Additional constraints are incorporated to obtain a tactical plan. Such constraints relate to spatial-temporal adjacencies and, rules that define criteria on how compatible actions at various asset networks should be combined together to form clusters while controlling the degree of optimality as compared to the original solution. Such novel approach will be capable of producing coordinated programs of works derived from strategic analysis which in turn signify the ability of governments to mitigate disruptions (road closure, temporally service suspension, dust, noise, etc.) and remain close to optimal solution (strategic) delivering infrastructures in good levels of service to support local economies.

5.2 Objectives

The objective of this research is to demonstrate the potential benefits of coordinating investments across infrastructure assets. This study presents a case study of a road corridor from the Canadian province of New Brunswick to demonstrate how the coordination of investments can be used to translate strategic planning into tactical programs of works.

5.3 Methodology

5.3.1 Classical Mathematical Formulation

Several mathematical formulations for optimizing decision in a network of spatially distributed assets have been given before (Watanatada *et al.* 1987, Vitale *et al.* 1996, and Li *et al.* 1998). The typical sense of the optimization is to maximize the aggregated network level of service (Equation 1) subject to a given budget per planning period (B_t). Other traditional constraints represent logical conditions such as the limiting maximum and minimum scale value for the level of service indicator, every asset is limited to receive no more than one treatment per year, and the prohibition of assets to receive treatments in a certain period of time immediately after receiving a specialized intervention (for example bridge deck replacement or pavement overlay). However, no considerations have been given to operational limitations such as maximum amount of projects happening in parallel, contractor's maximum capacity (financial, labor and/or equipment), or the clustering of investments to minimize disruptions to the public or to avoid utility cuts. Equation 1 shows the traditional mathematical formulation used for strategic planning in asset management.

$$MAXIMIZE \;\; Z = \sum_{i=1}^{N} \sum_{t=1}^{T} L_i Q_{i,t} \tag{1}$$

$$\text{Subject to} : \sum_{i=1}^{N} \sum_{t=1}^{T} \sum_{j=1}^{J} C_{t,j} x_{i,t,j} L_i \leq B_t \tag{2}$$

$$Q_L \leq Q_{i,t} \leq Q_U \tag{3}$$

$$\sum_{j \in J_{t,i}} x_{i,t,j} \leq 1 \quad \{\text{for all times, } t \text{ and for each asset } i \text{ ….}\} \tag{4}$$

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

$Q_{i,t}$ = level of service of asset i on time t,

L_i = Length (size) of the asset (segment) i

$C_{t,j}$ = Monetary Cost of treatment j on time t

Q_U, Q_L = Upper and lower bound for level of service indicator

B_t = Planning budget on time t

Final solution will generate chains of variables $x_{i,t,j}$ (asset i, time t and treatment j) that represent sets of assets at different periods of time receiving treatments that give the most cost effective solution in terms of the objectives (traditionally related to level of service or cost). In a linear programming approach this mathematical formulation is complemented by a total enumeration consisting in a huge decision tree that enumerates all feasible paths of asset level of service across time. This enumeration process maps expected consequences of applying every available treatment at every asset at each time step during the analysis horizon. Heuristic formulations can solve the problem in an approximate manner.

5.3.2 Coordination of M&R Activities

Integer (binary) linear programming was used to conduct a strategic analysis. Object oriented commercial software Woodstock (Feunekes et al. 2011) was coded for such a purpose. Such an optimization model dealt with the long-term features of the management system. Therefore, other aspects such as adjacency and proximity relationships and constraints were not considered for the strategic planning. The result of such optimization scheduled actions for 20 years all over the network, addressing objective and constraints previously defined (Equations 1 and 2). A hierarchical approach followed. New spatial constraints were introduced. The idea behind this hierarchical approach is that such results can be a base for the following tactical and operational planning. Then a heuristic approach was employed to find the possible candidates of assets capable of clustering together. Heuristic methods are approximate algorithms which help to solve complex problems. Approximate methods are good alternatives when a huge complex problem with many data must be solved and exact methods cannot solve these types of problems within appropriate amount of time (Talbi 2009).

Results from the optimization model (strategic analysis) included the optimal schedule what assets to fix and when to fix throughout the planning horizon. The next step was to coordinate activities, by clustering adjacent assets which received treatments within a given time window. In the other words, segments within specific distance (adjacent distance) can be grouped together while time proximity (temporal distance) dictates the number of periods of time that a treatment can be deferred or advanced from its original scheduling. These constraints ascertain the asset segments which are possible for clustering together. For example, as illustrated in Figure 5.1, within the prescribed adjacent distance segment 4 and 10 are receiving treatments 2 and 3 respectively on year

1, while segment 9 is receiving treatment 3 on year 2 and segment 12 is receiving treatment 1 on year 3. Assuming temporal distance is set to two years, these four segments will be grouped together, creating a new group of asset segments (group 1).

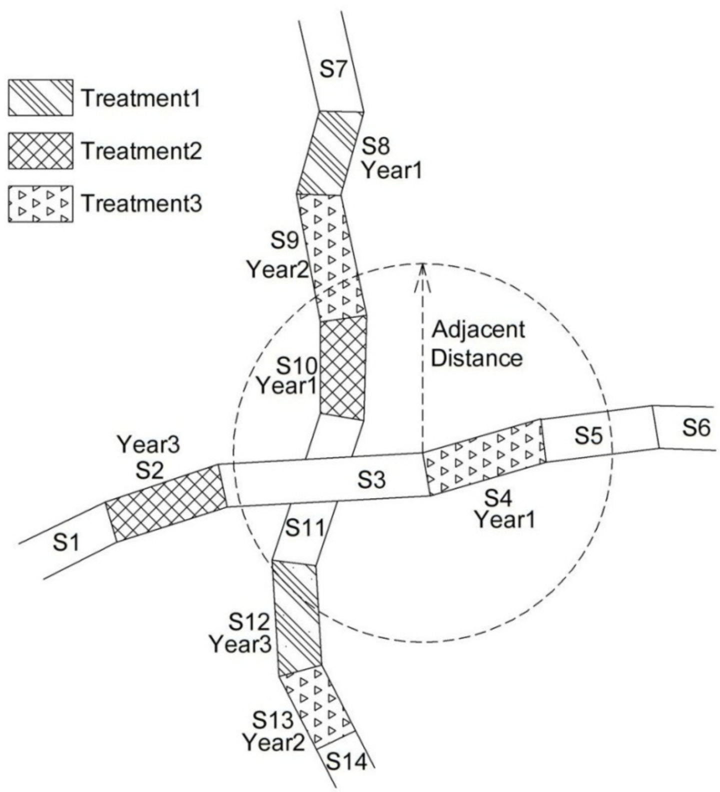


Figure 5. 1 Spatial and Temporal Constraints

Figure 5.2 illustrates the concepts of time and space openings. Recalling from previous example, segments 4, 9, 10 and 12 were assigned into group 1, similarly group 2 could have been formed from joining segments 16 and 17. These two groups can now be joined if they are within a distance called space opening which indicates willingness of accepting separation between two groups scheduled on the same year if by operational standards make more sense to assign them to the same contractor or undertake both projects (groups) at the same time. An extension to this concept is that of time opening in which two groups spatially within an acceptable space opening but separated in time (scheduled at different periods) can be joined for similar reasons as the above noted. This results in a second temporal movement (advance or deferral) of the assets in one of the groups to match the other.

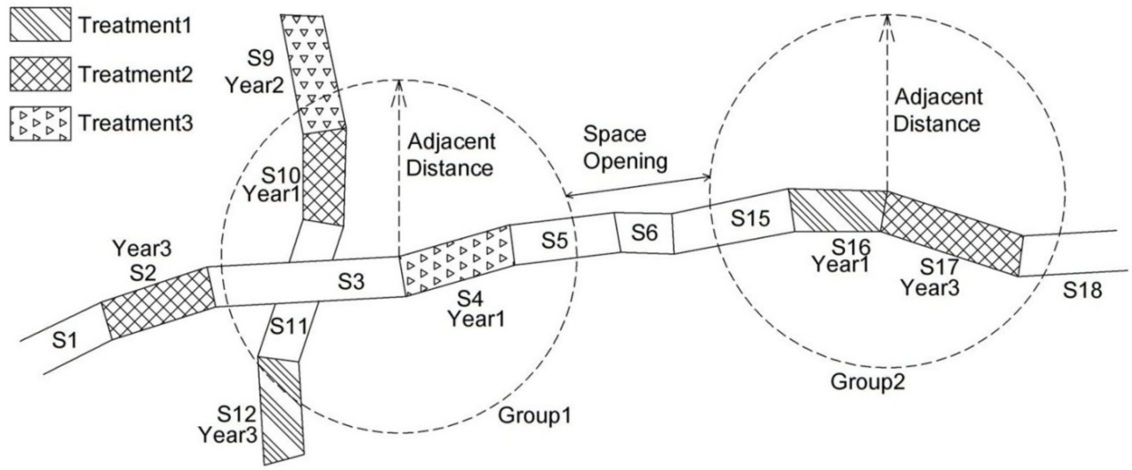


Figure 5. 2 Spatial and Temporal Openings

Other elements must be taken into account for performing an analysis capable of developing coordinated tactical plans. Besides spatial and temporal constraints, one must consider the compatibility of actions for the generation of groups (called blocks by the software). Not all of M&R actions can be implemented together. This consideration depends on agencies' decision, resources, contractor's specialization, compatibility of machinery, time required per task, etc. In this case study, all the M&R actions of roads and bridges are assumed compatible with each other, merely for the purpose of having a richer scheduling to illustrate the process.

5.4 Case Study – Route 1 of Province of New Brunswick, Canada

The case study presents in this paper is based on actual data from the province of New Brunswick. Route 1 (from the Canada-United States border at St. Stephen near Bangor Maine, to Route 2 at River Glade near Moncton) and any assets within 1 km from the centreline of this route were selected. The corridor consisted of 520 lane-km of asphalt concrete (AC) pavement, 910 lane-km of chip seal roads, and about 177554 m^2 of bridge deck area. Applied treatments followed local DOT policies and are presented in Table 5.1 along with corresponding effectiveness and unitary cost as locally estimated for 2007.

Table 5. 1 Treatment Definition and Cost

Item	Treatment	Operational Window	Unit Cost ($)
Asphalt Pavement	Micro-surfacing	Crack < 20 and rutting <= 0.5 mm	50,000 /lane-km
	Minor Rehabilitation	Arterial IRI <= 2, Collector IRI <=3, local IRI <=4, for all PSDI >= 65	200,000 /lane-km
	Major Rehabilitation	Arterial IRI <= 2.5, Collector IRI <= 3.5, Local IRI <= 5, for all PSDI >=50	300,000 /lane-km
	Reconstruction	Apparent Age > 15	600,000 /lane-km
Chipseal	Reseal	VIR >= 4	26,000 /lane-km

Item	Treatment	Operational Window	Unit Cost ($)
Roads	Major Rehab (double seal)	Age >= 8	46,000 /lane-km
Bridge	Deck Rehabilitation	60 <= DECKBCI <= 75	From 152 to 190$/m^2$
	Deck Replacement (wood only)	DECKBCI <= 80	345 / m^2 (wood only, if applicable)
	Bridge Rehabilitation	SUBBCI <= 50	3500 / m^2

For the strategic planning (20 years horizon) the entire highway network of New Brunswick is considered since the agency's budget (NBDoT) is distributed at the whole network, therefore, using annual budget as a constraint and seeking to maximize roads and bridges condition. The results of this procedure returned an identification of treatments assigned to network assets at several moments on time for 20 years analysis. As expected, this optimal schedule of treatments resulted in scattered actions across time and space. This schedule was translated from the strategic plan into a tactical plan. Route 1 was spatially isolated and a spatial buffer of 1 km from the centerline used to select all surrounding assets on that corridor. Real life applications would replicate this analysis on other corridors of the network. Temporal and spatial parameters required for coordinating actions are presented in Table 5.2.

Table 5. 2 Specification of Coordination Parameters

Parameter	Value	Description
Adjacent distance	2000 m	Assets within 2000m of each other have the possibility of being merged in a block
Temporal distance	2 years	Allow actions to be deferred/advanced 2 years
Space opening	2500 m	The maximum distance between groups of assets to be merged into one group
Time opening	2 years	Temporal lapse to allow groups of assets within space opening but at different periods to be merged into one group

An exploratory analysis was conducted to test sensitivity of results to values of the parameters; it was observed that minor changes to the model parameters largely influenced final results. Possible reasons are the small size of segments and dense areas nearby cities. In the real world, agencies must carefully consider all pertinent operational aspects and use the criteria of senior engineers regarding resource allocation to define feasible values for the coordination parameters. Figure 5.3 shows the road corridor of route 1 and illustrates results from the re-allocation of assets scheduled to be treated after a coordination of activities.

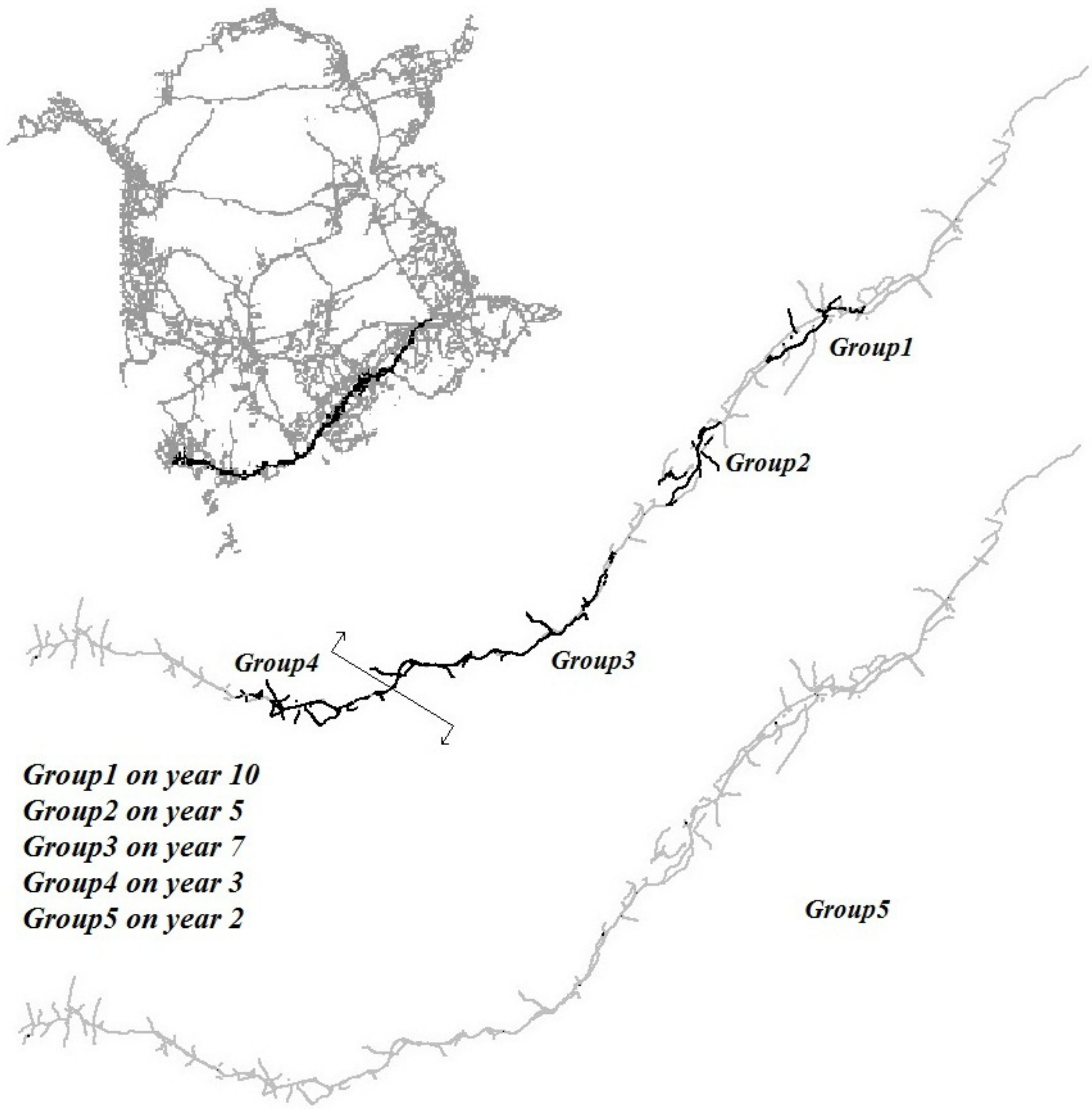


Figure 5. 3 Results of Coordination for Corridor of Route 1 New Brunswick

The first fifteen years of a 20 year strategic plan were used for this case study (to remove the frontier effect of the optimization algorithm unable to capture long term effects of actions deployed towards the final periods of time in the optimization process). Based on these temporal and spatial constraints, five different groups of assets are obtained as shown in Figure 5.3. For instance, group 3 and group 4 are immediate neighbours, but one must note that these two different groups are receiving treatments on year 7 and 3 respectively, beyond the 2 year time adjacency stipulated. Although spatial constraint might make them to be merged, time constraint doesn't allow for that. Also, group 5 contains fourteen different asset segments on the whole corridor receiving treatments on year 2 (for better representation, assets of this group are shown alone on corridor at the bottom of figure 5.3). Group 5 and 4 are scheduled at only 1 year distance but spatial adjacency prevents them from being merged into one group.

Tables 5.3 and 5.4 present -for the corridor only- a summary of uncoordinated scheduled activities for years one to fifteen (Table 5.3) from the original strategic analysis and one from the coordinated schedule (Table 5.4).

Table 5. 3 Summary of Actions before Coordination

	Uncoordinated								
Period	**Pavements (km)**				**Chipseal (km)**		**Bridges (m^2)**		
	Micro-surfacing	Minor Rehab	Major Rehab	Re-construction	Double Seal	Reseal	Deck Rehab	Deck Replacement	Bridge Rehab
1	16.9	18.9	1.1	0.0	0.0	4.8	30,906.6	0.0	0.0
2	37.5	16.6	3.7	0.0	5.8	12.9	526.4	0.0	0.0
3	12.8	7.4	4.4	0.0	12.7	19.4	0.0	0.0	0.0
4	1.0	1.1	14.1	1.5	0.0	23.5	0.0	0.0	0.0
5	1.7	3.1	11.2	4.7	0.0	20.2	0.0	0.0	0.0
6	6.8	0.0	7.1	15.0	0.0	30.6	9,249.6	825.1	38.1
7	6.4	5.4	11.0	0.1	0.0	34.3	0.0	0.0	0.0
8	10.4	23.9	0.3	0.0	0.0	40.2	0.0	0.0	0.0
9	11.4	18.3	0.0	0.0	0.0	44.4	0.0	0.0	0.0
10	16.0	17.6	0.0	0.0	0.0	37.4	0.0	0.0	0.0
11	10.1	2.5	0.0	0.0	25.6	36.2	12,873.0	2,753.9	0.0
12	10.2	6.4	0.0	1.1	0.0	19.0	0.0	0.0	0.0
13	15.6	26.3	0.0	1.2	0.0	38.2	0.0	0.0	0.0
14	15.5	9.4	0.0	0.0	0.0	21.2	0.0	0.0	0.0
15	22.1	15.4	0.0	0.0	0.0	28.8	0.0	0.0	0.0
Total	194	172	53	23	44	411	53,556	3,579	38

Table 5. 4 Summary of Actions after Coordination

Period	Coordinated								
	Pavements (km)				**Chipseal (km)**		**Bridges (m^2)**		
	Micro-surfacing	Minor Rehab	Major Rehab	Re-construction	Double Seal	Reseal	Deck Rehab	Deck Replacement	Bridge Rehab
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	4.0	1.5	0.0	0.0	0.0	0.0	19,236	0.0	0.0
3	0.0	3.1	0.3	0.2	4.1	68.6	446.3	49.6	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	2.6	0.0	2.1	1.2	5.7	31.8	683.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	12.7	0.0	5.0	12.0	4.3	49.9	1,287	317.9	38.1
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.1	6.6	35.1	137.9	857.4	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	19	5	7	13	21	185	21,790	1,225	38

It is important to note that the coordinated schedule is not the only treatments happening, depending on the coordination parameters other assets will be left uncoordinated reflecting the results from the original strategic plan. Even though treatments on these assets could not be grouped, they are still valid and must be implemented on the specific year as per the original schedule. Therefore, the final result is a combination of coordinated and uncoordinated treatments; consequently it should be close to the optimal solution. The degree of optimality for every asset type is obtained by dividing the value of the objective after coordinating by that before coordination. Degrees of optimality for the case study are illustrated in Figure 5.4. During the fifteen years of analysis, the average degree of optimality for pavement roads, chip-sealed roads and bridges was 83%, 67% and 91% of optimal solution respectively. Decaying levels of optimality of chip seal roads objective value as compared to that of pavements or bridges (closer to optimal value) reveal a more sensitive asset to the coordination exercise (advancing/deferring).

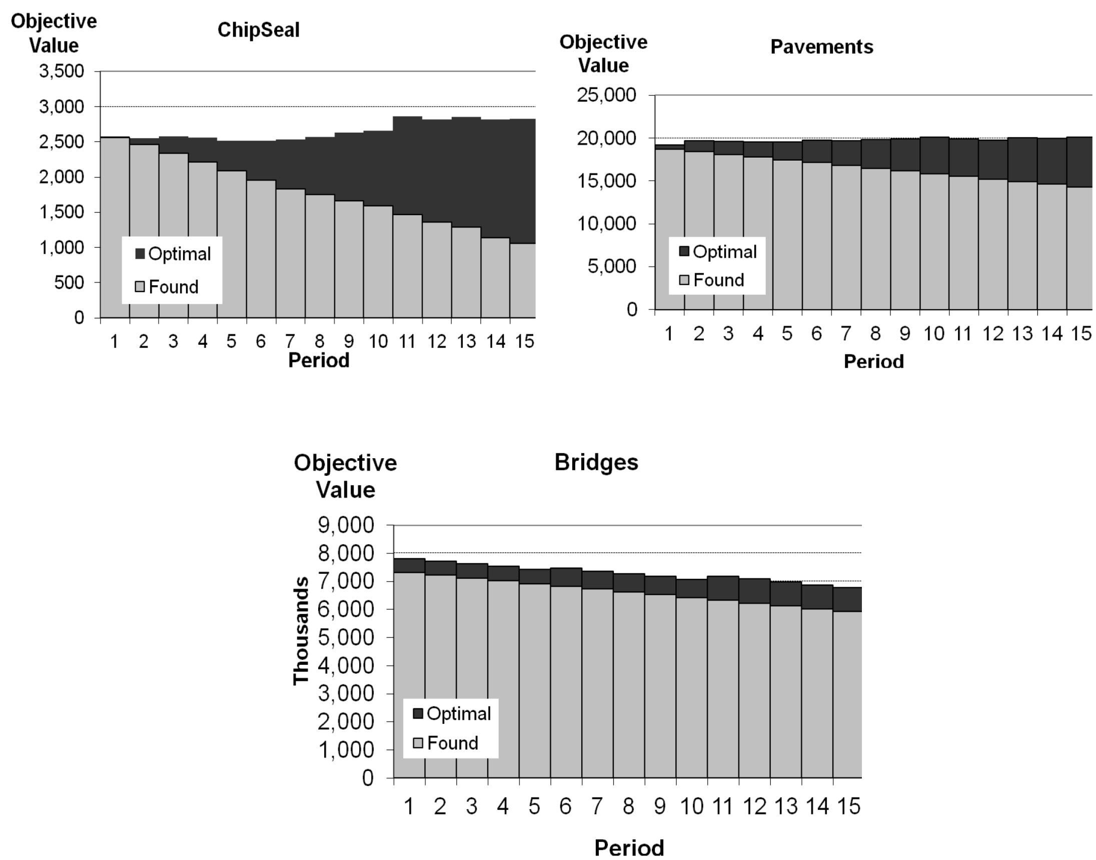


Figure 5. 4 Degree of Optimality for Pavements, Chip-Sealed Roads and Bridges

As notice, there is a clear trade off between the benefits of coordination and drops in degree of optimality. Thus, paying special attention to this measure is one of the additional agencies' responsibilities when developing tactical plans.

5.5 Conclusions

This paper presented an approach for the generation of coordinated programs of maintenance and rehabilitation works across different types of road infrastructure on a corridor. It shows how the coordination of investments can be used to translate strategic planning into tactical programs of works. Optimal schedule of maintenance and rehabilitation actions in strategic plans are scattered across time and space; such a solution is not ready for implementation through tactical plans. The coordination of activities returns a sub-optimal (compared to the original results) set of actions capable of addressing practical inefficiencies of uncoordinated programs of works such as the utility cut problem or frequent disruptions to the final user and agencies' resources.

For the case study of route 1, five groups of treatments on assets within an adjacent distance were created; several treatments were deferred or advanced from its original timing resulting in packages of M&R actions of spatial clusters on years 2, 3, 5, 7, 10. Degree of optimality had a larger impact on chip sealed roads (33% away from optimal), then a moderate impact on AC pavements (17% away) and a small impact on bridges (9% away), as they already had a strategic constraint preventing treatment repetition in less than 5 years.

Coordination of treatments is capable of producing operational plans, however the solution is very sensitive to parameters defining adjacency between assets and proximal distance of openings between groups in time and space, therefore for real life applications such parameters must be carefully defined taking into consideration operational capabilities of workmanship, equipment as well as other circumstances such as weather, a consultation process with senior engineers and project managers is recommended to establish reasonable parameters.

Other consequences in social cost from disruption to users, losses to businesses, etc should be incorporated in addition to the parameters herein defined for the coordination. This is left for future research.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This research has presented an extension to traditional performance-based optimization for strategic management of road infrastructure. The method started by expanding traditional mathematical formulation and by proposing the use of a coordination approach to translate long term plans into tactical plans. The approach presented in this research should not be limited to pavements or bridges; it can be extended to all kinds of physical assets and infrastructures to reach more sustainable management systems; supporting economic activities and living environments for our communities.

The first goal of this research was to find an approach capable of incorporating environmental impact, from maintenance and rehabilitation treatments, into road management systems. GHG emissions and energy consumption were identified for each available treatment to improve pavement condition. The original objective, at the decision support tool, was expanded to minimize equivalent CO_2 gas emissions and energy usage. In this sense, the expanded formulation aimed to maximize asset condition, and to minimize environmental impact, user and agency cost. Selection of treatments followed not only cost-effective considerations but also environmental impact, therefore achieving a sustainable road management for long term analysis. This was achieved through linear programming software WOODSTOCK. A case study for a portion of roads in the province of Alberta was used to demonstrate that the method not only returned similar results in the original objectives (cost and condition) but went beyond by selecting treatments more environmentally friendly; energy consumption dropped 19% and a reduction of 24% was observed in GHG emissions. Budget remained invariable at 30 million dollars.

The second task of this thesis aimed to translate strategic plans into tactical plans. Another case study, this time for a corridor along route 1 in New Brunswick, served to demonstrate how to obtain tactical plans from strategic results of performance-based optimization. A one kilometre spatial buffer was used to select all assets within such a distance from the road centre line, this included parallel asphalt roads, bridges and chip sealed roads. Bridges were divided per subcomponent into deck, superstructure and substructure and treatments allocated to each subcomponent following NBDOT treatment's definitions. An initial model with $272 million prepared a strategic analysis for 18 years, allocating treatments across the entire network. Commercial software STANLEY (within WOODSTOCK) was used to re-allocate treatments in time and space, to take advantage of adjacencies, therefore advancing or deferring treatments at neighbour assets (segments) and creating groups of assets to be treated at the same time. The software identified five clusters on years 2, 3, 5, 7, 10, with groups of proximal assets rescheduled to be treated at the same time. The rest of assets remained at their original schedule and were not coordinated. In terms of degree of optimality of the objective condition, bridges were very inflexible in being reallocated, only 9% in average was moved to another point on time, 17% of asphalt pavements were reallocated (therefore reaching 83% of optimal results) and 33% of chip sealed roads (in average) were reallocated ending with (67 optimality score).

6.2 Lessons Learned and Recommendations for Future Research

Other criteria apart from space, time, asset compatibility and goal achievement should be incorporated into the model to prepare operational plans (within a given year). Some of those criteria should regard to social cost of disruptions, scheduling of crews, inspectors, machinery, equipment, material availability, business losses, etc.

In terms of modeling, accurate costing, environmental impact (gas emissions, energy usage, etc) measures, treatment effectiveness and asset performance are crucial for capturing tradeoffs between condition, cost and environmental impact. In this research some of such values were estimated (unit cost), others incorporated from local practices (treatment characterization) and some assumed to follow values identified at the literature review (gas emissions and energy usage) in the agreement that they were intended for this academic work. For real life applications, it is possible to measure more accurately the indicators of energy consumption and GHG emissions from locally observed characteristics of projects, such as type and source of materials, distance between extraction sites, manufacturing sites, factories and placement position. Thus, more accurate indicators could be developed.

Parameters related to space and time proximity as well as space and time openings and treatment compatibility should come from senior engineers and project managers and reflect operational capabilities and practices. Practitioners and researchers may be interested in conducting corridor or zonal analysis, across different types of infrastructure.

In general, both approaches of this thesis are practical and can be easily included in infrastructure management systems to achieve more sustainable systems; gaining benefits for agencies, users and the environment.

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