# Incorporation of Road Safety into Road Management Systems

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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

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Road collisions negatively affect the lives of hundreds of Canadians per year. Unfortunately, safety has been typically neglected from management systems. It is common to find that a great deal of effort has been devoted to develop and implement systems capable of achieving and sustaining good levels of condition. It is relatively recent that road safety has become an important objective. Managing a network of roads is not an easy task; it requires long, medium and short term plans to maintain, rehabilitate and upgrade aging assets, reduce and mitigate accident exposure, likelihood and severity. This thesis presents a basis for incorporating road safety into road management systems; two case studies were developed; one limited by available data and another from sufficient information. A long term analysis was used to allocate improvements for condition and safety of roads and bridges, at the network level. It was confirmed that a safety index could be used to obtain a first cut model; meanwhile potential for improvement which is a difference between observed and predicted number of accidents was capable of capturing the degree of safety of individual segments. It was found that the completeness of the system resulted in savings because of the economies obtained from trade-off optimization. It was observed that safety improvements were allocated at the beginning of the analysis in order to reduce the extent of issues, which translated into a systematic reduction of potential for improvement up to a point of near constant levels, which were hypothesized to relate to those unavoidable collisions from human error or vehicle failure.

# DEDICATION

*I proudly dedicate this work to my parents and my sister for their immense love and unconditional support. Also, I would like to acknowledge the inspirational instruction and guidance of Professor Luis E. Amador for giving me a deep appreciation and love for the beauty of study; may this be the beginning of a better life for the generations to come.*

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## LIST OF ABBREVIATIONS

The following table describes the significance of various abbreviations and acronyms used throughout the thesis. Nonstandard acronyms that are used in some places to abbreviate the names of certain mathematical variables or treatments are not in this list.

| Abbreviation | Definition |
|---|---|
| AADT | Annual Average Daily Traffic |
| AC | Asphalt Cement |
| Acc (EXP) | Expected number of accidents |
| Acc (OBS) | Observed number of accidents |
| CF | Causal Factor |
| CPM | Crash Prediction Models |
| CSR | Crack Sealing Roads |
| IRI | International Roughness Index |
| LOS | Level Of Service |
| LP | Linear Programming |
| PCI | Pavement Condition Index |
| PFI | Potential For Improvement |
| PMS | Pavement Management Systems |
| RMS | Road Management Systems |
| SDI | Surface Distress Index |
| SI | Safety Index |

# CHAPTER 1
# INTRODUCTION

## 1.1 Background

Road agencies, departments of transportation and infrastructure, increasingly experience budget limitations every year, although they are still legally responsible for delivering adequate levels of maintenance, safety and mobility. Decision makers constantly struggle with the complex process of funds allocation amidst competing alternatives to deliver the most cost effective solutions. In the past, this process was biased by the subjective selection of alternatives without a careful consideration of the long term impacts in the asset's lifespan and in the overall network. Today, many agencies have implemented transportation, road or Pavement Management Systems (PMS) in order to optimize the allocation of treatments in order to achieve the most cost-effective solution, normally maximizing condition while minimizing cost. However, other relevant objectives (*i.e.* road safety and mobility) are vaguely considered if not forgotten. The possibility to fully incorporate road safety in Road Management Systems opens the doors for an improved decision making process in which user needs are better addressed.

State of the practice in road safety engineering use Collision prediction models (CPM) to predict expected number of collisions normalized per traffic volume-segment length and unit of time (year). The result of comparing CPM outputs with historic records results in the potential for improvement (PFI) which is an indicator of conflicting segments of road where abnormal circumstances are provoking higher rates of accidents. In service safety audits should also be periodically conducted to determine conflicts and identify hazards.

Hence, practitioners proceed to identify viable corrective measures and to manually conduct independent cost-benefit analysis to determine the most desirable alternative to mitigate (or fully correct) each problem.

This research proposes the incorporation of road safety into road management, such that a global optimization analytical tool will find the optimal path to take full advantage of cost-effectiveness of individual treatments (what treatment?), associated with individual road segments (where?), and benefits of advancing or deferring a certain treatment (at what time?). It will seek an allocation that will minimize costs, maximize pavement condition and minimize expected number of collisions (normalized per volume of traffic-segment length-unit of time) and therefore provide the highest return on investment over the whole network of roads in the long run.

Collision Prediction modelling will play a major role for incorporating safety into road management systems. The precise knowledge of type and severity of expected collisions (and safety conflicts) over time is not a simple task as it requires the identification of all possible causal variables, their main effects and interactions. A reliable detection is in most cases an impossible task and modeling has to be based on observable variables and approximate forecast.

It has been a common practice to address the problem of developing collision prediction modeling by looking at historical trends on any one road (segment or intersection) despite the fact that historical trends reflect very particular conditions regarding the causal factors. Level of Service (Traffic), environmental exposure and geometric design are some of the causal factors that cause dissimilar behaviours among assets.

Several classical approaches fall short on many desirable features for a developing reliable collision prediction modeling. Deterministic performance deterioration (i.e., condition decay) models were developed based on historical data. Probabilistic models such as the Markov Chain are popular techniques to forecast the future states of infrastructure assets, due to their ability to capture uncertainty of the prediction of any response in a matrix format. These theories employ the *transition probability matrix* for capturing the evolution of the infrastructure element over time. However, this type of probabilistic model is only an extension of deterministic models expanded to reflect the likelihood of an asset to fall within a given range of discrete states. Therefore, Markov Chain fails to explicitly consider the relationships between causal factors and the response.

Presently, stochastic theories are also popular on practical applications and commercial software. Approaches such as Bayesian statistics have the advantage of considering randomness associated to the causal factors and its impact on the response, besides they rely on mechanistic relationships between the response and the available causal factors. Therefore, the stochastic approach allows a more realistic inclusion of uncertainty into the many possible conditions an asset can undergo over its lifetime. At present, the majority of infrastructure agencies are still using deterministic approaches to develop their performance models. In general, most of models used in current practice lack a mechanism to measure the uncertainty associated with the predictions. A few agencies have tried to incorporate an updating mechanism to adjust their short term forecast on either safety or condition.

This research specifically seeks to develop a practical framework (with practical case studies) for the incorporation of road safety into Road Management Spatial Planning Systems.

## 1.2 General Objective

The main goal of this research is to incorporate road safety into road management systems as an independent objective to achieve good levels of service. Within that general objective, however, two specific tasks were defined for two specific cases of insufficient and sufficient data available.

### *1.2.1 First Specific Objective*

In cases of insufficient data regarding accident records, the objective is to initiate a first cut model to make use of a site specific Safety Index to achieve good levels of service while minimizing costs.

### *1.2.2 Second Specific Objective*

In cases of sufficient accident records available, the objective is to more accurately incorporate road safety by using potential for improvements to achieve and sustain good levels of service while minimizing costs.

## 1.3 Scope and Limitations

The main scope of the work is to prove the possibility of incorporation of road safety into road management systems in integration with other objectives and other assets. However, there are limitations due to a lack of available data or a lack of a precise knowledge. This research is limited to road safety and pavement conditions for highways and only pavement conditions for bridges. Safety of intersections and bridges are not included in this research.

Accidents are not divided into different levels of severity including fatalities, personal injuries and property damage only accidents and everything is assumed to have one level of severity.

Conflicts as another measurement of safety which do not necessarily lead to accidents are not considered.

Finally, accidents are not separated with regard to the time of the day of their occurrence.

It should be mentioned that future research and effort can be dedicated to improve the limitations of this study.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Road (Pavement) Infrastructure Management Systems

### *2.1.1 Historical Advances*

A worldwide attention has been paid to infrastructure management systems and their economic benefits since the late $20^{th}$ century. Governments and federal agencies realized that preserving assets and maintaining sustainability during their life-cycle can result in savings (New Zealand Asset Management Support, 2006). Infrastructure in general consists of inter-related assets that help countries to support economic activities and supply basic services to the population. Any failure in a single component can adversely affect other subsystems and lead to economic losses and disruption to the public. Asset management is recognized as the core of infrastructure management systems and is defined as *"a systematic process of maintaining, upgrading, and operating physical assets cost-effectively"*. Such a systematic process along with a rational combination of engineering and management principles provides an efficient framework to support decision making on fund allocation of governments and federal road agencies (AASHTO, 1997) (Federal Highway Administration, 1999). Other definitions of asset management are consistent with the AASHTO and FHWA principles. Per instance, the Transportation Association of Canada (TAC) defines asset management as a systematic combination and collaboration of human, information and technology to most effectively allocate funds among alternatives (TAC, 1999).

Transportation Asset Management evolved from pavement management systems were one can find the first applications of such concepts. Literature of Pavement Management Systems (PMS) goes back to 1960's when an international effort was made around the world to develop a comprehensive approach for managing road infrastructure (Haas and Hudson, 1994). A Pavement Management System refers to a systematic approach to guide decisions for maintenance and rehabilitation; it follows an optimum direction in achieving minimum required levels of service while minimizing costs. This requires a comprehensive collaboration among all phases mainly, planning, designing, constructing, maintaining and rehabilitating, monitoring and evaluating pavement conditions (AASHTO, 1993) (Tessier and Haas, 1977). Although pavement management systems were conceptually advancing and increasingly growing during the 60's, actual applications of such systems date to mid and late 70's, with regional implementations in Netherlands, United kingdom, Washington and Arizona States in US (Haas, 2001). In late 1970's, however, a significant progress was made in the area of implementing PMSs in Arizona (US). Until then, the Arizona Department of Transportation (ADOT) used to schedule only re-constructions. However, it gradually tended to move from reconstruction to rehabilitation for the following reasons:

-A huge network of roads had been already constructed, and it was not necessary to construct new roads anymore.

-Existing roads were aging and deteriorating and needed to be rehabilitated and maintained in order to perform at an adequate level of service.

-Federal funds from FHWA (Federal Highway Administration) were allocated to rehabilitation more than reconstruction.

-Keeping the roads above a certain performance level could save money in the long run. Hence, ADOT found obvious needs to utilize a systematic and administrative approach to better allocate investments. Such an approach must consider all influential factors as well as both short term and long term effects. The system was implemented in 1980 and it was found to be successful due to savings in the order of $14 million in investments (K.Golabi et al. 1982).

Although benefits of any project can be divided between users and agency benefits, at the end of the day, the focus should be placed in the public. However, agencies could also benefit from this approach by reducing subjective decision making and increasing cooperation and coordination of actions. Furthermore, using such highly data needed systems makes it necessary to store and manipulate data and accordingly results in transferring data to the following generation of experts and engineers (Tessier and Haas, 1977).

In the 60's decade, the primary goal of PMSs was to "improve the efficiency of decision making" by using the optimum rehabilitation strategies for a specific project which is referred to ***a project level*** approach (Haas, 1992), it was gradually found out that the system could be applied at ***a network level*** as well (Haas et al., 1994). A project level management involves a process of selecting optimum treatments (M&R) during the lifespan of the pavement while a network level management seeks the optimum combination of actions and alternatives for the entire network of roads during their life-cycle. This research seeks the incorporation of road safety into the set of alternative investments used to deliver adequate levels of service at the network level for road management.

According to Shahin (1994), a PMS generally consists of four components namely: network inventory, condition evaluation, performance prediction models and planning methods. Although most management systems follow the same framework, the following description of components is presented in terms of pavements due to the scope of this research.

### *2.1.2 Data Management and Condition Assessment*

Perhaps the most important part of a management system is having efficient data management, normally in the way of an inventory for the entire network. A network of roads consists of pavements, bridges, culverts, pipelines and so forth. Each of these assets has structural and functional properties (i.e. length, traffic, material, diameter, geometric characteristics, etc.) for which we define performance indicators (i.e. roughness index, erosion indicators, serviceability index and so forth). An efficient asset inventory must consider a dynamic registry capable of expanding to register updated records of indicators across times which are produced after deploying annual treatments during the life-cycle of asset in the network. Thus, inventory as the heart of PMSs plays a vital role in the overall framework (Hudson et al., 1997). Infrastructure management systems are highly data needed. The more accurate data collected, the more precise decisions made. Improvement of data capture and management methods has been absolutely an important milestone in advancing pavement management systems. Data manipulation and storage were in the form of "cabinets of records" by the time PMS concepts first evolved.

Unsurprisingly, management systems could not have been improved efficiently by lying on such weak methods of data collection and storage. Development of new technologies in various areas of data collection such as profile measurement instruments, imaging methods and most importantly Geographic Information Systems (GIS), facilitated improvement of PMSs during time. Finally, upgrading systems, technology and methods of data collection, storage, analysis and management has been well emphasized by researchers as a key future need in the area of pavement management systems (Haas, 2001).

Condition evaluation is the next component in which various states of pavements (traditional in terms of condition) are established to identify current deficient segments of roads in order to plan for M&R actions. Various types of evaluation were used to determine conditions. Using condition evaluating instruments, monitoring pavements and subsequently using indicators such as a roughness index or an inspection ratio or so forth are only some examples of condition evaluation procedures. However, the sole evaluation is useless if not combined with prediction models which forecast future states of pavements in terms of conditions.

### *2.1.3 Prediction Models and Decision Making Approaches*

Historically, until the late 1970's, pavements used to be rehabilitated or reconstructed based on subjective engineering judgments or periodic evaluation (the latter is still applied to confirm forecasting analysis). Pavements expected to reach minimum level of service were candidates to be rehabilitated (worst first scenario) without the need to consider future condition states. Timing of treatments was largely made by looking at a set of criteria related to the applicability of maintenance actions. Maintenance and Rehabilitation (M&R) actions were then based on subjective judgment, consisting of rates or numerical indexes. A budget line across the entire life cycle of pavements was used to prioritize projects by contrasting maintenance needs with available funds (Figure 2.1). After modifying and re-evaluating alternatives (postponing or advancing actions), projects implementation was planned over the entire life cycle (Tessier and Haas, 1977). Three different situations were possible: lack of money, surplus of funds (compared money requirements) or balanced budget. Actions could be postponed or advanced for those cases lacking sufficient budget or having a surplus of money. The other possible strategy was to use a portion of the money required to fund future strategies in current needs. The entire procedure was subjective and biased by human criteria.

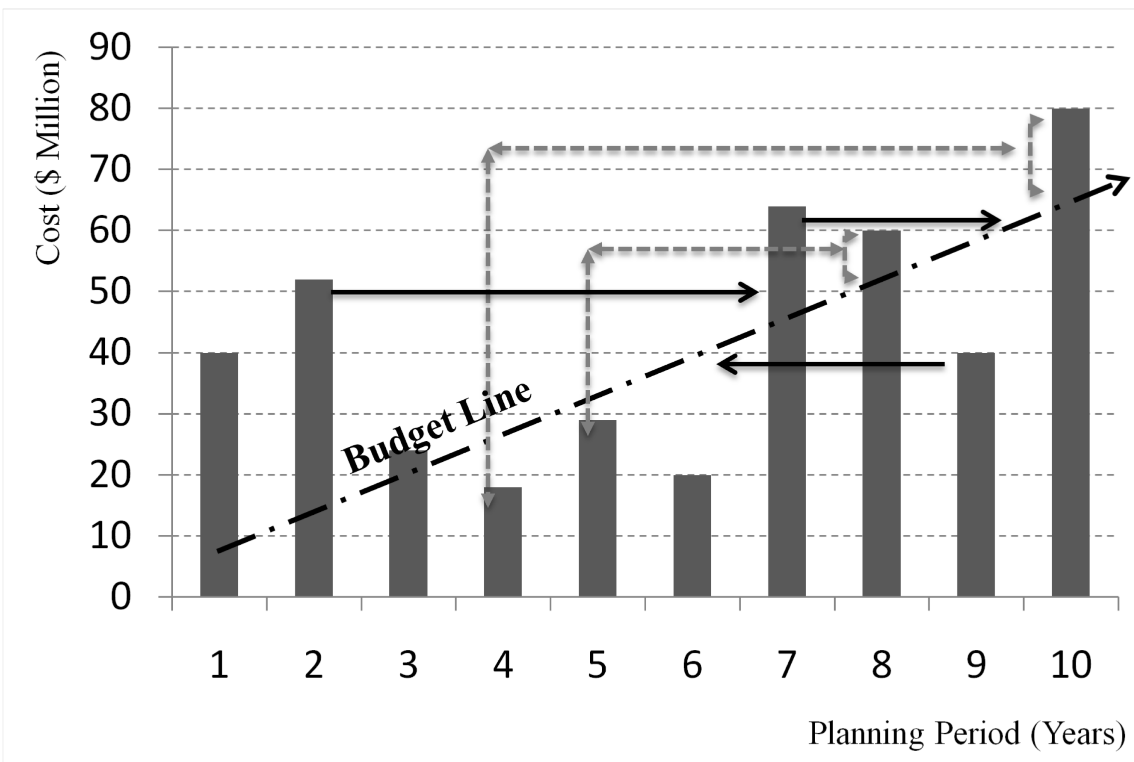



Figure 2.1 Subjective prioritization of alternatives (Adapted from Tessier and Haas, 1977)

The aim of such life-cycle analysis was to minimize costs while achieving required level of service during the life-cycle of pavements. To decrease subjective decision makings and increase accuracy of future planning, it was necessary to predict pavement condition, considering both deterioration and after rehabilitation performance.

Performance prediction models serve to predict pavements condition and performance. According to Haas (2001), the need of prediction models emerged at the time of developing the concept of serviceability as a measurement of level of service. There are three types of prediction models including empirical, mechanistic-empirical and reliability-based prediction models. Empirical models use historical data from empirical observations while mechanistic-empirical models make use of both empirical observations to calibrate coefficients and estimated pavement distresses and responses. Reliability-based models are the third type which incorporates probabilities related to uncertain nature of pavements. Bayesian regression is a particular case of the latter. Although pavement condition depends on maintenance and rehabilitation actions, it cannot be exactly predicted due to the presence of unexplained factors (uncertainty). Hence, it was important to incorporate the uncertain nature of pavements in the overall system. This was done by incorporating probabilities in performance prediction models. In fact, long term impacts of decision making were not considered in traditional models due to the inability to predict future pavements condition. In 1981, ADOT was one of the first agencies that implemented a probabilistic performance prediction model based on Markov Chain approach. The model included variables indicating the probability of a pavement being in certain conditions in quantum periods of time. The result of implementing this kind of model was prodigious enough that universal attention turned into using Markov models. According to Chu (2007), researchers studied the Markov method and its functionalities following the success in Arizona. Ben Akiva et al (1993), Black et al (2005), Garnahan et al (1987), Golabi and Pereira (2003), Golabi and Shepard (1997), Mbawana and Turnquist (1996) have presented significant researches on Markov models (As cited in Chu, 2007). Chu has categorized the prediction models into static and dynamic prediction models. Static models are those deterministic models which do not consider uncertainty such as a classical regression. On the other side, there are dynamic models such as Markov approaches which capture the uncertain nature of pavements. However, Chu has expressed some disadvantages of this method. To illustrate the deficiency it is necessary to explain the concept of Markov approach.

Assuming a pavement that is currently in state ***i***, the Markov model indicates the probability ($\mathbf{P}_{ji}$ ) of reaching state ***j*** by applying action ***l*** in a quantum period of time ($\mathbf{a}_t$). It can be displayed as following:

$$Prob(\mathrm{x}_j | x_i, a_t : 1) = P_{ji} \quad [2\text{-}1]$$

Being in state ***j*** in the next period of time only depends on the state ***i*** in which the pavement currently is and, the action that is applied in state ***i***. In fact, it does not take into consider action treatments which may apply *during* the time between states ***i*** and ***j***. This is in fact a disadvantage of the Markovian approach (Chu, 2007).

Another disadvantage of a Markov model is that it does not consider the role of causal factors which may affect the response. The only factor that is considered as an explanatory variable is the current state of the pavement. In fact, the Markov models is deemed a memory less or history independent model, which depends only on immediate past and does not consider a comprehensive set of casual factors in previous past history of the entity. This can affect the reliability of the model. On the contrary, Chu (2007) has proposed some dynamic methods which are capable of considering the dynamic nature of treatments (reliability based models).

The next component after predicting pavement performance is prioritization and planning of future actions. The first objective method (after the subjective ranking method) employed at early stages of PMS was cost-benefit analysis by the mid 1970's. According to Haas et al. (2006), a cost-benefit analysis as a part of an efficient PMS, was based on minimizing costs while maximizing benefits (achieving certain required level of service), which improves the aforementioned method on planning actions by simply tracing a budget line. As such, costs and benefits are categorized into two main groups: agency and users. However, at the end of the day, it is the public that must get the final benefits considering that the money spent in road infrastructure was originally collected from taxes and levies. In addition, it is noteworthy that a careful consideration of user costs and benefits was proposed by Haas in 1977. However, the benefits might be somehow subjective regarding difficulties in their quantification. Thus, later on they suggested monetizing the benefits as negative costs (Hudson et al., 1997). The cost-benefit method resulted in two main limitations. First, it needed projects to have the same benefits due to the fact that it did not fully and directly consider benefits. Second, this method was not capable of evaluating different service life periods of the projects. Hence, the service life of all projects should be the same (Haas, 2006). Rather Life-Cycle Cost Analysis (LCCA) was proposed early after the development of pavement management systems in the late 1970's. Projects can be evaluated based on costs of various phases during their life-cycle including planning; constructing, maintaining and even recycling (salvage values). Costs of every action to be applied at different years during the life cycle were determined and returned to the present value by using the traditional Present Value function (Equation 2-2).

$$PV = \sum_{t=1 \ldots n} \frac{A}{(1+r)^t} \qquad [2\text{-}2]$$

Where: A: costs of actions

r : discount factor

t : year

Subsequently, projects were prioritized and selected based on various strategies including low construction costs, low maintenance and rehabilitation costs or even low operating costs (Haas et al. 1994, TAC 1997, Hudson et al. 1997). In general, costs can be categorized as initial and future construction, rehabilitation, periodic maintenance, and residual salvage value. Other cost such as vehicle operating costs (VOC), user delays and accidents (road safety related) can also be incorporated in the analysis. Economic losses and user delay costs are often difficult to estimate and in some cases of such magnitude that agencies traditionally do not explicitly incorporate them into the analysis. Such costs, however, become important criteria to compare alternatives at the end of analysis period and should be considered (Haas, 2001).

Vast implementations of LCCA have made road agencies capable of having a decision making tool to select the best solutions based on monetary values. Indeed, traditional applications of life-cycle cost analysis approach solely dealt with monetary goals as the only objective in a linear programming optimization approach. Several attempts, however, have been made to develop a management framework with a decision making system capable of combining two or more objectives (Revelle et al., 2003). In other words, LCCA is not capable of incorporating other dynamic indicators in addition to costs. Per instance, performance of assets is importantly affected by M&R actions during the life cycle. This somehow displayed the weakness of LCCA by not looking at other asset indicators except costs which do not necessarily relate to sustainability or performance.

The main idea behind LCCA was to create a combination of indicators of various objectives substituted by cost given to provide a common dimension. Keeping the objectives in their original dimensions (dissimilar units) has been historically discouraged. One way of solving a trade-off problem is by focusing on mapping the boundary of the feasible space, and of identifying a non-inferior set of alternatives (Revelle, 2003). Several decision making software packages, such as HDM-III (Watanatada et al., 1987) and HERST (FHWA, 2009), have addressed the need to consider multi objective optimization, however, being incapable of considering other assets (i.e. bridges, culverts and so forth) apart from road segments.

## 2.2 Road Safety

### *2.2.1 Introduction*

Although pavement management systems had been well advanced and implemented, actual integration of different component systems such as bridge management systems, maintenance management systems, congestion, safety and so forth had not been established until recently. Road agencies and transportation engineers gradually became involved with a variety of assets which required more attention to safety, environmental impacts and user costs (factors that had been dominated before by simply-recognized maintenance and construction costs). A need of integrating various components in a united systematic approach capable of maximizing return on investments and of achieving required levels of service came into consideration in early 2000s (Haas, 2001). Road safety has been identified as an essential component which should be incorporated in road management systems. Hass and Tighe (2000), addressed this necessity by indicating various classes of safety with regard to management systems along with public sensitivity of their effects (Table 2.1).

This research was the first one that directly took into account road safety as an independent objective for a more comprehensive management system. Historically only skid resistance had been taken into account in some pavement management systems (Haas, Tighe and Falls, 2001). In this respect, a comprehensive list of contributing factors inducing accidents was proposed a decade ago which categorized the factors into three main groups namely, road factors, vehicle and human factors (Tighe et al., 2001). From a management/engineering point of view, feasible countermeasures only exist for road factors. Meanwhile, consequences caused by vehicle failures and human factors (both random and nature) can be mitigated by applying treatments that reduce accidents severity.

Table 2.1 Classes of factors associated with safety attributes (Haas, 2001)

| **Type of factor** | **Safety Element Measures or Indicator** | **Sensitivity to Drivers** |
|---|---|---|
| Surface Texture or Friction | • Macrotexture and microtexture characteristics, such as International Friction Index (IFI)<br>• Skid resistance or skid number measures<br>• Vehicle tire type standards | Low |
| Pavement Roughness or Riding Quality | • Riding comfort rating, International Roughness Index (IRI), etc.<br>• Roughness and speed relationship | High |
| Pavement Surface Distress | • Severity and extent of surface distresses, such as ruts, faults, potholes, cracks, spalls, etc.<br>• Distress index | Middle |
| Pavement Geometric Design and Location | • Widths of lanes and shoulders, median, and pedestrian paths<br>• Cross slopes of pavement surface | Middle |
| Visibility of Pavement Surface Features | • Pavement surface color and reflectivity<br>• Lane markings and signings<br>• Visibility at night and bad weather conditions | High |
| Paving Materials and Pavement Mix Design | • Type of pavement<br>• Texture and color of paving materials<br>• Mineralogy and anti-resistance properties | Low |
| Road Safety Measures and Facilities | • Safety warning signs<br>• Safety protection facilities | High |
| Environmental and Weather Conditions | • Place and time of accident occurrence<br>• Roadside obstacles and safety facilities<br>• Overall precipitation, such as fog, rain, snow and wind, etc. | Highest |

This research proposes to fully consider road safety including exposure, severity and likelihood into road management systems. Although assessing safety follows the same procedures which have been applied on pavement conditions, accidents by nature behave differently in comparison with pavements. In other words, pavement deterioration is always associated with a decrease in the condition index (PCI) and requires periodic investments to sustain acceptable levels (applying treatments) whereas safety issues result in increased risk of crashes and require treatments to decrease such an index. On the other hand, pavements will always deteriorate, while collisions may increase or decrease from one year to another. In fact, considering the random nature of road accidents, one cannot assure that unsafe conditions of roads get worse in time. To explain more clearly, it should be noticed that human error, vehicle failures and other random variables influence the likelihood of crashes. The aforementioned phenomena emerge the need to consider uncertainties and probabilities in the models.

According to Hauer (1997), potential for improvement for a road can be determined by assessing a before-after study. The difference between current observed number of accidents and the predicted number of accidents can capture the potential for improvement. Such future number of accidents is determined using prediction models (E. Hauer, 1997). Recognizing the potential for improvements leads to the applications of appropriate treatments from a handful of alternatives. Applying treatments in a network of roads generates thousands of alternatives which are not equal in costs or in their final performance result. Hence, it is required to prioritize alternatives to reach the most cost-effective solution and this is possible only through an optimization.

### *2.2.2 Road Safety Definition*

The first image of road safety coming to mind may be the number of accidents happening in a road. According to the Highway Safety Manual (HSM, 2010) of the American

Association of State Highway and Transportation Officials (AASHTO, 2003), a crash is defined as a set of events that result in injury or property damage due to collisions of at least one motorized vehicle and may involve another vehicle or a non-motorized user such as a bicyclist, a pedestrian or an object. Although this subjective definition may cover the concept of safety, it cannot represent a reliable and comprehensive definition from the engineering point of view. According to Hauer (1997), accidents differ in severity and accordingly in costs. Fatal, injury and Property Damage Only (PDO) accidents are the main three categories used to cluster accidents by severity. On the other hand, solely reporting number of accidents as an indicator of safety could be misleading considering the fluctuations and unstable trend of accidents in a road network. This comes from the random nature of accidents and the uncertainty associated with forecasting crashes. Hence, it is required to somehow coin and stabilize the cluster of accident counts in time. Tracing the annual average of accident counts shows more stable results (Highway Safety Manual, 2010) although the concept of average is not well defined in safety. To sum up, accident frequency (i.e. the number of accidents per unit of time, per volume of traffic, per kilometre) seems to be a well established indicator in the literature (Highway Safety Manual, 2010 and Hauer, 1997) to start defining a model that captures safety while normalizing by traffic volume or segment length. However, it should be considered that there might still be differences due to reportable and non reportable accidents, their classification of fatal, injury and PDO accidents (Property Damage Only), monetary differences and health policy discrepancies in various jurisdictions, and the presence of conflicts which are neglected from the scope of this research.

### 2.2.3 Safety Analysis

Safety analysis refers to the evaluation of accident likelihood and exposure and is required to address hazardous sites (interchanges, intersections, mainline, merging or turning lanes). Such an analysis requires comparing different safety states with each other in time. One of the first approaches to safety analysis was developing a raw crash rate defined as a crash frequency over a measure of exposure. Exposure is simply defined as the volume of traffic passing a specific road segment.

$$R_i = \frac{f_i \times 10^\wedge 6}{365 \times (P \times L_i \times Q_i)}$$

Ri = accident rate of site i (accidents/million veh-km)

fi = accident frequency at site i (during the period of analysis)

P = period of analysis (years)

Li = section's length of site i (km)

Qi = Average annual daily traffic of site i (AADT)

By knowing accident rates of various sites, experts could systematically address hazards in the network. However, this approach has important drawbacks including a lack of capability to consider natural variability in crash frequencies and also a lack of consideration of a non-linear relationship between crashes and traffic volume. Finally it does not take advantage of historical trends of accidents. It should be noticed that accidents occurrence may vary in short periods of time due to their randomness. Raw rate models are not directly time dependent which means they do not take into account time variability. Moreover, crash occurrence does not necessarily relate linearly with the volume of traffic, but rather it can follow a wide range of non-linear relationships. This obviously poses the need to take into account the history of accidents which can accordingly lead to elicit a reliable empirical relationship between volume of traffic and the number of accidents (Highway Safety Manual, 2010). Yet, the most important and crucial deficiency of such an approach is that it does not reflect contributing factors which provoke accidents. As a matter of fact, it somehow acts statically while the three mentioned causal factor groups change dynamically in time. This induced the appearance of a total different approach to accident and safety analysis proposed by Hauer in 1997. As illustrated in figure 2.2, an observational before-after study preferably attempts to estimate the variation on the number of accidents if a certain treatment is applied or not. The difference will then show the effectiveness of the treatment. Considering that some treatments may have long term effects, the total trend of this difference can be a good indicator of safety (Hauer, 1997). Figure 2.2 illustrates the concept of an observational before-after study and the potentials for improvement in the long run.

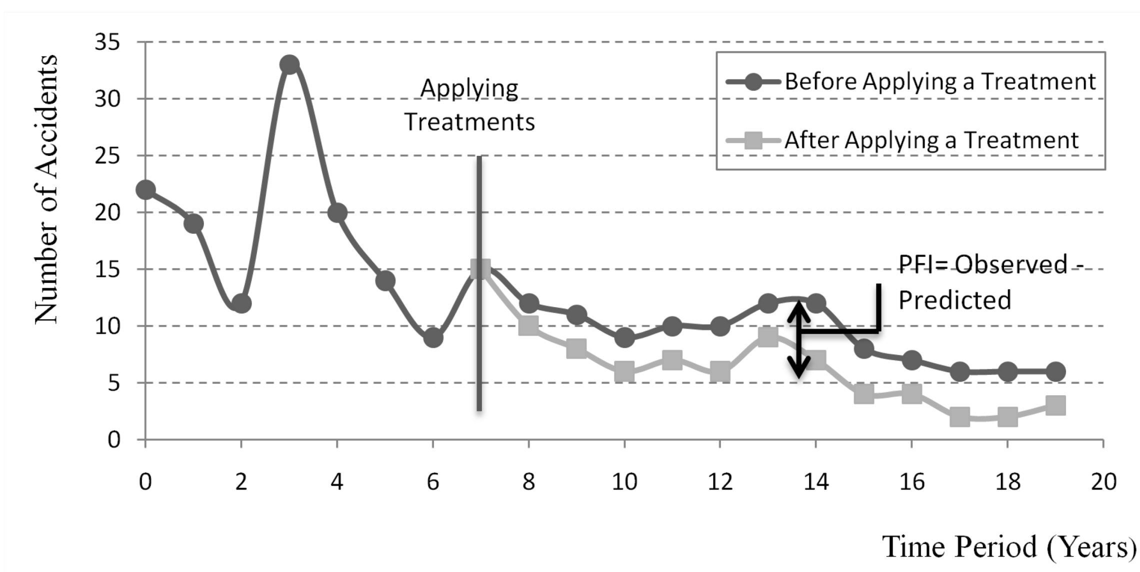



Figure 2.2 An observational Before-After Study (Adapted from E. Hauer, 1997)

A before-after study, determining the potentials for improvement in the future, requires a reliable accident forecasting. This would result in the difference between what would have been if no treatments were applied and, the state of the road after applying treatments. There are three main approaches to before-after studies including Naive, comparison group and reliability-based before-after studies. In the naive approach, the PFIs are determined simply based on the difference of observed number of accidents in the before period and expected number of accidents in the after period (Figure 2.2).

Although the approach does not take into account the history of accidents and empirical data, it indicates the basics of before-after studies. On the other side, before-after studies do make use of accident history by tracing the trend of observed data. It should be noticed that the trend of observed and predicted accidents are not the same. In fact, the aim is to minimize the difference between the observed number of accidents (which typically follows a trend) and the predicted number of accidents (which is calculated in the crash prediction model). The method makes use of empirical data averaging the last three or five years of accidents which usually gives a more reliable trend. This reliability comes from the fact that there are always outliers and unusual factors in the database which may cause bias. This bias can be mitigated simply by using the trend. Simple regression can be used to get the trend of accidents history. It can also be observed that factors change very slowly in time, thereby assuming the trend of previous years to be somewhat constant.

The third approach and the most reliable one is a Bayesian Reliability-Based Prediction Model which captures the risk of happening accidents in time. In the latter approach, a certain risk is given to every individual variable in the model as well as to the final response (the future number of accidents). Hence, every individual explanatory variable in the model can vary in the pre-defined interval. Taking into account the entire accident history (population), the final variables carry specific amount of risk which explain the uncertain nature of accidents. To generate a prediction model which can forecast the future number of accidents; it is required to identify causal factors affecting the likelihood of accidents. According to Transportation Association of Canada (TAC), causal factors can be categorized into three main groups including road factors, environmental factors and human factors (TAC, 2004). Similarly, Sayed (2002) proposes the causal factors in three main generic groups which are exposure, consequences and probability where exposure identifies how much road users are exposed to safety hazards, consequences express the severity of hazards and the probability determine the likelihood of occurring crashes. Indeed, these representative groups cover all other affecting variables. However, there might be other factors (i.e. vehicle factors) that are not related to road agencies. In fact, it must be considered that every factor considered should include an appropriate treatment to improve deficiencies caused by that factor. The latter casual factor requires manufacturing regulations which might not be related to the scope of this research.

At the end of this chapter, it should be noticed that in the framework of safety analysis which was explained above, a controversial discussion may arise that despite the fact that the PFIs (the differential indicator for safety) are minimized even to zero, there may still be accidents. Hereby, two points may clarify the argument. First, there is always small number of accidents due to unexplained factors and random nature of accidents. Per instance, uncontrollable causal factors such as driver's impairment, alcohol related accidents or even vehicle failure can lead to accidents which can be captured in the models. Second, the aim of this study is to rank and prioritize mitigating actions among different alternatives based on a common indicator which can be a differential one. In other words, uncontrollable factors influence the entire network and because the final objective is to prioritise sets of actions, the effects of such factors are negligible.

# CHAPTER 3
# METHODOLOGY

## 3.1 Introduction

Road agencies, federal governments and municipalities yearly invest millions of dollars on actions and improvements to achieve adequate levels of service in their road networks. Levels of service can be divided in terms of pavement conditions, highway capacity, general accessibility, road safety, environmental impact and so on and so forth. Due to scarcity of resources, it is critical to systematically plan for future investments and to allocate funds among alternate courses of action. In this regard, decision makers take advantage of road management systems to achieve good levels of service while minimizing expenditure during the life cycle. This research proposes and applies a framework to guide decisions for road management; in particular to choose sets of actions to achieve and sustain good levels of service for two objectives namely, road safety and pavement condition. To accomplish such a task the proposed methods supported by enumeration of all possible courses of action that had the potential to improve current conditions of individual segments of roads and to sustain good levels across time during the analysis period. Figure 3.1 illustrates such enumeration of sets of actions for road safety. Similarly other enumeration mechanism could be deployed for pavement conditions ($Q_{ijt}$) and costs ($C_{ijt}$) associated to improvements.

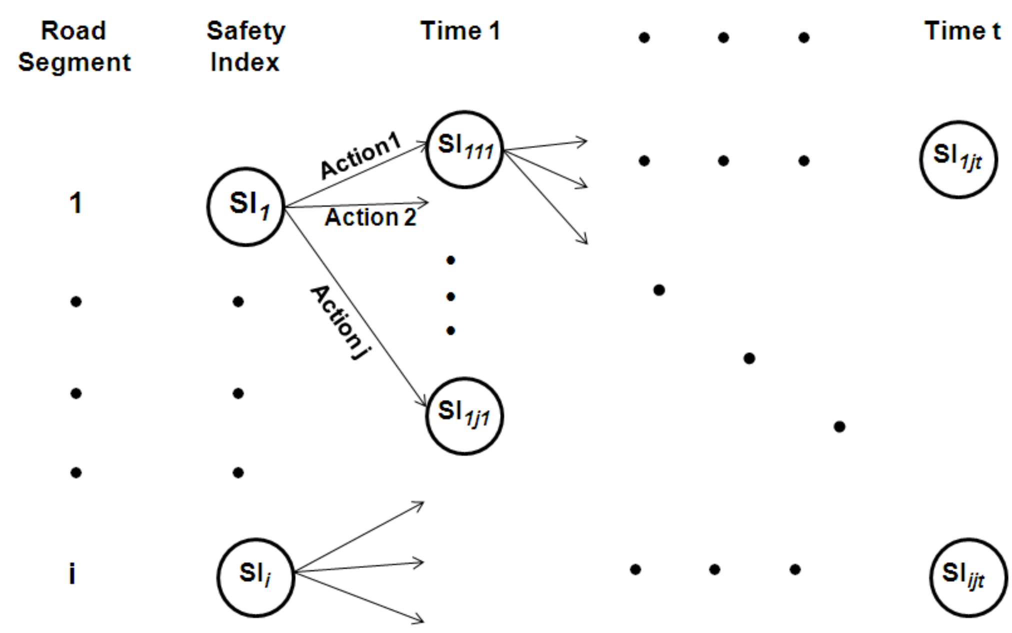



Figure 3.1 Enumeration of courses of action for Safety Index (SI)

Decisions are supported by an optimization algorithm which utilizes the abovementioned enumeration process considering all possible combinations of actions "*j*" to be applied on road segments "*i*" across time "*t*". After obtaining all possible combinations, it is required to evaluate and compare different alternative paths per road segment and to identify an optimum solution by selecting one path per segment, particularly in this thesis a solution will have the least costs and the highest level of service during the life cycle while consistently achieving target mean network LOS. Hence, it is emphasized the need to look at the performance of the objectives (safety and conditions) in addition to the final levels of service and total costs. The decision making tool is a performance-based optimization (NAMS 2006) in which there are two criteria to compare alternatives including the total value per objective at the end of the analysis period and mean annual aggregated levels of performance for the network. Obviously such a comparison needs a performance function and a performance deterioration model able to capture rates of deterioration or change of safety indicators across time. To that end, accident prediction models and pavement condition deterioration curves help identify future states of road segments as well as their performance during the life cycle.

## 3.2 General Framework and Components

Similar to every management system, the proposed framework for incorporation of road safety consists of three main parts including preparing an inventory, creating accident prediction models and finalizing an optimization process follows by a dominance and performance analysis. Figure 3.2 clearly illustrates the general framework for incorporation of road safety into road management systems. The steps are explained respectively in following sections.

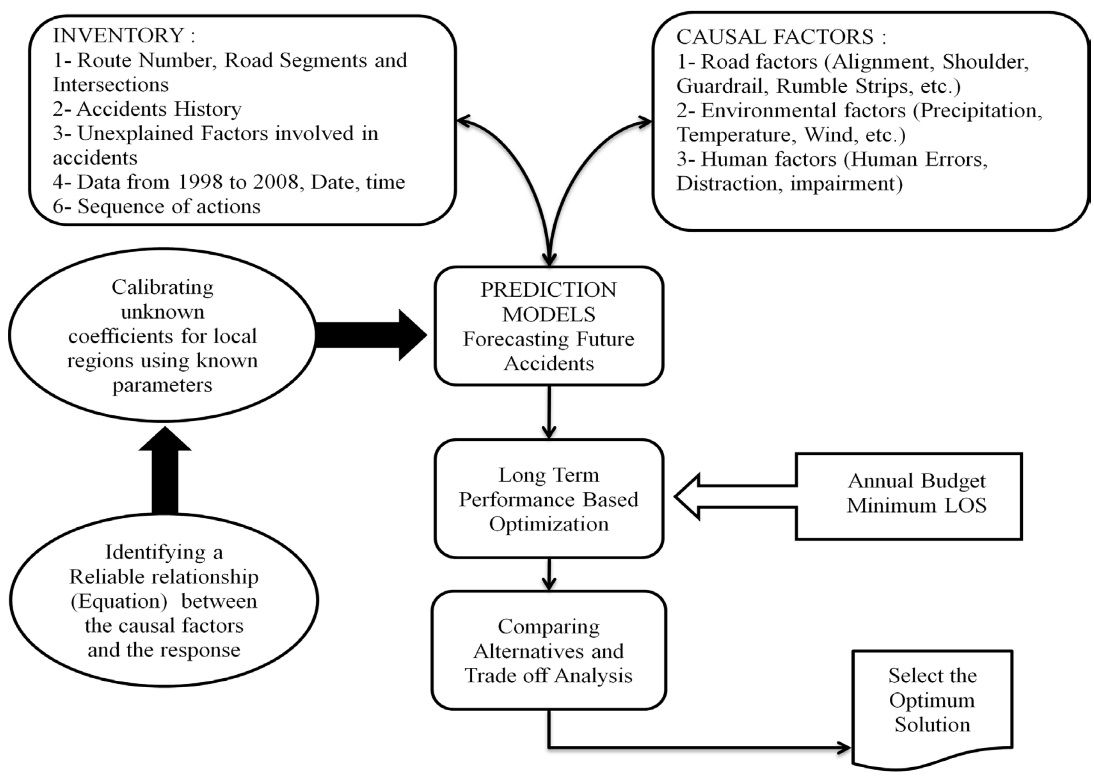



Figure 3.2 Incorporation of Road Safety into Road Management Systems, Generic Framework

## 3.3 Inventory and Assessment of Needs

According to the literature one of the most sensitive parts of any management system is an inventory. In an overall view, the final reliability and accuracy of the results highly depends on the quality of data. An assessment of needs should be done to figure it out what kind of information is available and what data is required. The inventory mainly consists of two parts including general information regarding road segments, intersection names, time and date of accidents and accident causal factors divided in three categories namely, road, environmental and human factors. It should be noticed that data consistency and conformity is very important in an integrated road management system which deals with multiple objectives (i.e. pavement conditions, safety, mobility and accessibility). Hence, spatial analysis on inventory can highly increase the accuracy of the model by using commercial spatial software. Joining multiple inventories and creating buffers for specific considerations are among the helpful tasks available at most spatial software.

On the other hand, it is noteworthy to mention that data updating is essential regardless of how comprehensive the inventory can be. New problems, methods, tools and regulations may arise as the time goes on. Hence, it is highly required to collect data, perform safety audits in case of road safety and update the inventory. Also, unexplained future factors and their effects on models can be captured by using future updated database.

## 3.4 Safety Analysis and Performance Prediction Models

As mentioned above, in order to plan for sets of future actions based on a performance-based optimization, it is required to use safety performance models which present total values of safety indicators as well as their performance during the life-cycle. Safety performance prediction models relate a response (an indicator of road safety) to explanatory variables (accident causal factors). Safety performance curves then show the progression of safety indicators in time which help looking at the performance of safety as one of the objectives. Thus, the main issue in this part is to identify accident causal factors and their relationship with total number of accidents. Due to the two specific cases happen regarding the data collection related to causal factors, it seems necessary to separate the safety analysis used when sufficient data is and is not available. Hence, defining two different safety approaches is required before any further explanation.

Two main approaches have been applied for the safety analysis, regarding two specific cases of insufficient and sufficient data available, including a static safety index and a dynamic potential for improvement. Bearing in mind that data collection and analysis is the vital part of the management systems, the two approaches have been proposed to most effectively making use of available data.

### *3.4.1 Static Safety Index*

In the first approach, a safety index is derived based on static peripheral features of the road network. Road agencies and federal governments always face data shortages. Even in cases of sufficient and comprehensive data available, random factors such as a change in land use, commuting behavior or even development of new methods and tools will provoke needs. On the other side, waiting for future implementations in order to collect data may not be logically justifiable especially when noticing of hazardous sites and weak spots in the network which can impose dramatic costs to road agencies. Consequently, developing a safety index based on the available static road features as well as environmental conditions can be a very good representative of causal factors provoking accidents in the network. The index is obtained by a function having various explanatory variables which are accident causal factors. According to Leur and Sayed (2002), contributing factors in a safety analysis can be divided into three main groups including exposure, severity and likelihood. A safety index can be derived by multiplying those three generic factors. Measurements such as traffic volume ($X_1$) and length ($X_2$) of road segments can be representative of exposure while factors such as speed ($Y_1$) can reflect severity. Accident likelihood can be obtained based on an average of various road features which affect occurrence of accidents such as presence of guardrails ($Z_1$), pavement marking ($Z_2$), rumble strips ($Z_3$), shoulder conditions ($Z_4$), lane width ($Z_5$) and so on and so forth. The generic mathematical form of safety index used in this study is presented in equations 3-1 and 3-2.

$$SI = [EXPOSURE] \times [SEVERITY] \times [LIKELIHOOD] \quad [3\text{-}1]$$

$$SI = [(X_1) \times (X_2) \times \ldots \times (X_k)] \times [(Y_1) \times (Y_2) \times \ldots \times (Y_m)] \times [(Z_1 + Z_2 + \ldots + Z_n)] / n \quad [3\text{-}2]$$

High values of safety index are representative of hazardous roads. Thus, the effort of the management strategy is to reduce the safety index in order to reduce the risk of accident occurrence. It should be noticed that the Safety Index does not act similarly in different conditions of exposure, severity or likelihood. As a result, levels of each factor can be used to develop different performance curves. Per instance, different curves can be established based on levels of volume of traffic or safety index itself.

Safety index approach can be highly advantageous in cases that accident data are not available in such a way that it correlates accidents with peripheral features. The index, however, acts statically in time meaning that it does not take into account the history of accidents so that it can capture the risk associated with random nature of accidents by making use of the trend. Accidents are random variables and occur with a certain amount of risk in time. The risk can be estimated by incorporating a history of accidents in the same network.

### *3.4.2 Potential for Improvement (PFI)*

This approach is applied in order to make use of accident history and create a dynamic model capable of capturing changes of contributing factors in time while accounting for accidents associated with randomness related to underlying factors. The latter approach requires developing safety models based on accidents records in addition to static road features. Hence, it is important to define causal factors and correlate them with the actual number of accidents taking into account the risk. This way, unknown coefficients of explanatory variables are calibrated for the local accident records and the risk related to accidents randomness can be captured. The final indicator of road safety used in this approach is Potential for improvement which is the difference between observed and expected number of accidents. The PFI approach which is basically named as an observational before-after study is mainly derived based on Hauer's efforts in this respect (Hauer, 1997). The generic mathematical form of the PFIs used in this research is shown in equations 3-3 and 3-4 in the following:

$$Acc = \beta(X_1)^{\alpha_1}(X_2)^{\alpha_2}...(X_n)^{\alpha_n}\, e^{[\gamma_1 Y_1 + \gamma_2 Y_2 + ... + \gamma_m Y_m]} \quad [3\text{-}3]$$

$$PFI = Acc(OBS) - Acc(EXP) \quad [3\text{-}4]$$

Where:

$X_i$ and Yi are explanatory variables and $\beta$, $\alpha_i$ and $\gamma_i$ are unknown coefficients for local conditions.

Again different performance curves can be established based on levels of traffic or PFIs to differentiate performance of PFIs in various conditions.

### *3.4.3 Safety Performance Prediction Models*

Crash (Accident) Prediction Models (CPMs) try to correlate observed accidents with various causal factors such as: traffic flow, segment's length, environmental factors and roadside features. Depending on the type of road site (highways, ramps, intersections and etc,.), a different mathematical function is either developed, tested and adopted from the observed data or adapted and calibrated from previous studies. Per instance, number of accidents in highways is traditionally related to the length of segments and traffic flow, while for intersections there is no length and accidents are related to traffic flows at the junction of two approaches. Such models are at the core of safety analysis in such a way that they serve to predict accidents supporting before-after studies. After deriving the generic mathematical form for the model, the unknown coefficients for variables are calibrated using the database. Accident's occurrence can be modelled as random variables following a probabilistic distribution. Normal distribution, Poisson and Lognormal Poisson distributions are used in this research. Normal distribution were used in the first paper of this thesis due to its simplicity, common acceptance among scholars and the need to prepare a first cut model capable of addressing the main task of this thesis, to integrate safety into road management. The model used local observations to estimate coefficients of explanatory variables. Such fitting of historical data resulted in local calibration, therefore enabling the model for prediction of future levels of safety. In this step, a full Bayesian approach that uses a Markov Chain Monte Carlo simulation (MCMC) to visit the parameters space and generate such values for the coefficients. Initial values for the coefficients (priors) as well as confidence intervals were established, to check for convergence it is advisable to run several MCMC chains from dissimilar departing points. To claim convergence, those chains should meet and stay together, although microscopic variations are expected (called mixing).

## 3.5 Decision Making Tools

Planning actions to be applied on road segments during their life cycle on the basis of potential for improvements is the main goal to accomplish low levels of safety (deemed good). After predicting accidents, major questions regarding long term plans are: what type of actions should be applied on which segments and in what period of time such that the system gives the optimum combination with the least costs and the highest levels of service. Looking at the performance of both objectives (safety and condition) plays a significant role to enforce good levels across time. Hence, the decision making tool that is used in this study is a performance-based optimization which keeps track of annual mean values of each objective for the road network. Traditional Pareto dominance analysis was expanded; adding a performance in charge of verifying the attainment of consistent good levels across time.

### *3.5.1 Linear Programming*

Linear Programming (LP) is used as a tool for planning in this research. The method considers the entire set of combinations of courses of actions generated by an enumeration process as explained before and seeks to reach the most optimum solution is. Two main elements are defined through the optimization process: objectives and constraints (Revelle, Whitlatch and Wright 2004). The process attempts to achieve the objective while subject to constraints. Objectives and constraints can be replaced by each other: objectives can be expressed in terms of total costs of actions while constraints can be in terms of levels of service for safety indicators. Obviously, the effort is to minimize total costs of actions meaning that safety indicators for current years should consistently decrease across time. The proposed mathematical formulation of optimization process is presented in Equations 3-5 and 3-6[1]:

$$\text{MINIMIZE}: Z = \sum_{t=1}^{T}\sum_{i=1}^{b}\sum_{j=1}^{J} C_{t,j}\, x_{t,i,j}\, L_i \qquad [3\text{-}5]$$

Subject to:

$$\sum_{t=1}^{T}\sum_{i=1}^{a} PFI_{t,i} L_i \leq \sum_{t=1}^{T}\sum_{i=1}^{a} PFI_{t-1,i} L_i \qquad [3\text{-}6]$$

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

Where: $x_{t,i,j} = \{0, 1\}$; "*1*" if treatment *j* is applied on asset *i* on year *t*, "*0*" otherwise

$PFI_{t,i}$ = Potential For Improvement of asset *i* on year *t*

$C_{t,j}$ = Unitary cost ($) of treatment *j* on year *t*

$X_{tij}$ = Binary decision variable: 0 no action is applied, 1 an action is applied

$L_i$ = length of road segment *i* (Km).

[1]Traditional studies such as World Bank HDM-III (Watanatada, 1987) and ICMPA (Lytton, 1994) provide similar formulations.

Or the whole process can be repeated on the same basis while replacing objectives and constraints as suggested before. Indeed, the other way is to minimize safety indicators (Safety Index of PFI) while not going beyond a certain annual budget that is imposed to the system. Equations 3-7 and 3-8 present such mathematical formulation:

$$\text{MINIMIZE} \quad Z = \sum_{t=1}^{T} \sum_{i=1}^{b} PFI_{t,i} L_i \qquad [3\text{-}7]$$

$$\text{Subject to}: \sum_{t=1}^{T} \sum_{i=1}^{b} \sum_{j=1}^{J} C_{t,j} x_{t,i,j} L_i \leq B_t \qquad [3\text{-}8]$$

with the same definitions of variables.

### *3.5.2 Multi-Objective optimization and trade-off analysis*

Incorporation of road safety into road management systems requires safety to be integrated with other objectives and other assets which involves a multi-objective optimization that is more complex. Although the same procedure is applicable for other objectives individually, when combining objectives it is important to simultaneously optimise different -often- contradictory objectives. Per instance, safety indicators should be minimized while pavement conditions should be maximised for the network. Such analysis is known as trade-off and when conducted by linear programming is traditionally implemented by aggregating objectives in order to change the problem from a multi-objective to a single one. A linear combination of two objectives was used in this thesis by associating changing weights to the objectives and creating an accumulated single objective to be maximized (Equation 3-9).

$$\text{MAXIMIZE} \quad Z = \alpha 1 \sum_{t=1}^{T} \sum_{i=1}^{a} L_i PCI_{t,i} - \alpha 2 \sum_{t=1}^{T} \sum_{i=1}^{b} PFI_{t,i} L_i \qquad [3\text{-}9]$$

It is noteworthy that due to converse effects of safety in comparison with pavement condition the sign in front of the last term is being subtracted. Allowing weights to vary is indeed a trick to generate various scenarios based on relative importance given to each objective. Weights are arbitrarily selected on a percentage scale from zero to one hundred percent, depending on how much importance is desired per objective.

The final step in choosing the most optimum solution is a comparison process in which various scenarios are evaluated, compared and the final solution is selected. The analysis is known as dominance-inferior analysis (Revelle, Whitlatch and Wright 2004) because various scenarios are compared to see which one is dominated and which one is not (deemed non-inferior). Traditional analysis consisting on a comparison of total value per objective per scenario at the end of analysis period for the entire network was expanded by looking at annual mean values per objective per scenario, which in fact reflects annual performance. Normally, the highest values for pavement conditions and the least values for safety indexes lead to the most desirable solutions. However, the performance part of the analysis allowed to clearly visualize performance of every objective during its lifespan. Indeed, the more sustained a performance curve was the higher the chance of selecting such alternative as the most optimum solution.

### *3.5.3 A Two-Stage Optimization Process*

At the end and after explaining definitions, equations and terminology within the body of this chapter, an overall flowchart of the optimization process used in this study is presented. It is noteworthy that the exact amount of budget required for maintain good LOS may be unknown or may not match current levels of funding. Thus, a two stage optimization was applied on the system in order to obtain minimum required budget to achieve optimal levels of service (Figure 3.3)

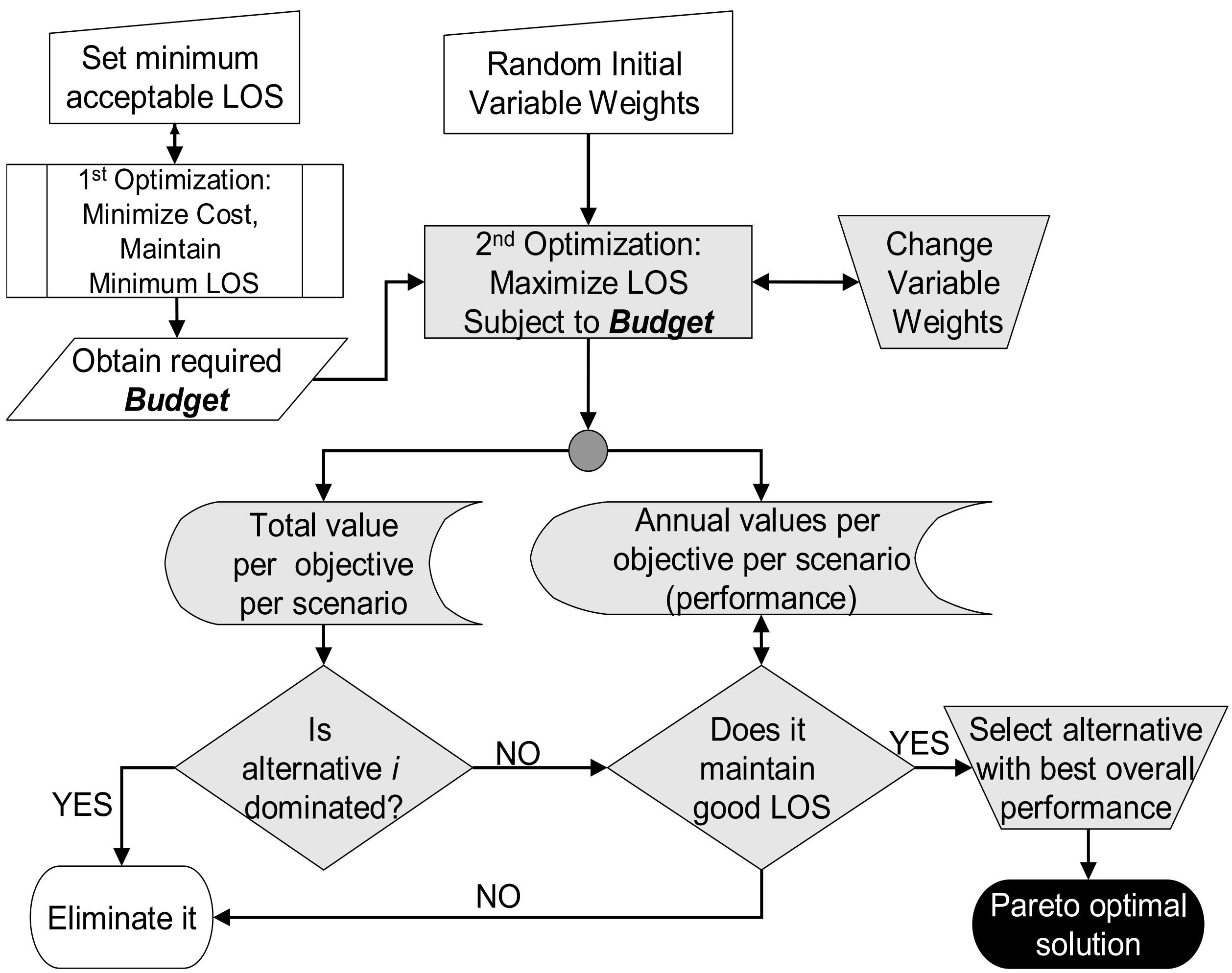



Figure 3.3 A two-stage optimization process

At the first stage, total cost of actions is put as the objective to be minimized subjected to certain desired levels of service. At the end of this stage, the result is the minimum required budget to achieve good LOS which is entered as the constraints for the second stage. The mathematical expression of the first stage is shown in equations 3-10 and 3-11:

$$\text{MINIMIZE: } Z = \sum_{t=1}^{T}\sum_{i=1}^{b}\sum_{j=1}^{J} C_{t,j} x_{t,i,j} L_i \qquad [3\text{-}10]$$

Subject to:

$$\sum_{t=1}^{T}\sum_{i=1}^{b} L_i Q_{t,i} \geq \sum_{t=1}^{T}\sum_{i=1}^{b} L_i Q_{t-1,i}$$

$$\sum_{t=1}^{T}\sum_{i=1}^{a} PFI_{t,i} L_i \leq \sum_{t=1}^{T}\sum_{i=1}^{a} PFI_{t-1,i} L_i \qquad [3\text{-}11]$$

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

Where: $x_{t,i,j}$ *and* $y_{t,i,j}$ = {*0, 1*}; "*1*" if treatment *j* is applied on asset *i* on year *t*, "*0*" otherwise

$Q_{t,i}$ = Condition Index for asset *i* on year *t*
$PFI_{t,i}$ = Potential For Improvement for asset *i* on year *t*
$C_{t,j}$ = Unitary cost ($) of treatment *j* on year *t*
$L_i$ = length of road segment *i* (Km).

Now, at the second stage, levels of service are entered as objectives and the constraint is the minimum budget obtained in the previous stage. Here, different weights are associated to objectives to create an aggregated global objective. Mathematical expression of the second stage is shown in equations 3-12 and 3-13:

$$\text{MAXIMIZE } Z = \alpha_1 \sum_{t=1}^{T}\sum_{i=1}^{a} L_i Q_{t,i} - \alpha_2 \sum_{t=1}^{T}\sum_{i=1}^{b} PFI_{t,i} L_i \qquad [3\text{-}12]$$

$$\text{Subject to}: \sum_{t=1}^{T} \sum_{i=1}^{b} \sum_{j=1}^{J} C_{t,j} x_{t,i,j} L_i \leq B_t \qquad [3\text{-}13]$$

Where: $\alpha 1$ and $\alpha 2$ variable weights for the analysis for asphalt pavements and road safety (correspondingly)

$x_{t,i,j}$ and $y_{t,i,j}$ = binary decision variables; road $i$ to receive treatment $j$, on year $t$

$Q_{tij}$ and $PFI_{tij}$ = condition and Potential For Improvements of asset $i$ on period $t$ after receiving treatment $j$ and

$L_i$ = length of road segment $i$ (Km).

$B_t$ = Annual Budget on year $t$

$C_{t,j}$ = Unitary cost ($) of treatment $j$ on year $t$

Allowing weights to vary, different scenarios are generated and are compared based on two criteria as explained before. If a scenario passes the two criteria, it will be shortlisted. Finalist scenarios are then compared and an optimum solution can be selected by the decision maker.

# CHAPTER 4
# AN INITIAL ROAD MANAGEMENT SYSTEM FOR OPTIMIZING PAVEMENT CONDITIONS AND ROAD SAFETY: A CASE STUDY OF TANZANIA

## 4.1 Abstract

Initial implementations of pavement management systems seem to ignore road safety and pay more attention to condition. However, road fatalities are of such magnitude that United Nations recently launched a "Decade of Action for Road Safety 2011-2020" in an attempt to reduce fatalities around the world. Pavement management should consider means to reduce crash frequencies by allocating corrective measures to mitigate exposure and, reduce severity and likelihood. However, data availability normally impedes such incorporation. This paper presents a case study for the initial development of road management systems in Tanzania. Indices for safety and surface condition were developed. Dominance and performance criteria were applied for selecting a solution that achieved and sustained optimal levels of service in both indicators. Safety and condition deficiencies were corrected within 5 years with the majority of improvements dedicated to surface treatments and some geometric corrections. The lack of safety audits resulted in an inability to predict long term deficiencies. Three generic corrective measures were created to account for such unknown issues and deployed after the first tactical plan.

## 4.2 Background

It is typical for initial implementations of pavement management systems to face shortages of information. Even if an agency has a track record of collected information, it is not rare that at the time of implementation, new needs for data may appear. At such a point two decisions are possible: to collect the required information (expending a few additional years) or, to use what is available to obtain a first cut model, capable of demonstrating the advantages of implementing a management system, improving such a model as new data becomes available in the future. In many cases this also goes in line with taking advantage of a favorable political climate.

Traditionally, initial implementations of road management systems are dedicated to achieve optimal levels of condition while dealing with budget restrictions (Haas *et al.,* 1994, Tighe *et al.,* 2001). Other important objectives (i.e., mobility, safety, accessibility and social cost) are normally left for a future stage (Feunekes *et al.* 2011). Engineers have historically considered skid resistance as the mean to incorporate safety into pavement management (Ong and Fwa 2007), however this approach is deficient as it lacks of a full consideration of the ample range of factors related to accident likelihood, exposure and severity. It was a decade ago that a framework with a comprehensive list of factors for a more integral incorporation of road safety was proposed (Tighe et *al.,* 2001). Even though such an approach recognized the presence of human, road and vehicle factors when explaining accidents (collisions), it was clear that safety-improvements can only mitigate their impact (Odgen 1996). Since the point of view of pavement management, direct countermeasures only exist for road factors. Human and vehicle factors can only be mitigated due to their random nature, by improvements mostly in the form of safety hardware (i.e., guardrail, rumble strip) reducing accident's severity. In addition, the allocation of safety improvements relies on performance based on observed collisions, failing to consider conflicts. The absence of such a variable could mislead decisions when conflicts turn into accidents, if traffic volumes surpass certain thresholds or when enforcement drops (PIARC 2003).

Several attempts have been made to develop a management framework with a decision making system capable of combining two or more objectives. Computing software such as HDM-III (Watanatada *et al.,* 1987) and HERST (FHWA 2009) recognized the need to incorporate several objectives in the analysis, however, their formulation was based on the monetization of all objectives to achieve a common dimension and, their analytical frameworks relied on lifecycle cost-benefit analysis. This chapter uses a direct consideration of safety and condition indicators; it applies traditional linear programming formulation for allocating investments and finding mean annual budget requirements for sustaining good levels of safety and condition. A case study of the Tanzania road network, where limited information was available, is employed to establish a first cut model. This model explicitly considers several individual safety issues and proposes -in the understanding of its limitations- a method capable of balancing dissimilar units which translates into a budget exercise capable of supporting strategic planning. The author does recognized the need to complemented and expand this initial model as new data becomes available in the future (from in service road safety audits).

## 4.3 Objective

To develop an initial road management system for two objectives: condition and safety, under constrained availability of information and to prepare a strategic analysis in order to identify required levels of budget to achieve and sustain good levels of service in road safety and pavement condition.

## 4.4 Methodology

### *4.4.1 Safety Performance model*

Performance models for condition and safey are well documented in the literature (Watanatada 1987, Haas *et al.,* 1994, Paterson and Ottoh-Okine 1992), for safety, performance models can take the form of a safety index that changes across time (De Leur and Sayed 2002) or a measure that captures the potential for improvement (Hauer 1997, Anasttasopoulos and Mannering 2008).The latter considers, the unavoidable amount of accidents related to the randomness of human errors and vehicle failures (El-Basyouny and Sayed 2010). It serves as a base level in the prioritization of improvements when contrasted with predicted accident frequencies.

A safety index, based on exposure, severity and accident likelihood (probability), was developed in this case study on the basis of fundamentals in the literature (De Leur and Sayed 2002*)* in the absence of a record of accidents that could be correlated with a set of causal factors (fixed, random or variable) for the development of a more refined safety performance model. Each of the aforementioned elements (exposure, severity and likelihood) was given a factor from zero (negligible) to three (deficient). All factors were combined by multiplying their individual effects to obtain a final safety index for each segment of the network (Equation 4-1). A factor of three was derived from each element resulting in a factor of 27 behind the whole equation. Each variable in the equation was normalized by the maximum amount along the road network resulting in a 0 to 27 scale calibrated to produce safety performance models by fitting traffic progression from very low volume roads to nearly levels of service of saturation (between LOS C and LOS D). Land use was used to establish a functional classification of the roads due to the lack of information on traffic volumes. Some DOTs have used functional classification to segregate the network on different levels of traffic intensity. Same work was applied in this study and six performance curves were developed based on land use and severity levels of the Safety Index in order to differentiate the performance behavior of Safety Index in different conditions of traffic volume and safety index. Three levels of severity for safety index including low from 0 to 3, medium 3 to 9 and high 9 to 27 in addition to two levels of traffic intensities, urban and rural, were used to develop safety performance curves as it is illustrated in figure 4.1.

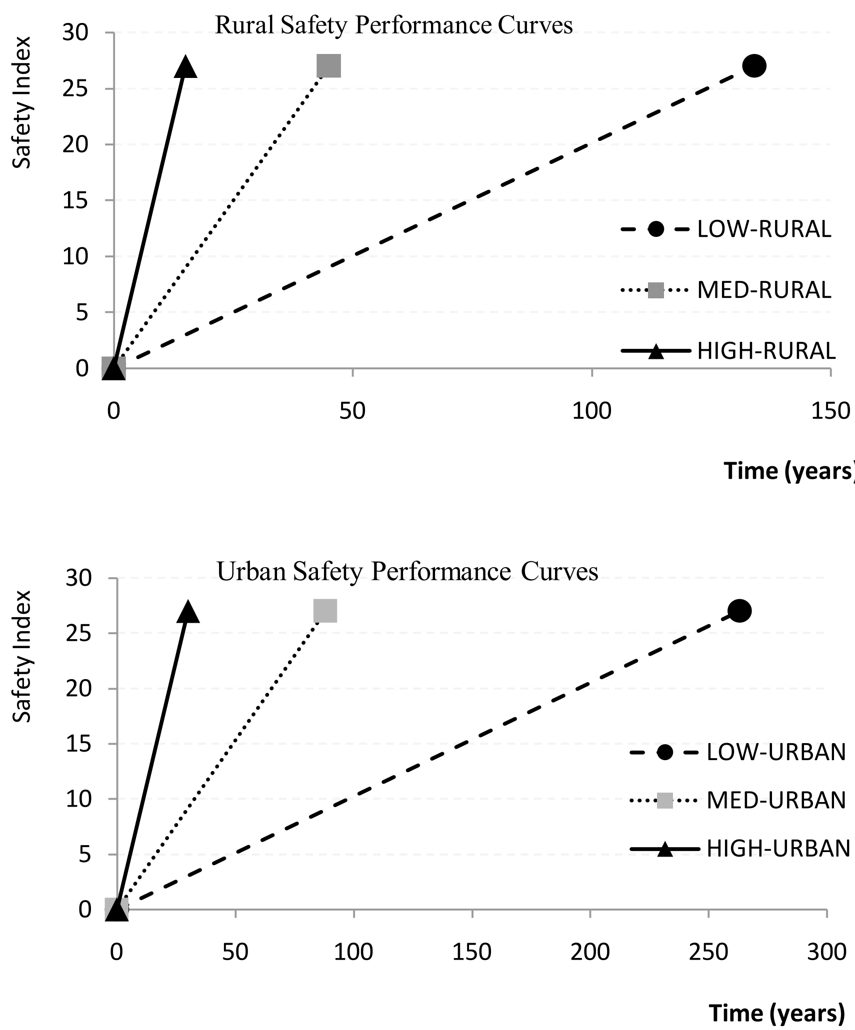



Figure 4.1 Safety performance curves for rural and urban areas

Further a traffic index ($V_i$) per land use was created; assuming values in the zero to one scale, for four land uses (Urban, Interurban, Rural, Forest Reserve). Based on this, a combined factor for severity and exposure was obtained by adding such traffic index with a normalized ratio of length (L), for each segment. The proposed mathematical formulation of safety index is given in equation 4-1.

$$SI = 27\left(\frac{V_i}{V_{MAX}}\frac{L_i}{L_{MAX}}\right)\left(\frac{S_i}{S_{MAX}}\right)\left[\frac{CF_{i1}}{6}+\cdots+\frac{CF_{i6}}{6}\right] \quad [4\text{-}1]$$

Where: $V_i$ and $V_{MAX}$, $L_i$ and $L_{MAX}$ and $S_i$ and $S_{MAX}$ = traffic volume index, length and speed at the $i^{th}$ segment and maximum value in the network, correspondingly. $CFi_1$ to $CFi_6$ = contributing factor of likelihood including the presence of guardrail, shoulder conditions, road alignment, surface raveling, surface bleeding and lane width.

Pavement Deterioration models followed traditional shaped curves created by the author in the absence of sufficient information to create curves based on historical observations.

### *4.4.2 Treatments for safety and condition*

Two treatments for surface were identified: microsurfacing (to correct minor rutting issues) and mill-overaly (to correct major rutting and bleeding). Tables 4.1 summarize safety treatments effectiveness represented by extension of service life (in gain of years) or gain in safety index, and their cost. It should be noticed that, microsurfacing and mill-and-overlay treatments could be triggered by either objective (safety or condition), their effectiveness in terms of safety are the same because they correct all surface deficiencies. In the absence of local information on cost, each improvement in the model was given a value based on 2007 CAD$ per lane-meter as observed in the province of New Brunswick (Feunekes *et al.* 2011). Three levels of safety index were established (low, medium and high), and the network was segmented accordingly. Low safety index went from zero to three, medium from three to nine and high from nine to twenty seven.

Effectiveness was based on the following assumptions: road realignment will eliminate not only geometric issues but will also correct pavement surface, shoulder and lane deficiencies. Therefore effectiveness of realignment was based on a reset to the base level of the safety index due to the correction of all 6 factors in the likelihood of the model, it should be noticed that this did not reset the safety index to zero because of the presence of random factors as explained before. Any corrections on shoulder or lane width will reset the individual component of safety to zero but only partially improve the overall safety index. Any treatment correcting surface problems (rutting or bleeding) will be treated similarly contributing only partially to reduce the overall safety index. In addition, it will have an effect in pavement condition. Three generic safety improvements were allocated in the model (as explained before) in order to account for the existence of other safety issues for which information was unavailable, in addition to future safety deficiencies not currently identified but linked to increases in traffic growth. The three generic improvements obey different levels of required corrections, namely: minor, medium and major road safety issues. Generic future treatments are shown in table 4.2 in the following.

Table 4.1 Treatment Effectiveness (Gain in years or in Safety Index) and Cost (CAD$)

| | | URBAN LOCATION | | | RURAL LOCATION | | | CAD$ / meter |
|---|---|---|---|---|---|---|---|---|
| | PFI | Low | Medium | High | Low | Medium | High | |
| ROAD SAFETY IMPROVEMENT | Realignment | Reset to $SI_0$ | Reset to $SI_0$ | Reset to $SI_0$ | Reset to $SI_0$ | Reset to $SI_0$ | Reset to $SI_0$ | 600 |
| | Mill and overlay | 15yrs or ΔSI=4.05 | 9 yrs or ΔSI=8.10 | 3 yrs or ΔSI=8.10 | 12 yrs or ΔSI=3.37 | 6 yrs or ΔSI=6.75 | 3 yrs or ΔSI=6.75 | 200 |
| | Micro-surfacing | 15 yrs or ΔSI=4.05 | 9 yrs or ΔSI=8.10 | 3 yrs or ΔSI=8.10 | 12 yrs or ΔSI=3.37 | 6 yrs or ΔSI=6.75 | 3 yrs or ΔSI=6.75 | 50 |
| | Widening Shoulder | 5 yrs or ΔSI=1.35 | 3 yrs or ΔSI=2.7 | 1 yrs or ΔSI=2.7 | 4 yrs or ΔSI=1.13 | 2 yrs or ΔSI=2.25 | 1 yrs or ΔSI=2.25 | 75.6 |
| | New Shoulder | | | | | | | 151.2 |
| | Guardrail | | | | | | | 62.5 |
| | Lane Widening | | | | | | | 55 |

KEYS: $SI_0$ = Initial road safety index, ΔSI = gain in safety index. Low, medium, high = Safety Index

Table 4.2 Future Generic Treatment Effectiveness (Gain in years or in Safety Index) and Cost (CAD$)

| | | URBAN LOCATION | | | RURAL LOCATION | | | CAD$ / meter |
|---|---|---|---|---|---|---|---|---|
| | PFI | Low | Medium | High | Low | Medium | High | |
| GENERIC TREATMENTS | Major safety issues | Reset to $SI_0$ | Reset to $SI_0$ | Reset to $SI_0$ | Reset to $SI_0$ | Reset to $SI_0$ | Reset to $SI_0$ | 500 |
| | Medium safety issues | 15yrs or ΔSI=4.05 | 9 yrs or ΔSI=8.10 | 3 yrs or ΔSI=8.10 | 12 yrs or ΔSI=3.37 | 6 yrs or ΔSI=6.75 | 3 yrs or ΔSI=6.75 | 200 |
| | Minor safety issues | 5 yrs or ΔSI=1.35 | 3 yrs or ΔSI=2.7 | 1 yrs or ΔSI=2.7 | 4 yrs or ΔSI=1.13 | 2 yrs or ΔSI=2.25 | 1 yrs or ΔSI=2.25 | 50 |

Treatments dedicated to improve pavement condition are presented in Table 4.3. Effectiveness was modeled by an extension of service life. Reconstruction resulted in a full correction of road safety (including alignment) and rejuvenation of both: structure and surface.

Table 4.3 Treatment Effectiveness for Pavements (lifespan extension in years) and Cost

| | | | **AC-HIGH** | **AC-LOW / ST-HIGH** | **ST-LOW** | **Cost, CAD$ per meter** |
|---|---|---|---|---|---|---|
| CONDITION | ASPHALT | Crack sealing | YR 2 | YR 3 | - | 2 |
| | | Micro-surfacing | YR 7 | YR 8 | - | 50 |
| | | Mill and overlay | YR 9 | YR 10 | - | 200 (per lane) |
| | | Major Rehabilitation | YR 15 | YR 22 | - | 300 (per lane) |
| | | Reconstruction | Back to zero | Back to zero | - | 500 (per lane) |
| | SEALED | Second Seal | - | YR 6 | YR 6 | 14 |
| | | Minor Rehabilitation (level and reseal) | - | YR 10 | YR 10 | 26 |
| | | Double Seal (pulverize & seal) | - | YR 14 | YR 14 | 46 |

KEYS: AC = Asphalt, ST = Surface treatment, HIGH and LOW = intensity of transit.

### *4.4.3 Optimization model*

A multiobjective formulation based on linear programming optimization was used for this case study. Detailed mathematical formulations of linear programming optimizations for condition or safety can be found elsewhere (Watanatada *et al.* 1987, Lytton 1994, Li and Madanu 2008). Equations 4-2 and 4-3 summarize the mathematical formulation for this case study.

$$\text{MAXIMIZE } Z = \alpha \sum \sum L_i Q_{tij} + \beta \sum \sum S_{tij} L_i \qquad [4\text{-}2]$$

$$\text{Subject to}: \sum_{t=1}^{T} \sum_{i=1}^{b} \sum_{j=1}^{J} C_{t,j} x_{t,i,j} L_i \le B_t \qquad [4\text{-}3]$$

Where: $\alpha$ and $\beta$ are variable weights for the analysis, $x$ is a binary decision variable for safety or condition, $Q_{tij}$ and $S_{tij}$ = condition and safety index of asset $i$ on period $t$ after receiving treatment $j$ and $L_i$ = length of segment $i$, $C_{t,j}$ = Unitary cost ($) of treatment $j$ on year $t$ and $B_t$ = Annual Budget on year $t$.

The formulation herein presented, explicitly incorporates indices from two conflicting objectives instead of monetizing them. A global objective resulting from combining both safety and condition through a weighted sum (Revelle et al., 2003) was used to examine the dominance of one over the other by changing the variable weights $\alpha$ and $\beta$ (i.e., different relative importance of the objectives).

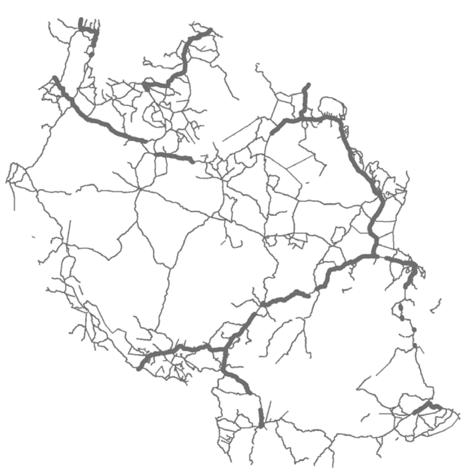
Results from the optimization procedure used to identify the non inferior set of possible solutions meaning the least safety index and the highest pavement condition index is the most desirable alternative, were further refined using a performance criterion that compares the degree of achievement and capacity to sustain good results across time.

## *4.5* Case Study – sections of the Tanzania road network

### *4.5.1 The Tanzania Road Network*

Tanzania's is a low income country with an estimated road network of 86,000 Kilometers (Figure 4.2) of which 7% are paved roads. In terms of safety, fatalities reached 2,595 in 2007 which translates to 5.8 per 100,000 people (World Bank 2011). For a country with a GDP per capita of $514 (in 2010) this goes in line with the findings of Koptis and Cooper (2005) and Mumford (2011), therefore one can argue that, as the country develops, there is a very high likelihood of reaching levels between 16 and 25 fatalities per 100,000 as predicted by the aforementioned models. This outlines the need for developing a road management system that considers safety to mitigate such tragedies.

The first step for the model was to prepare a joint database for safety and condition. Safety data was available in geospatial format, meanwhile condition information was found in a spreadsheet. Both databases were merged based on route and link number. The latter produced a subset of records of approximately 3,000 km of paved roads (distinguished in Figure 4.2). In particular they consisted on (a) records of condition: IRI, rut depth, bleeding, raveling, shoulder condition, (b) geometric data: shoulder width, lane width, horizontal and vertical curves, existence of guardrail, (c) other information: land use, pavement surface condition, presence of vegetation and drainage condition. Figure 4.2 also presents a summary of segment counts per level of deficiency. Deficiency for roughness (IRI) ranged from 0 (none) to 5 (very deficient), for rutting from acceptable (0) to deficient (1) to highly deficient (2), raveling and bleed strip range from acceptable (0) to highly deficient (5), guardrail, shoulder, alignment and lane width deficiencies ranged from none (0) to very high (4).



| **Deficiency** | **0** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|---|
| Roughness[1] | 0 | 279 | 2034 | 5214 | 1131 | N/A |
| Rutting | 3069 | 3927 | 1155 | N/A | N/A | N/A |
| Raveling | 4182 | 1929 | 696 | 918 | 282 | 144 |
| Bleed strip | 6390 | 327 | 96 | 558 | 114 | 666 |
| Guard rail | 8256 | 234 | 117 | 51 | N/A | N/A |
| Improve Shoulder | 6 | 252 | 4026 | 4374 | N/A | N/A |
| New Shoulder | 5787 | 2559 | | 312 | N/A | N/A |
| Alignment | 3486 | 1404 | 567 | 3201 | N/A | N/A |
| Lane Width | 732 | 180 | 6852 | 891 | N/A | N/A |

Keys: [1] very good IRI < 1.5, good IRI from 1.5 to 2, fair from 2 to 3, poor from 3 to 5 and very poor > 5.

Figure 4.2 Tanzania Road Network and Inventory of deficiencies (segment counts)

### *4.5.2 Safety Performance Modeling*

Six safety performance models were developed for Tanzania depending on land use and safety index. Land use was divided into urban and rural. According to the World Bank (2011), economic development of Tanzania reached 6% of GDP growth in 2009 and, population growth for the same year near to 3%. Both amounts were assumed to correlate to rural and urban development, and to traffic growth. Thereafter maximum traffic capacity per lane was based on 1800 vehicles per lane per hour. The lifespan of any segment, for safety performance, was limited by such level of service and derived from the traditional equation of compound growth.

Factor of likelihood (Equation 4-1) was based on six contributing factors as follows: pavement surface from roughness, skid resistance from raveling and bleeding records, adequate coverage of guardrail from length of horizontal and vertical curves combined with roadside grades, shoulder adequacy (width and surface), lane width compliance (standard width from 3.5 to 3.7 meters) and intensity of curves (vertical and horizontal). Specific safety improvements were established for each of those factors as shown on Table 4.1. No data was available for other elements (i.e., pavement marking, traffic signs and etc.). They should, however, be included in future updates of the model when such information becomes available.

## *4.6* Results and discussion

A first analysis was conducted to identify required levels of budget to achieve optimal values of safety and condition (Figure 4.3), budget fluctuated from zero to forty three millions, and with an average of CAN $12.91 million dollars per year to achieve optimal levels of service (Scenario G). With such a budget it was possible to achieve and maintain optimal values of both condition and safety indexes, while minimizing expenditure (Scenario G, Figures 4.3 and 4.4). The analysis proceeded by running a series of scenarios based on variable levels of budget aimed to minimize safety issues and maximize condition, it was found that sustainable results could be achieved with as little as CAN$8 million (Scenarios A to F).

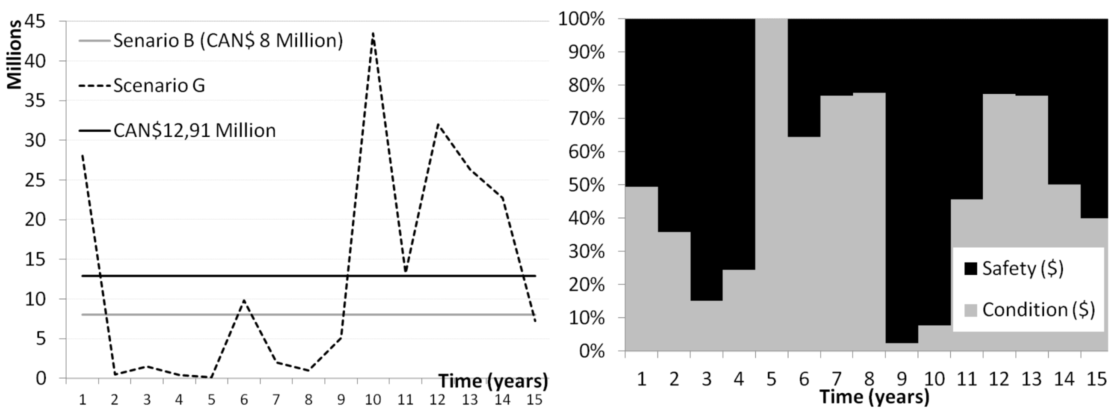



Figure 4.3 Mean annual expenditure and budget allocation for Scenario B.

A weighted global objective (Equation 4-2) was used to combine condition and safety. Variable weights α and β were used to establish six scenarios intended to determine the ideal solution. A two stage analysis followed; first by determining dominance criteria for every scenario, during a 15 year period of analysis and fixed budget of CAN$ 8 million and, secondly, by looking at the performance criteria of each non inferior solution. Scenarios C, D and E were dropped off the analysis, because they were inferior and dominated by scenario B (Table 4.4). Plots of performance (mean levels of network safety and condition) across time were used to determine the goodness of each solution in terms achievement and sustainment of acceptable results (Figure 4.4). Alternatives A and

F were discarded after analyzing their performance and realizing that they produced solutions that achieved better values of one objective in detriment of the other one (Figure 4.4).

Table 4.4 Dominance and Performance Criteria for a fixed budget of CAN$8 million

| ***Scenario*** | ***Objective 1 ($\alpha$)*** | ***Objective 2 ($\beta$)*** | ***MAXIMIZE Pavement Condition*** | ***MINIMIZE SAFETY INDEX*** | ***DOMINANCE CRITERIA*** | ***PERFORMACE CRITERIA*** |
|---|---|---|---|---|---|---|
| A | 0.9 | 0.1 | 361.4E+07 | 2.2E+07 | Non Inferior | PCI dominated |
| B | 0.7 | 0.3 | 357.2E+07 | 2.0E+07 | Non Inferior | Final Solution |
| C | 0.5 | 0.5 | 356.1E+07 | 2.0E+07 | Dominated by B | |
| D | 0.4 | 0.6 | 355.3E+07 | 2.0E+07 | Dominated by B | |
| E | 0.3 | 0.7 | 351.4E+07 | 2.0E+07 | Dominated by B | |
| F | 0.1 | 0.9 | 325.8E+07 | 1.9E+07 | Non Inferior | SI Dominated |

Note: Scenario G is not included because it has a variable budget

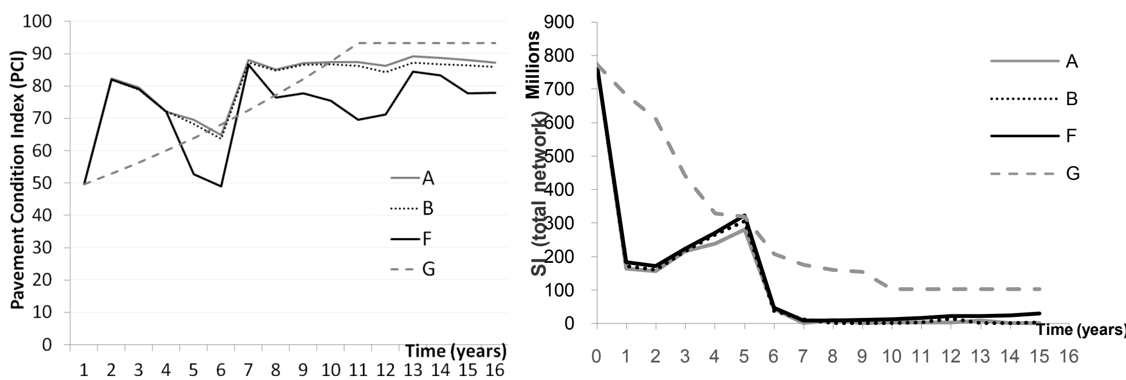



Figure 4.4 Mean Network Condition and total Safety Index for the network

It was confirmed that, as suggested in the literature (Haas *et al.,* 1994), applying a silo approach (1 million for safety and 7 million for condition) based on alternative B (Scenario B1) worsen the results by producing a shift that delayed the recovery rate of both safety and condition (Figures 4.5 and 4.6). Such a delay signifies higher social cost in the form of avoidable collisions and safety issues (property damage, fatalities and injuries), economic losses (vehicle operating cost, passenger hours) and regional productivity drop in competitiveness from deferred maintenance and rehabilitation.

It was found that the approach of maximizing condition and minimizing safety by means of a global objective with relative weights of 0.7 and 0.3 for condition and safety (correspondingly) produced almost as good results as the optimization with variable levels of budget (Scenario G) but with a much lower and stable budget requirement (38 % less).

It was noticed that, disregarding the scenario, the amount of roads with safety issues, reached similar values towards year 5, this can be explained by the fact that the corrections of known safety issues finalized at that time and an increase of traffic growth produced a rise in related safety issues for which the provision of a generic treatment was introduced in the system to model future issues that are unknown at this time.

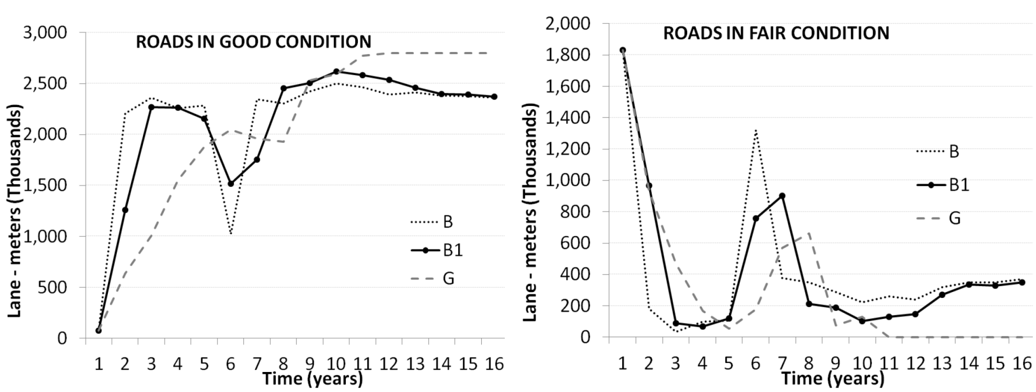



Figure 4.5 Qualitative Progression of Road Condition

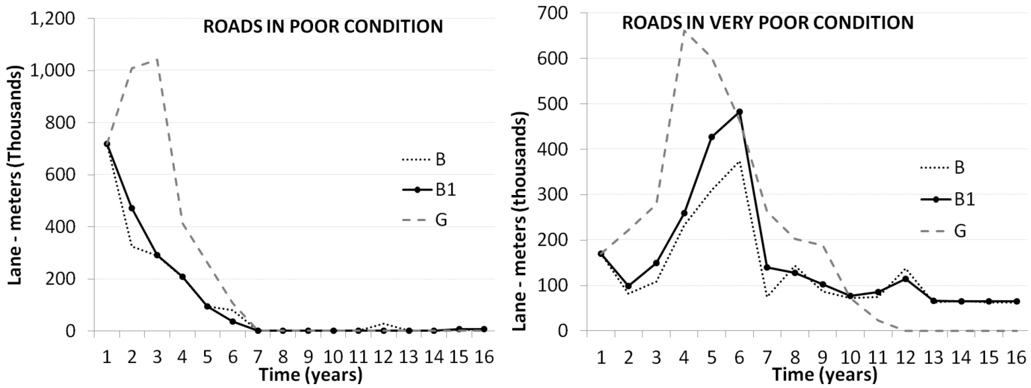



Figure 4. 6 Qualitative Progression of Road Condition

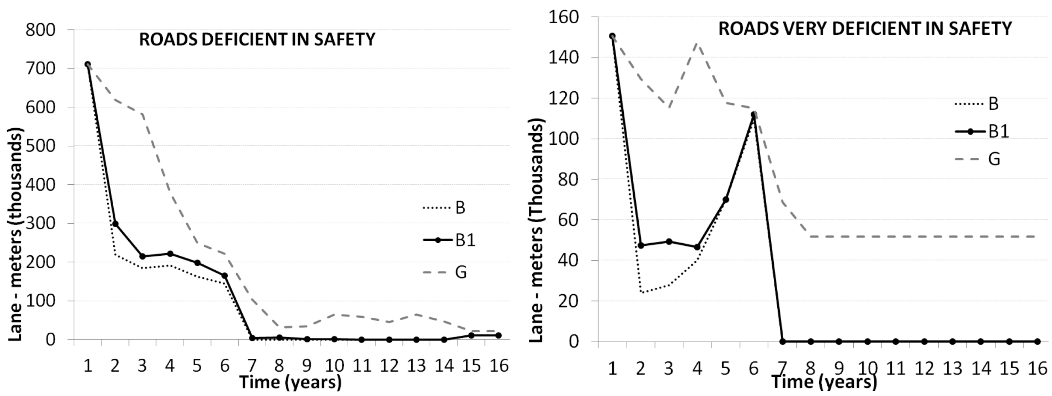



Figure 4.7 Qualitative Progression of Road Safety.

As seen before (Figure 4.6), scenario B not only represented a more balanced solution by allocating treatments for improving road condition and reducing safety issues during the analysis period but also requiring lower and certain (stable) levels of budget. Tables 4.5 and 4.6 show the allocation of resources on both objectives of Scenario B (two levels of budget). For the CAN$8 million budget, it was observed that the system focused more on applying individual treatments than realigning roads. In particular surface treatments received the large majority of funding allocated for road safety and condition combined, followed by some investments in shoulders.

An increase in budget to $12.91 million dollars, for the same scenario (B), resulted in a very similar allocation of resources as shown on Table 4.6. Minor differences can be observed such as some heavy investments towards correcting geometric deficiencies in years two and three, which resulted in combined safety and condition improvements.

It was observed that disregarding levels of funding, resources were used in years 1 to 5 to stabilize safety and condition, thereafter investing on preserving both objectives at acceptable levels. However, this observation contradicts future needs on capital upgrades to correct inadequacy of crossings and intersections once traffic volumes have surpassed certain thresholds, for which a deeper understanding of deficiencies from in service audits is required.

Table 4.5 Investments Allocation with CAN$8 million - Scenario B (in Thousands of CAN$)

| Period | Shoulder Improvement | New Shoulder | Mill and overlay | Micro surface for Safety | Safety minor | Safety Major | Crack sealing | Micro surface for Condition | Minor Rehabilitation | Major Rehab | Second Seal |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1,921 | 2,117 | 0 | 0 | 0 | 0 | 0 | 3,269 | 679 | 0 | 14 |
| 2 | 71 | 3,563 | 29 | 1,463 | 0 | 0 | 0 | 1,690 | 1,025 | 0 | 158 |
| 3 | 23 | 1,040 | 68 | 5,663 | 0 | 0 | 156 | 157 | 210 | 241 | 441 |
| 4 | 95 | 142 | 134 | 5,666 | 0 | 0 | 186 | 107 | 0 | 645 | 1,024 |
| 5 | 3 | 0 | 0 | 0 | 0 | 0 | 9 | 7,077 | 0 | 0 | 910 |
| 6 | 0 | 0 | 0 | 0 | 1,629 | 242 | 14 | 5,137 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 1,843 | 0 | 175 | 5,981 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 1,780 | 0 | 46 | 6,174 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 1,941 | 0 | 10 | 182 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 1,870 | 0 | 17 | 607 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 1,882 | 0 | 191 | 3,467 | 0 | 0 | 0 |
| 12 | 30 | 0 | 0 | 0 | 1,780 | 0 | 0 | 6,190 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 1,843 | 0 | 7 | 6,150 | 0 | 0 | 0 |
| 14 | 38 | 0 | 0 | 0 | 1,812 | 0 | 0 | 4,013 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 1,885 | 0 | 0 | 3194 | 0 | 0 | 0 |

Table 4.6 Investments Allocation with CAN$12.91 million - Scenario B (in Thousands of CAN$)

| Period | Realignment | Shoulder Improvement | New Shoulder | Mill and overlay | Micro surface for Safety | Safety minor | Safety Major | Crack sealing | Micro surface for Condition | Minor Rehabilitation | Major Rehab | Second Seal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1,975 | 5,104 | 0 | 600 | 0 | 0 | 0 | 2,495 | 1,953 | 600 | 182 |
| 2 | 4,025 | 53 | 820 | 149 | 5,225 | 0 | 0 | 0 | 717 | 1,669 | 0 | 250 |
| 3 | 10,977 | 24 | 714 | 76 | 315 | 0 | 0 | 0 | 157 | 210 | 0 | 436 |
| 4 | 247 | 88 | 223 | 0 | 6,355 | 0 | 0 | 4 | 4,924 | 215 | 0 | 853 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12,144 | 0 | 0 | 766 |
| 6 | 0 | 0 | 0 | 0 | 0 | 1,629 | 213 | 0 | 10,390 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 1,823 | 0 | 0 | 11,087 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 1,774 | 0 | 22 | 11,055 | 0 | 0 | 0 |
| 9 | 0 | 4 | 0 | 0 | 0 | 1,909 | 0 | 0 | 5,837 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 1,773 | 0 | 0 | 11,137 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 1,826 | 0 | 0 | 10,847 | 0 | 0 | 0 |
| 12 | 0 | 13 | 0 | 0 | 0 | 1,773 | 7 | 0 | 11,117 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 1,829 | 17 | 0 | 11,063 | 0 | 0 | 0 |
| 14 | 0 | 23 | 0 | 0 | 0 | 1,911 | 0 | 0 | 3,238 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 2,004 | 0 | 0 | 0 | 0 | 0 | 0 |

Even though this first allocation of investments was used for a strategic analysis, a coordination of treatments for safety and condition will be required to prepare tactical and operational plans. A more detailed knowledge of all safety issues (pavement marking, traffic signs, etc) impedes to perform a reliable coordination at this initial stage. It is recommended that in service road safety audits be conducted in the network in order to better typify safety deficiencies in order to refine this first cut model.

## *4.7* Conclusions

This paper has illustrated the initial development of a network level lifecycle-optimization for road safety and pavement condition. The proposed model developed safety performance models based on land use and potential for improvement. Ability to predict long term road safety deficiencies was limited to site-specific issues which can only be learnt from safety audits. Therefore safety deficiencies were split into known and unknown. Known safety issues were corrected in about five years, traffic growth was used, from that point on time, to reflect the increase in unknown safety related issues and, generic safety corrective actions, at three different levels (surface corrections, new hardware and realignment), were incorporated in the analysis to consider investments needs in a long term budget exercise. In practice, tactical and operational planning will require in service safety audits to identify deficiencies in order to prepare future tactical plans.

Traditional dominance analysis, complemented by observing road safety and pavement condition performance, was used to identify recommended weights to combine both objectives into a global indicator for the linear programming optimization. It was found that traditional practices of achieving and sustaining good levels of service would have demanded a mean annual budget of almost CAN$13 million, with large variations on budget requirements (base case), meanwhile a maximization scenario with a fixed budget of $8 million, for a weighted objective (0.3 and 0.7 for condition and safety, correspondingly), resulted in almost as good results as the base case but, in average with 38% less budget. It was observed that known safety deficiencies got corrected during the first 5 years, disregarding level of funding. The majority of the investments were allocated in surface-related treatments that helped improve both: condition and safety (i.e., micro surfacing). When more resources were available, large investments for correcting geometric issues were observed in years two and three which translated into joint safety and condition improvements.

It was demonstrated that, although an important portion of the resources were invested in surface treatments, the sole use of skid resistance to correct surface defects related to safety would have failed to incorporate other safety deficiencies for which data was readily available.

Results from this paper should be understood within the aim to have a first cut model, capable of providing guidance in budget requirements and of preparing a first tactical plan. It presents the opportunity to prioritize investments for improving road safety and pavement condition with a good degree of certainty in the short term, in the understanding that these results must be complemented and updated after conducting road safety audits on the entire network to better identify safety deficiencies at specific sites. In such a case, a more reasonable allocation of resources will result after allocating treatments to correct safety deficiencies related to exposure, severity and likelihood. For a low income nation as Tanzania, this first model signifies the possibility to align its management framework to be compliant with United Nations call on reducing fatalities during the 2011-2020 decade.

# CHAPTER 5
# NON-MONETIZED MULTI-OBJECTIVE DECISION MAKING SYSTEM FOR ROAD MANAGEMENT

## 5.1 Abstract

This chapter presents a performance-based optimization approach for conducting tradeoff analysis between safety (roads) and condition (bridges and roads). Safety was based on potential for improvement. Road condition was based on surface distresses and bridge condition was based on apparent age per subcomponent. The analysis uses a non-monetized optimization that expanded upon classical Pareto optimality by observing performance across time. It was found that achievement of good results was conditioned by the availability of early age treatments and impacted by a frontier effect preventing the optimization algorithm from capturing of the long term benefits of deploying actions when approaching the end of the analysis period. A disaggregated bridge condition index proved capable of improving levels of service in bridge subcomponents.

**KEYWORDS**: bridges; roads and highways; accidents; systems management; multi-objective analysis; optimization

## 5.2 Background

Civil infrastructure management seeks to achieve and sustain good levels of performance across different asset types (Patidar *et al*., 2011). Transportation agencies deal with challenging allocation of resources among competing objectives for several asset types (bridges, pavements, culverts, traffic signs, etc.) (Falls *et al.,* 2006). Lifecycle cost optimization has been extensively used to support decisions on treatment allocation across time. Based on the ability to forecast future levels of service, the analysis can be extended to road corridors or entire networks. Lifecycle cost optimization is traditionally supported by mathematical programming due to the large scale nature of managing a road corridor or a network.

Performance-based optimization (NAMS 2006) has been used in single objective applications because of its ability to forecast future levels of service and of using mathematical programming (linear and non-linear) to allocate treatments in order to achieve and maintain target levels of service across time. Dealing with two or more conflicting objectives requires accepting tradeoffs between them. Also, multiple objectives are normally measured by dissimilar units, requiring the use of monetized expressions to search for the minimum cost while attaining minimum levels of service (Watanatada *et al.* 1987). In addition, linear programming is incapable of solving for more than one objective, therefore requiring the use of approximate solutions (heuristic methods) or employing tricks to run linear programming analysis for several objectives, namely: goal programming or weighted global objective.

One way of solving a trade-off problem is by identifying a non-inferior set of alternatives (Revelle 2003). Pareto dominance analysis has been employed to guide the process of combining and selecting a final solution (Revelle 2003, Sharma *et al.*, 1999, Taber *et al.*, 2009). However, this procedure is somehow static, being incapable of dealing with changing values of the objectives across time. Additionally, there is a lack of non-monetized methods to solve multiple objective problems.

Today, transportation agencies struggle with fixed annual budgets to accomplish good levels of service in the form of roads in good condition, with low rates of accidents and good levels of mobility (Falls *et al.,* 2006, Tighe *et al.,* 2001). Pavement Management itself is a well developed field; with an accurate knowledge of deterioration and safety performance from a handful of experiments and direct observations of treatment effectiveness from treatments applied every year (AASTHO 1962*,* Watanatada 1987, Paterson and Attoh-Okine 1992*,* De Leur and Sayed 2002*,* Ong and Fwa 2007). However, for bridge and pipes, although monitoring tools are available (Rolander *et al.,* 2001), record of historical observations on bridge deterioration falls short in comparison to their lifespan. Availability of treatments for bridges reduces as one move down in the structure; while for decks and superstructures it's possible to rehabilitate, for some substructures the only option is replacement. Bridge performance still relies on expert criteria and field observations to create a health index (Falls 2006*,* Miyamoto *et al.,* 2000 ) more than on mechanistic statistical relationships of causal factors to the performance response.

This paper presents a case study of a highway corridor, lifecycle cost optimization (base case scenario) was compared with a non-monetized (performance-based) approach used to conduct tradeoff analysis on treatment allocation for achieving condition and safety goals for roads and condition objectives for bridges. Such approach was limited to a road corridor and should be expanded to incorporate other considerations of economic relevance and public demand of each road link when extrapolating this model to road network level exercises, in our case this road corridor maintained very similar levels of traffic and therefore was such criteria were neglected.

## 5.3 Objective

To propose a more accurate approach in cases of sufficient accident records available to incorporate road safety into road management systems and to conduct a trade-off performance-based optimization of competing objectives for the management of a road corridor.

## 5.4 Methodology

### *5.4.1 Lifecycle Optimization and Trade-off Analysis*

A two stage analysis was conducted: firstly an optimization analysis was used to identify required minimum levels of budget to achieve and maintain required levels of service (LOS) as expressed by safety and condition indicators (Figure 4.1). This analysis was also expected to emulate traditional lifecycle cost optimization and therefore used as the base case scenario (Watanatada et al 1987, Vitale et al., 1996, Ravirala *et al.,* 1996). Secondly a non-monetized (performance-based) optimization focused on attempting to achieve greater than required LOS for the performance of bridges and roads. Proposed equations 5-1 and 5-2 contain the mathematical formulation of the optimization algorithms used to find the required level of budget to achieve non-declining condition in roads and bridges and declining safety index (i.e., a reduction on accident rates)

Both analyses were supported by a large-scale decision-tree; containing an exhaustive generation of all possible paths of choices (and its consequences) for maintenance and rehabilitation at every time step during the lifespan of each and every asset. As such, the decision tree mapped expected values of every indicator of condition and safety (as well as associated cost) after receiving feasible treatments, and served to support the optimization. Sets of choices were selected and aggregated to produce total values per year of each objective function.

$$\text{MINIMIZE}: Z = \sum_{t=1}^{T}\sum_{i=1}^{b}\sum_{j=1}^{J} C_{t,j}x_{t,i,j}L_i + \sum_{t=1}^{T}\sum_{i=b+1}^{c}\sum_{j=1}^{J} C_{t,j}y_{t,i,j}D_i \quad [5\text{-}1]$$

Subject to:

$$\sum_{t=1}^{T}\sum_{i=1}^{b} L_i Q_{t,i} \geq \sum_{t=1}^{T}\sum_{i=1}^{b} L_i Q_{t-1,i}$$
$$\sum_{t=1}^{T}\sum_{i=b+1}^{c} D_i Q_{t,i} \geq \sum_{t=1}^{T}\sum_{i=b+1}^{c} D_i Q_{t-1,i} \quad [5\text{-}2]$$
$$\sum_{t=1}^{T}\sum_{i=1}^{a} S_{t,i} L_i \leq \sum_{t=1}^{T}\sum_{i=1}^{a} S_{t-1,i} L_i$$

$0 \leq Q_{t,i} \leq 100$ and $0 \leq S_{t,i} \leq 100$

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

Where: $x_{t,i,j}$ *and* $y_{t,i,j}$ = {*0, 1*}; "*1*" if treatment *j* is applied on asset *i* on year *t*, "*0*" otherwise

$Q_{t,i}$ = Condition Index for asset *i* on year *t*

$S_{t,i}$ = Safety Index of asset *i* on year *t*

$C_{t,j}$ = Unitary cost ($) of treatment *j* on year *t*

$D_i$, $L_i$ = Deck area ($m^2$) or length of road segment *i* (Km).

Once the base case scenario was established and its mean monetary requirements were used to obtain an annual budget, the analysis changed its purpose to optimize condition and safety across assets (2nd optimization - Figure 4.1), subject to such a budget. Equations 5-3 and 5-4 show mathematical condensed algorithms for the second part of the trade-off analysis. We used a weighted global objective. The sense of it (Equation 5-3) was to maximize, therefore safety was subtracted in order to minimize accident rates.

$$\text{MAXIMIZE} \quad Z = \alpha 1 \sum_{t=1}^{T} \sum_{i=1}^{a} L_i Q_{t,i,j} + \alpha 2 \sum_{t=1}^{T} \sum_{i=a+1}^{b} L_i Q_{t,i,j} + \beta \sum_{t=1}^{T} \sum_{i=b+1}^{c} D_i Q_{t,i,j} - \delta \sum_{t=1}^{T} \sum_{i=1}^{b} S_{t,i,j} L_i \qquad [5\text{-}3]$$

$$\text{Subject to:} \sum_{t=1}^{\mathrm{T}} \sum_{i=1}^{b} \sum_{j=1}^{J} C_{t,j} x_{t,i,j} L_i + \sum_{t=1}^{\mathrm{T}} \sum_{i=b+1}^{c} \sum_{j=1}^{J} C_{t,j} y_{t,i,j} D_i \leq B_t \qquad [5\text{-}4]$$

Where: $\alpha 1, \alpha 2, \beta$ and $\delta$ = variable weights for the analysis for asphalt pavements, sealed roads, bridges and road safety (correspondingly)

$x_{t,i,j}$ and $y_{t,i,j}$ = binary decision variables; road or bridge $i$ to receive treatment $j$, on year $t$

$Q_{tij}$ and $S_{tij}$ = condition and safety index of asset $i$ on period $t$ after receiving treatment $j$ and

$D_i$, $L_i$ = Deck area ($m^2$) **or** length of road segment $i$ (Km).

$B_t$ = Annual Budget on year $t$

$C_{t,j}$ = Unitary cost ($) of treatment $j$ on year $t$

Variable weights $\alpha 1, \alpha 2, \beta$ and $\delta$ were rescaled to remove the effect of the size of each network of assets. It should be noticed that, all roads (asphalt cement and chip-sealed) were driven by the same decision variable *x*, which allocated resources among cost and safety improvements, decision variable *y* was used to allocate resources for the improvement of any subcomponent of bridges (Equations 5-1 and 5-4).

Tradeoff analysis was conducted by extending classical Pareto (dominance) analysis to incorporate a performance criterion to consider the progression of individual indicators of every objective across time. Pareto (dominance) analysis is not new (Sharma *et al.,* 2009, Taber *et al.,* 1999), it seeks the improvement of all objectives, up to a point in which improving any one objective will result in detriment of another (dominated), therefore stopping. However, its applications are normally restricted to objectives on a single time step. Aggregating the value of the objectives for the analysis period into a total amount does help identifying a subset of alternative solutions, however, is incapable of selecting among them. To address this issue we use a lifespan performance criterion for each objective and every group of asset types to complement the Pareto analysis, to be able to identify a solution capable of maintaining good levels of service across time. Only those scenarios capable of reaching and sustaining good levels of service were selected for the final stage (Figure 5.1).

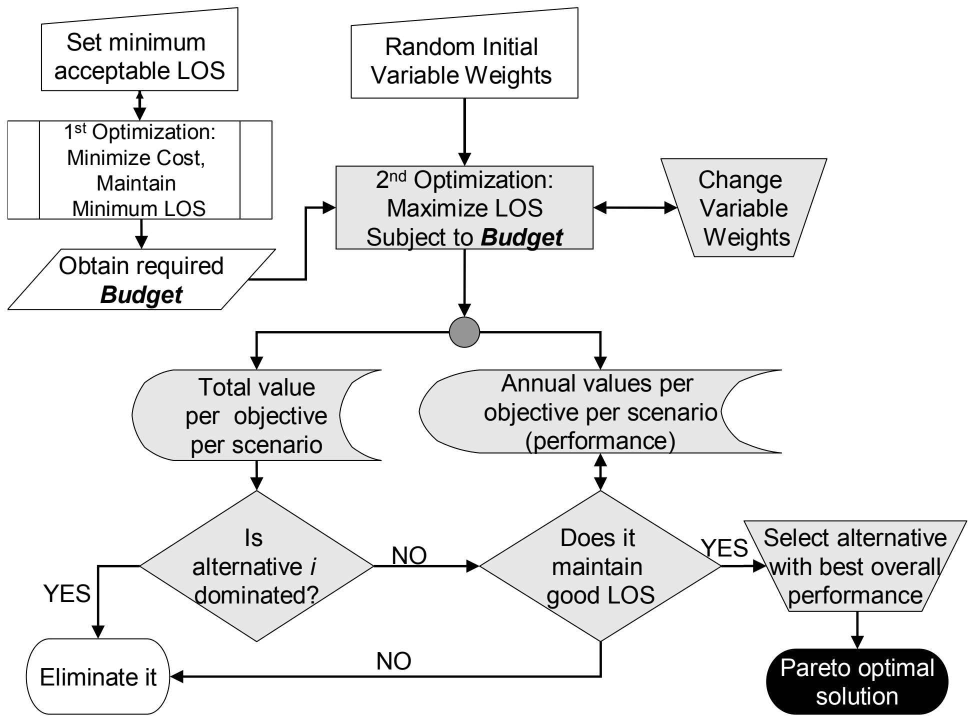



Figure 5.1 Flow Chart for Two Stage Analysis

An additional analysis was conducted by expanding Equation 5-3 (Equation 5-5) in order to disaggregate bridges by subcomponent. Constraints remained the same as shown on Equation 5-4. The term $Q_{t,i,j}$ was replaced by an equivalent expression, per asset and subcomponent type. To facilitate interpretation we used short names for each subcomponent (i.e., *SUPER* for superstructure, *SUB* for substructure) instead of variables, therefore sacrificing mathematical rigour.

$$Z = \alpha 1 \sum_{t=1}^{T} \sum_{i=1}^{a} L_i PCI_{t,i} + \alpha 2 \sum_{i=a+1}^{b} \sum_{j=1}^{J} L_i CSR_{t,i} + \beta 1 \sum_{t=1}^{T} \sum_{i=b+1}^{c} D_i DECK_{t,i} + \\ + \beta 2 \sum_{t=1}^{T} \sum_{i=b+1}^{c} D_i SUPER_{t,i} + \beta 3 \sum_{t=1}^{T} \sum_{i=b+1}^{c} D_i SUB_{it,i} - \delta \sum_{t=1}^{T} \sum_{i=b+1}^{c} S_{t,i} L_i \qquad [5\text{-}5]$$

Where: $\alpha 1, \alpha 2, \beta 1, \beta 2, \beta 3$ and $\delta$ = variable weights for the analysis,

$PCI_{t,i}$ *and* $CSR_{t,i}$ = Condition of Pavements and Chip-sealed roads, respectively

$DECK_{t,i}$ = Deck Condition at year *t* for asset *i* after receiving treatment *j*

$SUPER_{t,i}$ = Superstructure Condition at year *t* for asset *i* after receiving treatment *j*

$SUB_{t,i}$ = Substructure Condition at year *t* for asset *i* after receiving treatment *j*

$D_i$ = Deck area ($m^2$)

In this exercise all road segments and bridges were equally important as they all belong to the same road, *i.e.*, the Trans-Canada Highway, connecting New Brunswick with Quebec, having similar levels of AADT for all assets and their segments. Extending this formulation to the entire network requires a subdivision of assets into groups and the addition of additional indicators to represent economic relevance (contribution of a link to the movement of production) and public demand (i.e., commuters), that guides the decision making process to allocate funds first to those assets rendering a higher degree of service.

## 5.5 Case Study – OLD Trans-Canada Highway

### *5.5.1 The Trans-Canada Highway*

The Trans-Canada highway in New Brunswick, known as route 2, links the provinces of Nova Scotia, Prince Edward Island and Newfoundland and Labrador with Quebec and the United States of America. This highway has been under consistent upgrading for the last decade. Condition data from IRI, SDI and rut depth was used to produce a pavement condition index. Road safety as explained below was also incorporated in the analysis. Bridges were also considered in this case study. The available information was merged based on route and control section in a spatial database. For each segment of road an indicator of condition and safety was developed, condition was assigned to each bridge subcomponent (Falls *et al.,* 2006). Overall this corridor had: 121 Km of asphalt pavements, 64 Km of chip-sealed roads and 23,760 $m^2$ of bridge decks (use also as size for superstructure and substructure).

### 5.5.2 Safety Performance Modeling

Expected vehicle collisions were predicted by calibrating the functional form presented in Equation 5-6 (*De Leur and Sayed 2002*). A complete dataset of accidents was available from 1997 to 2007.

$$A = \beta\left(L^{\alpha_1}\right)\left(AADT_i\right)^{\alpha_2} e^{(\alpha_3 CF_1 + \alpha_4 CF_2 + \alpha_5 CF_3)} \qquad [5\text{-}6]$$

Where: A = predicted amount of accidents, $L_i$ and $AADT_i$ = Length and traffic volume of $i^{th}$-segment and $CF_1$ to $CF_3$ = contributing factors being CF1 = Density of curves (related to road alignment), CF2 = Number of rainy or snowy days per year and CF3 = Human errors

The coefficients varied depending on spatial location and environmental conditions. Thus, $\beta_i$ and $\alpha_i$ were calibrated for the road corridor using an accident database as the likelihood function in a full Bayesian regression model, more advanced safety performance models can be obtained using Poisson conjugated likelihoods, however, the aim of this paper was to demonstrate a method to deal with multiple objectives without monetizing them.

### *5.5.3 Treatments and Cost*

Treatments for road and bridge condition were based on 2007 NBDOT definitions for available actions to maintain and preserve their road assets (Table 5.1). Even though a clear identification of safety was possible by analyzing ten years of accident records, specific identification of needs per road segment was not available to clearly establish which treatments were required for which sections. Therefore in order to generate a monetary provision for safety, two generic levels of treatments based on mean cost of safety hardware and, correction of safety related surface issues, were used in this case study, the addition of a geometric correction was also incorporated for those locations with high intensity of accidents and geometric issues. Table 5.1 presents a summary of treatments for roads and bridges as used in this paper.

Table 5.1 Treatment Definitions and Cost ($)

| Item | Treatment | Operational Window | Unit Cost ($) |
|---|---|---|---|
| **Asphalt pavement** | Crack-sealing | Age <= 3 and 90 <= Crack <= 94 | 2,000 /lane-km |
| | Micro-surfacing | Crack > 80 and rutting <= 20 | 80,000 /lane-km |
| | Mill and overlay | IRI <= 2 and PSDI >= 65 | 175,000 /lane-km |
| | Major Rehabilitation | IRI <= 2.5 and PSDI >=50 | 400,000 /lane-km |
| | Reconstruction | Age > 15 | 600,000 $/lane-km |
| | Concrete to Asphalt | Age > 15 | 350,000 /lane-km |
| **Chip seal roads** | Second Seal | Age <= 5, VIR[2] <= 4 | 14,000 /lane-km |
| | Minor Rehab | VIR >= 4 | 26,000 /lane-km |
| | Major Rehab (double seal) | Age >= 8 | 46,000 /lane-km |
| **Bridge deck** | Resurface Deck with asphalt | 75 <= DECKBCI[3]<= 80 | 152 $/$m^2$ |
| | Rehabilitate the Deck | 65 <= DECKBCI <= 75 | 190$/$m^2$ |
| | Replace the Deck | 60 <= DECKBCI <= 70 | 345 / $m^2$ (wood only, if applicable) |
| **Bridge super-structure** | Superstructure minor rehab | 80 <= SUPERBCI[4]<=90[2] | 800 (years 1 to 50) |
| | Superstructure major rehab | Steel: 60 <= SUPERBCI <= 79 | 800 (years 1 to 40) |
| | | Wood: 60 <= SUPERBCI <= 79 | 1040 (years 1 to 40) |
| **Bridge sub-structure** | Rehab the Substructure | 60 <= SUBBCI[5]<= 80 | 2000 (years 1 to 20) |
| | Replace entire bridge | SUBBCI <= 59 | Large: 3500/$m^2$; Small: 100 |
| **ROAD SAFETY** | Minor Correction (hardware) | PFI <2 | $50 $ / lane |
| | Surface related Correction | 2 < PFI < 4 | 150 $/m lane |
| | Geometric Correction | PFI > 4 | 400 $/m lane |

Notes: [1]PSDI = pavement distress index; [2] VIR = Visual Inspection Rating; [3]DECKBCI, [4]SUPERBCI, [5]SUBBCI = bridge deck, substructure and substructure condition index (correspondingly)

## 5.6 Results and discussion

An analysis using a Lifecycle cost optimization for a period of twenty years was used as the base case (Scenario A) to determine required levels of budget to achieve and maintain good values of road safety and condition, budget requirement amounted to an average of

CND$1,850,000 per year. It should be noticed that, the analysis returned an amount of money required to maintain all networks at current levels of safety and condition (base case), because of the conflicting nature of minimizing total expenditure while improving LOS (Equations 5-1 and 5-2). Current levels of service (2006) for this corridor can actually be categorized as good (to very good) with mean pavement condition of 70, mean visual inspection index for chip-sealed roads of 75 and mean bridge condition of 79 (74 for decks, superstructures 81 and substructures 82). This level of budget was used to demonstrate that optimization can achieve better results with the same amount of money. It should be noticed that the latter is a more desirable approach and will return even better results when the mean level of service is mediocre to poor.

Variable coefficients ($\alpha 1$, $\alpha 2$, $\beta$ and $\delta$) were used to obtain several scenarios (Table 5.2) to perform Pareto dominance and performance analyses. Scenarios were analyzed in order to identify the Pareto optimality solution. A gradient approach was conducted to find the best values of the coefficients; this was done by changing the weights and analyzing its impact on the value of the objectives. The larger gradients were observed for chip-sealed roads and road safety, changes in weights for bridge and pavement condition exhibited the smallest amount of variation on their objectives. The first step was to eliminate inferior alternatives, dominated by other scenarios. It was difficult to distinguish dominance in some cases, we refined the analysis to allow one objective to become marginally dominated on those cases where one single objective was marginally inferior but all the others were superior. Dominated scenarios were ruled off the analysis (Table 5.2). The second step relied on a performance analysis in which the achievement and sustainment of good levels of service (across time) was used to determine which scenarios produced good results for some objectives (set as unbalanced) and which ones good values for all objectives. Scenarios D and I were identified as final potential solutions.

Table 5.2 Dominance and Performance Analysis

| Scenario | Weights | | | | Value of Objectives (15 year analysis) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | BCI $\beta$ | PCI $\alpha 1$ | CSR $\alpha 2$ | SI $\delta$ | **Total PCI** | **Total BCI** | **Total CSR** | **Total SI** | **Dominance Criteria** | **Performance Criteria** |
| **A** | 0.25 | 0.25 | 0.25 | 0.25 | 1.5E+05 | 3.05E+07 | 6.51E+03 | 2.96E+03 | Dominated by D | |
| **B** | 0.1 | 0.4 | 0.1 | 0.4 | 1.6E+05 | 2.80E+07 | 5.12E+03 | 2.29E+03 | Non inferior | unbalanced |
| **C** | 0.4 | 0.1 | 0.4 | 0.1 | 1.4E+05 | 3.15E+07 | 7.09E+03 | 3.86E+03 | Non inferior | unbalanced |
| **D** | 0.1 | 0.1 | 0.4 | 0.4 | 1.5E+05 | 3.05E+07 | 7.28E+03 | 2.60E+03 | Non Inferior | BALANCED |
| **E** | 0.4 | 0.4 | 0.1 | 0.1 | 1.5E+05 | 3.05E+07 | 4.08E+03 | 3.33E+03 | Dominated by D | |
| **F** | 0.3 | 0.2 | 0.3 | 0.2 | 1.5E+05 | 3.10E+07 | 6.78E+03 | 3.01E+03 | Marginally dominated by I | |
| **G** | 0.4 | 0.2 | 0.2 | 0.2 | 1.5E+05 | 3.10E+07 | 6.41E+03 | 3.23E+03 | Dominated by D, F and I | |
| **H** | 0.3 | 0.1 | 0.3 | 0.3 | 1.4E+05 | 3.10E+07 | 7.03E+03 | 3.13E+03 | Marginally dominated by I | |
| **I** | 0.3 | 0.15 | 0.25 | 0.3 | 1.5E+05 | 3.10E+07 | 6.83E+03 | 3.05E+03 | Non inferior | BALANCED |

Figure 5.2 shows values achieved by scenarios D and I compared to the base case (A) which achieved nearly constant values of average network performance. It can be seen that both scenarios attained close results for pavements (asphalt roads), similar trends were observed for bridges with marginal superiority of scenario I, although declining trends could not be avoided, because of the absence of a full range of treatments for all bridge subcomponents and materials. Chip-sealed roads for both scenarios (*D* and *I*) rendered better results than the base case (*A*), although scenario *I* failed to maintain good

LOS on the second half of its lifespan. Safety levels of scenario *D* reached an asymptotic trend at nearly 9% safety index. Scenario *D* returned better results than *I* for all objectives, except bridge condition. Scenario *I* was able to achieve superior values of bridge condition than the base case (almost at all times). However, neither scenario was capable of achieving and maintaining good levels of bridge performance (Figure 5.2). The observation of declining performance in bridges towards the end of the analysis period can be explained by a frontier effect from the lack of future periods (inability to account for long term impact of current actions) and a lack of shorter term treatments.

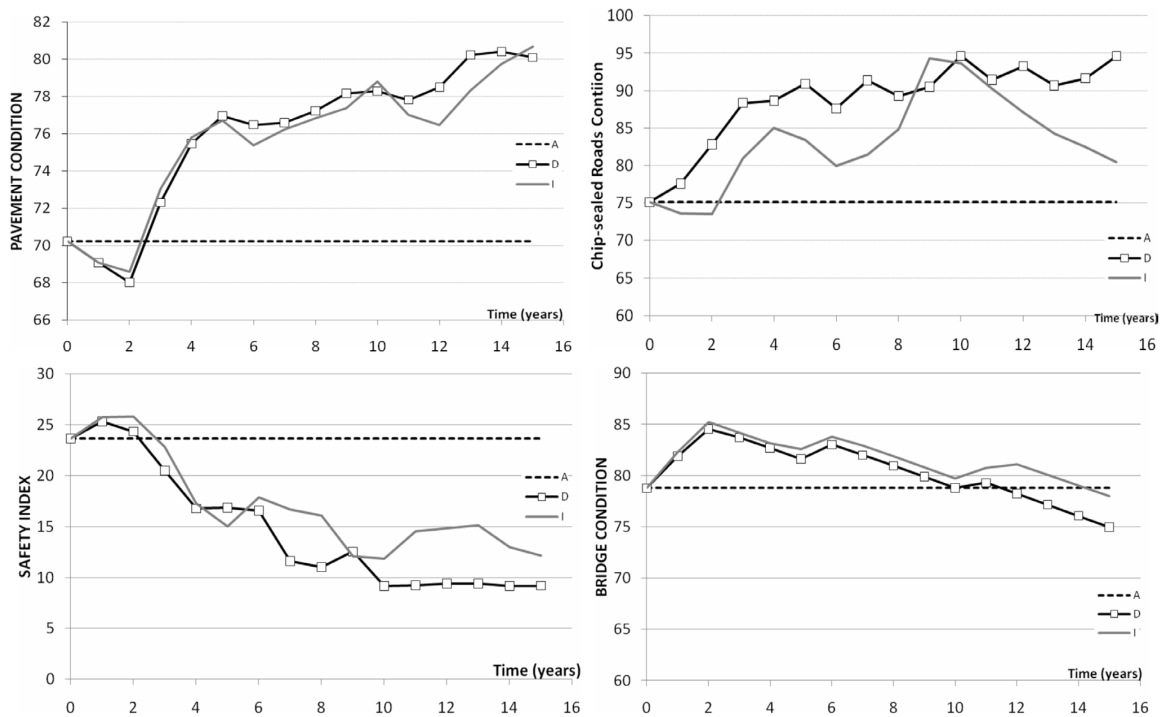
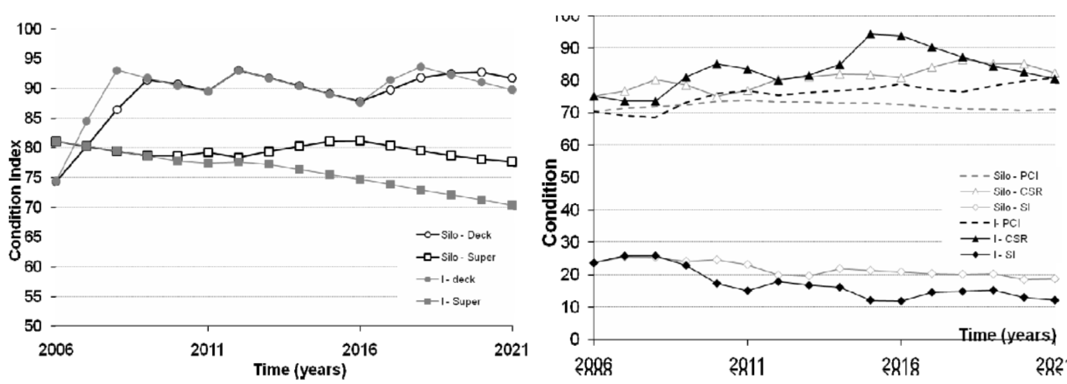



Figure 5.2 Mean Network Performance (Scenarios A, D and I)

Evidently the analysis could have continued looking for a more refined solution. However, the focus shifted towards achieving good levels of bridge condition. It was originally thought that the absence of a full range of treatments for some bridge subcomponents may have provoked a lack of sustainability in the performance. However, it was observed that, running a silo approach based on scenario *I*, with a fixed budget of 1.2 Million dollars dedicated exclusively to bridges, did allocate more treatments to bridge's superstructures and force them to reach better LOS than those observed at scenario *I* (Figure 5.3). As seen on Figure 5.3 the individual performance of bridge subcomponents revealed that all money on scenario *I* (and *D*) was dedicated to decks and no resources were allocated for superstructures (wood and steel) and substructures (concrete). Also, it was observed that a silo approach did not produce good results on the performance of the other assets/objectives, as compared to scenario *I*.




Notes: SI = Safety Index, CSR = Chipsealed road condition, PCI = Pavement Condition, Super = superstructure

Figure 5.3 Silo Approach versus trade-off analysis for Scenario *I*. Left: bridge subcomponents. Right: Road Condition and Safety

It became apparent that the aggregation of bridge subcomponents into one indicator, used in the overall mathematical algorithm (Equation 5-3), induced the focus of the optimization on attending decks (more cost-effective) while neglecting actions to maintain and/or improve superstructures and substructures. Therefore, a new objective as defined by Equation 5-6 (disaggregating bridges by subcomponent) was employed. All efforts were concentrated in achieving good levels of condition for decks and superstructures. Budget was kept in 1,850,000 and the departing values of the optimization coefficients, for a new scenario *K*, were based on scenario *I*. Previously given 30% weight to overall bridge condition was divided per subcomponents. After a few trials, it was found that giving a 9% for decks, 20% for superstructures and 1% for substructures achieved the best results. Figure 5.4 shows mean network values of performance per subcomponent, before and after disaggregating the weighted objectives; it also illustrates the values of performance for safety and condition for the road network after disaggregating bridges.

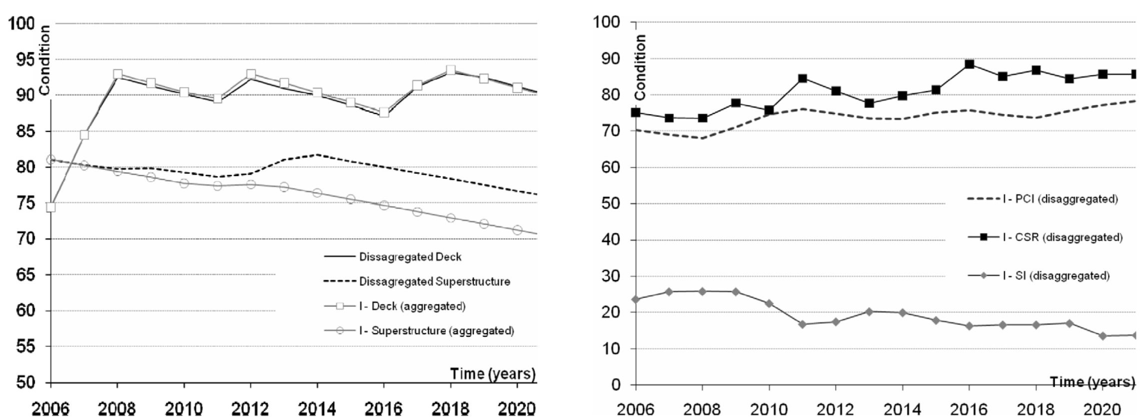



Figure 5.4 Aggregated and Disaggregated Performance. Left: deck and superstructure condition for scenario I. Right: road condition and safety

As seen, decks reached the same levels of performance; meanwhile superstructures achieved a much better performance -after disaggregating bridges per subcomponent- in the optimization analysis. A decay of superstructures after 2014 can be explained by the absence of treatments for early stages of the lifecycle, and will possibly remain until bridges have reached the trigger level of the next available treatment.

## 5.7 Conclusions

This research presents a case study of lifecycle optimization and tradeoff analysis for condition and safety on a road corridor. The approach can be extended to network-level optimization by incorporating measures of economic relevance and public demand per asset/segment on the system. The model expands upon traditional across asset optimization, however not requiring the use of monetization of dissimilar objectives, rather looking at the performance across time, and selecting those alternatives that consistently deliver networks in good levels of service.

The analysis presented employed a weighted global objective and linear programming optimization, supported by a decision tree reflecting all possible paths of consequences after hypothetically deploying available treatments during the lifespan of every road segment or bridge subcomponent. In specific it followed a two stage approach: A first scenario followed Lifecycle cost optimization was used to identify the level of budget required to achieve good levels of service for all objectives involved in the analysis. Such a budget was fixed for the second part of the analysis, in order to demonstrate that the performance-based trade-off optimization was capable of achieving and sustaining superior results than traditional Lifecycle cost optimization. Although not considered in this analysis, increments in budget will be beneficial for a faster achievement of the objectives.

The analysis presented in this paper expanded upon Pareto optimality by suggesting that; for multi-period analysis, it is important to observe performance across time, and that this additional criterion can be used to further narrow the final subset of possible solutions, by ruling off the analysis those alternatives incapable of sustaining good levels of service (LOS) across time (deemed unbalanced).

It was found that performance-based optimization achieved superior results than traditional Lifecycle optimization, reaching higher levels of service for all objective and asset types, using the same mean annual budget. Also, it was discovered that conducting an optimization with aggregated components for bridges did not return good results; resulting in a lack of sustainment of good LOS on superstructures, originally explained by a lack of a wider range of early life treatments. However, a silo approach with dedicated funding for bridges proved this explanation not to be entirely accurate. Therefore, disaggregated subcomponents were incorporated in the mathematical equation of the optimization algorithm. Performance of superstructures improved, however decaying on the second half of the analysis period. This was explained by the inexistence of a wider range of treatments (only replacement) for certain assets (bridge substructure), combined with a frontier effect on the optimization algorithm which prevented it from realizing of the long term benefits of deploying actions when approaching the end of the analysis period. This compromised the ability to sustain good levels of service and rather resulted in the need to undergo periods of decay up to a point in which condition reaches the trigger level pre-specified for replacement. Therefore, it is advisable to run longer analysis, extracting from them the required length of run and, whereas possible, to incorporate early stage treatments for maintenance and rehabilitation.

# CHAPTER 6
# CONCLUSIONS

## 6.1 Summary

This research sought to fully incorporate road safety into road management systems as an independent objective. Safety management systems included data management and inventory, accident prediction models, optimization and decision making leading to a selection of optimum preserving actions. To accurately address safety, accident contributing factors were derived based on the available data. Meanwhile, two main safety-analysis approaches were applied namely, a static safety index and a Potential For Improvements.

Safety indices were developed in cases of insufficient data. Aggregated measures of exposure, severity and likelihood based on explanatory variables were used to create a safety index for every segment. Pavement conditions were also considered as another objective and typified by a Pavement Condition Indices (PCI). Actions to improve safety and pavement conditions were applied on the network. Finally, the most optimum set of actions having the least costs and the most economic-sustained performance during the life cycle was selected using a linear programming optimization process.

Potential For Improvements (PFIs) for cases with sufficient data were identified as a more reliable method as it considered the history of accidents in the analysis. Road characteristics, environmental conditions and human factors in addition to traffic volume and segments length were considered as causal factors. A probabilistic method was used to calibrate the coefficients of a mechanistic model from local conditions to predict the future number of accidents. The difference between predicted and observed number of accidents (accident history) was then defined as a potential for improvement which was used to guide the allocation of resources to improve road safety. Similarly, pavement conditions were derived in terms of PCIs as another objective. Safety and conditions treatments were established and optimum solutions were identified using a linear programming optimization process. Finally, a dominance and performance analysis were proposed using weights for the two objectives as well as looking at the objectives in terms of performance during the life cycle in order to choose the best solution among competing alternatives.

## 6.2 General Conclusions

This research illustrated that it is possible to conduct an integrated strategic management of road infrastructure by fully considering road safety and conditions of several asset types. It was found that it is possible to decrease the accident risk as an indicator of safety (whether it is a safety index or a PFI) and more importantly to achieve and sustain good levels of service in terms of safety by first identifying hazardous segments and then applying mitigating actions. This would result in a safer network of roads while minimizing costs in the long term. The effects of incorporating safety found to be even more evident when looking at the integration of other assets such as pavements and bridges. Considering the capability of sharing budget among objectives, the overall efficiency of the system is improved in such a way that the money can be used from other sources when needed as well as injecting money to other assets in cases of addition budget availability.

In overall, it was observed that using performance based life cycle optimization saves money and achieves more sustainable results by looking at performance of the assets during their life cycle in addition to the traditional sole use of costs as the only objective. Looking at asset performance as the second criteria (in addition to costs) enhances selection of the optimum solutions by narrowing the final subset of alternatives in such a way that unsustainable (unbalanced) options are dominated and deemed out of the analysis.

## 6.3 Specific Conclusions

It was found that the use of a safety index for trade-off optimization between road safety and pavement conditions lead to save 38% in annual budget while achieving good levels of service. This showed the significance of using a weighted combination of road safety and pavement conditions to minimize costs and maximize levels of service. Using a safety index, however, possessed a major drawback related to uncertain nature of accidents from the lack of considering accident history in predicting future number of accidents hence being deficient as it is somehow static in time. In fact, the safety index approach is advantageous as a first cut model showing the significance of incorporating road safety into road management systems in the absence of a comprehensive history of accidents. Reliability of such an approach is highly dependent on available data from safety audits.

The use of potential for improvements was found to be able to be a more reliable procedure for predicting accidents and selecting an optimum solution. This method was capable of identifying minimum safety levels for which no improvement was possible.

For the specific case of the Trans-Canada highway (Route 2) in New Brunswick, the approach focused on reducing PFIs to zero and therefore reaching minimum levels of accident rate related to uncontrollable factors such as human errors and vehicle failures. In total, CAD$ 1.8 million were identified as the required annual budget for treating pavements, bridges and improving road safety. This also showed that the road network has been originally in relatively good conditions and the effort has been to maintain good levels of service during the life cycle of assets. On the other hand, it was discovered that an aggregated bridge indicator would result in lack of sustainability. This phenomenon was originally explained by the inexistence of a wide range of treatments for bridge components. Applying a silo approach showed the bridge-deck-indicator was able of reaching and sustaining good levels of service meanwhile that was not the case for bridge superstructures. Hence, the aggregated bridge indicator was divided into sub-components and the optimization process was re-applied using disaggregated objective indicators which resulted in better results. However, the superstructure indicator still decayed. It was concluded that two reasons were involved in explaining this lack of economic sustainability including the inexistence of a wide range of treatments for bridge superstructure and also a frontier effect happening at the end of the optimization process which prevented it from considering long term impacts of actions. As a result, it was concluded that it is required to run longer analysis time-period in order to derive appropriate time length not to have the frontier effect.

## 6.4 Future research

There are several aspects of road safety not considered in this study due to lack of data or time restriction. This study solely focused on highway safety, whereas intersections are also an important part of any road network located on both urban and rural regions. Urban intersections usually have less severe accidents (lower speeds) although more frequent than those at main line segments of rural highways. On the other hand, contributing factors for collisions at intersections are different from those of highways. They should be carefully analyzed as there are more variables involved on the safety performance of any intersection (i.e., traffic lights, width of intersections, street lighting, operational speeds on both directions, movement trajectories and conflicts). An attempt to incorporate intersection's safety as part of a management system was abandoned because it reveals high uncertainty when predicting collisions from datasets with small sample size and mean.

Another important area for future research can be dedicated to conflicts as a complementary indicator of road safety, especially for intersections and merging movements from ramps into highways. In the literature, it is noteworthy that safety has been addressed by looking at degree of inconsistency (from non-hazardous movements to conflicts) to levels of severity. Although not all conflicts result in collisions, they are still a significant vital part of road safety based on drivers' perception and should be used to warrant changes at hot spots requiring safety retrofitting. However, careful consideration of conflicts requires availability of data and appropriate tools of measuring such indicators. Also, it is noteworthy that accidents were not divided by severity due to aim of this research to obtain first cut models. It is very important that real life applications of the methods presented in this research fully break accidents by severity (fatal, injury and

PDO) as it improves the ability to discern which specialized treatments and hardware improvements are required to mitigate or reduce accident rates.

Illumination of roads plays a vital role in accidents that occur at night time or during dark weather conditions. Separately assessing accidents occurred at day and night and accordingly improving roads illumination can significantly result in safer roads. Segregation of accidents due to the time of day and normalization by traffic flows has been used to measures the need to provide street lighting, however such measure has not been tested versus other possible causal factors.

Intersections of roads and rail should also be studied by future research in order to integrate them into a surface transportation management system. Finally, objectives for roads (condition, mobility, safety, etc) should be integrated with other modes of transportation such as rails in order to achieve a cost-effective system for the movement of people and goods..

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