Strategic Total Highway Asset Management Integration

by

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AUTHOR'S DECLARATION

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

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

Abstract

The last decade has seen significant developments in highway asset management. A key component to successful asset management is long-term network investment planning. In order to successfully manage a significant quantity of aging roadway infrastructure and growing traffic volume, agencies are faced with challenges in developing reliable long term plans that maximize the network performance through value optimization.

Current practice typically involves relatively independent planning for the bridge and pavement networks; with a very slight number of situations allowing for reliable trade-off analysis between the two. While a situation in which the choice to improve two structures rather than one pavement section may yield a greater percentage increase in the bridge network performance, than the opposite choice would for the pavement network - the reliability of this choice being right and at the right time significantly decreases over time.

Introduction of mutually inclusive highway asset planning in this research, by integration of the bridges into an equivalent measure of the pavement network results in significant increases in the long-term planning reliability - is proposed. Data from the Ministry of Transportation of Ontario is used to demonstrate how this proposed approach would work. A key point of this Strategic Total Highway Asset Management Integration (STHAMi) approach is the Conceptual Structural Integration Factor (CSIF). Application of CSIF and Bridge Condition Index (BCI) integration into a pavement performance index allows for representation and treatment of bridges as equivalent pavement sections. This allows for a better comparison of the assets over time.

Compared to the traditional approach of mutually exclusive network level planning, STHAMi resulted in a higher percentage of network treated per unit of value, coupled with consistently higher annual network performance over the long-term.

In addition to significantly higher long-term sub-asset trade-off reliability, STHAMi offers potential for significant increases in organizational efficiency with respect to long-term highway asset planning. Key benefits include introduction of one pavement performance indicator as an all encompassing performance indicator for the complete highway asset, as well as the potential for long-term bridge network level planning execution within a pavement engineering oriented organizational unit.

Further STHAMi development is recommended through integration of other network performance measures such as operational and safety indicators.

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Dedication

To Vidovdan.

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Chapter 1 - Background

Incorporation of proper context is important when considering future development of highway asset management. Consistently applying the term “asset” to a highway network is relatively recent - compared to approximately a century of modern roadway construction. In Canada, the term was initially used during the Canadian Strategic Highway Research Program (C-SHRP) in the late 1980s early 1990s (AMQI 2012). A safe, reliable and sustainable highway network is an asset which allows for efficient movement of goods and people within its serving region. Economic growth is dependent on good pavement infrastructure. In Canada, 90 % of all goods and services are transported via trucks (Tighe 2011).

With widespread use of computers starting in late 1980s, transportation agencies have been able to store and access asset information in electronic databases for approximately a quarter of a century. Realizing the vast future needs of highway networks, the managing transportation agencies have been proactive in attempting to address aging networks and growing traffic demands while minimizing social and economic costs to the general public.

While the relatively traditional approach of material engineering advancement for improved asset performance is an essential means of reaching this goal of cost effective long life infrastructure, this thesis focuses on cross-asset funding allocation between pavements and bridges. Introduction of one objective performance measure for both pavements and bridges is a key contribution of this work, which uses data from the Ministry of Transportation Ontario to develop this concept.

The last decade has seen the development of long-term planning processes for highway asset management across managing agencies. The literature reveals that a number of different terms are currently used to describe this management process, including: strategic, total, and integrated.

This thesis examines a “strategic” approach by providing a 25 year investment plan. A “total” approach is proposed in that the 6 to 25 year plan should ideally carry the same reliability as a short-term (five year) plan. Finally, an “integrated” approach through conceptual conversion of the bridge network into the pavement network is proposed for comparison purposes. Subsequently the name of the process developed is “Strategic Total Highway Asset Management Integration” or STHAMi. In this thesis, the roadway network is referred to as the “asset” while the pavement and bridge networks are referred to as “sub-assets”. This is mainly due to the essential physical cohesion necessary between the two in order for a roadway network to exist with access control, and grade separation.

1.2 Purpose

The purpose of this thesis is to compare two prioritization methods for a 25 year investment strategy plan for a model highway network. These include:

- mutually exclusive bridge and pavement sub-asset planning; and
- mutually inclusive bridge and pavement sub-asset planning.

1.3 Scope

The thesis involves comparison of two long-term investment planning methods-namely:

Alternative A – a mutually exclusive annual budget and treatment for bridges and pavements

Alternative B – a mutually inclusive annual budget and treatment for bridges and pavements through STHAMi

Performance quantification for sub-assets includes a Bridge Condition Index (BCI) and a Riding Comfort Index (RCI), for bridges and pavements, respectively. Amongst others, these indices are currently used within the industry as a quantification of the sub-assets condition.

General costing and service life assumptions for maintenance, preservation and rehabilitation treatments are derived from the Ministry of Transportation of Ontario (MTO) sample data as well as from published Canadian and American academic sources. Organizational views and goals of the optimization are based on five years of work experience at operational, tactical and strategic units of the Provincial Highways Management Division within MTO.

The model highway network is not representative of any existing network. This assures protection of potentially confidential information; however, the behaviour of the fictional model network is derived from the analysis performed on MTO's historical cost and rehabilitation data of its existing network.

The focus of the thesis is the development and application of the Conceptual Structural Integration Factor (CSIF) which allows for direct sub-asset trade-off between pavements and bridges. This new approach involves mutually inclusive budgeting and treatment of bridge and pavement networks. Representing the RCI as an all encompassing performance measure for pavements and bridges provides a potential means of single objective optimization for the one highway asset. A sensitivity analysis with decreased annual funding is included.

1.4 Structure of Thesis

This thesis consists of seven chapters. Below is a brief summary of each chapter.
Chapter 1 contains a background of highway asset management as well as the purpose and the scope of the research.

Chapter 2 contains a literature review, which includes details of the most relevant documentation pertaining to transportation asset management, and cross asset trade-off analysis; covering the period of the last 20 years.

Chapter 3 contains a review of data sources and the development of the Conceptual Structural Integration Factor (CSIF), which is the key to trade-off analysis between pavements and bridges. An explanation of the semi-automatic programming method is included, as well as an organizational perspective of Strategic Total Highway Asset Management Integration (STHAMi).

Chapter 4 includes two 25 – year investment plans with equal budgetary restrictions; however, one is developed through the current mutually inclusive industry approach, while the other is developed through the newly proposed mutually inclusive STHAMi approach.

Chapter 5 contains economic and performance comparisons of the mutually exclusive versus the mutually inclusive approach.

Chapter 6 includes a sensitivity analysis of the two 25 – year investment plans developed at 75 % of the original budget used in Chapter Four.

Chapter 7 summarizes the key conclusions and recommendations of the research.

Chapter 2 – Literature Review

This chapter provides a review of literature material that has been instrumental for conceptualization and subsequent development of STHAMi. It includes private and public documentation spanning a time frame from 1984 to 2013. Publications from the Transportation Association of Canada (TAC), the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the Ministry of Transportation Ontario (MTO) have also provided a basis for this research. In addition, reports, dissertations, periodicals, and presentations from public and private representatives have also been referenced.

Canada's transportation focus during the majority of the 1800's was on railway transportation infrastructure. Invention of the internal combustion engine and the subsequent automobile gradually yielded greater demand for maintenance and improvement of roadways. Increased public pressure lead to the formation of the Ontario Good Roads Association (OGRA) in 1894. The association played an important role in the subsequent passing of the Highway Improvement Act in 1901 (MTO 1984). During the early 1900's the Ministry of Transportation Ontario was created to manage Ontario's roadways. They were responsible for design, construction and maintenance of the provincial highway network. Since then, the term of "rehabilitation" has been added to the suite of activities under their responsibility. With the peak of new construction in the late 1960s, the majority of present construction is focused on rehabilitation and maintenance is also a large part of their activities.

Increasing traffic growth requires continuous rehabilitation of pavements within a 10-20 year cycle; adding to these needs is a significant quantity of the bridge network requiring rehabilitation due to an achieved in service life span of 50 or more years. Significant investment is required to meet these needs. Ontario has dedicated a record of approximately $ 1.5 B and $ 2.25 B to meet these needs in 2011 and 2013, respectively (MTO 2012).

Considering the close proximity, and similar economic development over the last century; the above noted funding needs pattern is likely attributable to other Canadian provinces as well as the US. The ability to efficiently move goods and provide services has become increasingly important in the globalized context of the 21st century. In 2012, transportation infrastructure made up 26.8 % of the global contracting market at approximately $ 121 B, followed by the petroleum (23.0 %), buildings (20.1 %), power (10.4 %), industrial, other, water, sewer / waste, manufacturing, telecom, and hazardous waste markets (ENR 2012).

Highways and roadways in general form a significant and connecting link for public infrastructure, which is necessary for economic growth and appropriate social standards. Its economic importance is echoed in Ontario's Ministry of Finance Long-Term Report on the Economy:

"…Statistics Canada research findings suggest a $1 investment in public infrastructure lowers business costs by an average of 11 cents in Canada. The gains tend to be greater for industries such as manufacturing, transportation and retail, which rely more heavily on public infrastructure for the production of their goods. Public infrastructure's contribution to Canadian labour productivity averaged
0.2 percentage points per year from 1962 to 2006, accounting for an average of nine per cent of labour productivity growth during this period. Infrastructure has a wide range of benefits, including a positive impact on productivity. New or rehabilitated infrastructure promotes efficiency by lowering business costs."(MFO 2010).

It is likely that this high degree of societal economic dependence on roadways eventually resulted in pavements and bridges being referred to as an "asset" in the 1980s, a relatively financial term within popular culture. Hence, the term "Highway Asset Management" became synonymous with pavement and bridge management. This new term likely suggested the formal beginning of the need for collaboration between the traditional care

takers of highway infrastructure – being the engineers – and the traditional users of the term – being the economists.

A unique insight into the relationship is provided in the *Engineers and Economists Think Differently* article published in the fortnightly newsletter (Burns 2006). Considering the age of built infrastructure, economists started to address it relatively late. The 1980s involved much discussion regarding its nature and whether an identical approach can be taken to it as with private sector assets. "An asset is an asset" was the general economist accepted view - which was opposed by engineers. Present difficulties of accurately assessing infrastructure needs may be attributed to this initial assumption of treating infrastructure as another industry asset. Applying averaging principles based on the law of large numbers as in the private industry is a procedure which may, depending on the specific situation, be of concern; as well as introducing finite spans on indefinite asset lives for the purposes of performing depreciation. A major issue identified is "reversibility": "*When you are dealing with abstract notions and concepts in a model, moving back and forward in time is equally easy. In marginal cost models for example, one can increase the supply (a little) and observe the price result. If it is not satisfactory then one can reduce the supply and put the system back as it was. Life is not like that for infrastructure assets. One of the reasons that Infrastructure asset management is so challenging is that decisions are usually not reversible – or reversible only a great cost. Damming a river to create a dam, for example, destroys habitats for both man and beast and generally they cannot be put back again. This is a dramatic example. But changing the alignment of a road may have similar impacts on residents, local businesses, and the environment. Irreversibility is an important issue. I don't think that either economists or engineers can have the final word on this. This ability to shape a model from first principles in order to achieve a desired solution is something that economists and engineers have in common. Economists and Engineers can build on this!"*(Burns 2006).

Asset management development in Canada, as summarized by Sparks at the University of Saskatchewan was introduced through the Canadian Strategic Highway Research Program (C-SHRP) in the late 1980's early 1990's (Sparks 2006). Focused on getting a

"better bang for the buck" through application of better science and technology, it involved all the highway managing agencies in Canada. Information sharing with Australian highway agencies was instrumental during the multi-year program. The Roads & Traffic Authority of New South Wales introduced the concepts and principles of asset management through their Asset Control Technology Group. This included identifying better management in addition to better science and technology as a means of getting a "better bang for the buck for pavement". Subsequently, C-SHRP Management Committee formally introduced asset management on its cross – Canada "Briefing Tour" in 1992. "*The discussions during this tour lead to an asset management pilot project with Saskatchewan Highways championed by the Deputy Minister, Clare Kirkland as well as another asset management pilot project with the City of Saskatoon championed by then Director of Public Works, Jan-Mark Gustafson. This was the birth of asset management in Canada!*" (AMQI 2006).

In 1996, asset management formally commenced in the US, "AASHTO and FHWA hosted an executive-level AM seminar with results documented in FHWA's Asset Management: Advancing the State of the Art into the 21st Century Through Public-Private Dialogue (1997)…" (TRB 2013).

Today, a common definition of transportation asset management has become widely accepted, according to AASHTO "Transportation Asset Management is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life-cycle. It focuses on business and engineering practise for resource allocation and utilization, with the objective of better decision making based on quality information and well-defined objectives." (TRB 2013).

While engineering is an intrinsic part, it is also important to note the business or organizational aspect of highway asset management. Typically, the organization is the means through which the engineering and other organizational units manage a highway network. Perhaps a simplified explanation of infrastructure asset management was expressed through the view of a private firm - technical director of asset management for

North America: “Asset Management is no longer a tool for efficiently engineering our environment, but rather a tool for effectively managing our engineered environment” (AMQI 2004). Adding the term “strategic” further supports the above mentioned definitions, and defines its purpose. In its Infrastructure Asset Management Framework the Ontario Ministry of Energy and Infrastructure states: “Strategic Asset Management – A level of asset management that is focused on assessing investment needs and trade-offs to meet the long-term goals and strategies of an organization.” (MEI 2008).

Assuming the general goal of managing agencies is to approach infrastructure asset management - such that future network performance is maximized while funding optimized; a single objective function for maximizing network performance according to available or forecasted budgeting may provide a quantitative means of interpreting the goal. However, a key challenge is finding a unified performance measure for two distinctly different sub-assets of the highway network asset: pavements and bridges. The source of this challenge lies in the historical and likely still current approach to management where the “…bridge management systems were developed by bridge engineers, and pavement management systems were produced by pavement engineers. Typically, there is little, if any, data exchange between systems. Furthermore, there is little consistency with respect to investment decision procedures.” (USDOT 1999).

An example of bridging this gap is found in Ontario’s platform where executive users are able to interact with both sub-asset systems via one platform: *“…ESS [system platform] addresses this issue by enabling users to specify cost-scaling factors for the costs and benefits produced by each system, as illustrated in Figure 1. Scaling costs and benefits helps place candidates generated by multiple systems on a level playing field for economic analysis. For example, if the unit costs in an agency’s pavement management system include indirect costs for design and construction oversight, but the unit costs in its bridge management system do not, users can specify a cost-scaling factor that increases the costs of all bridge candidates. The costs and benefit of each work candidate are scaled by the appropriate cost-scaling factor before the IBC analysis is performed. It is anticipated that a detailed analysis of the costs and benefits of each system included in*

the ESS will be performed in order to establish standard default values for the cost-scaling factors." (Bradbury et al. 2005).

The second half of the last decade has seen an increasing interest for asset management to incorporate trade-off analysis between different sub-assets, especially pavement and bridges - such that optimal performance of the overall network is achieved.

NCHRP Report 545 for analytical asset management tools provides an insight: *"A gap analysis conducted in the first phase of the study revealed that many existing asset management systems are not being used to their full potential. A need was identified for tools that could be integrated with existing systems to improve an agency's ability to analyze and predict the impacts of investments at the network and program levels on overall system performance…Staff also expressed interest in exploring how the tool could be used to look at tradeoffs across corridors as well as across assets."* (TRB 2005).

Further development of trade-off analysis as a key component of asset management is witnessed by the University of New Brunswick:

"…Trade-off analysis is a complex process that tries to answer: what asset type, what segment, what treatment works the best and when to treat the asset over the planning horizon so as to meet a given agency's objective. Long term investment planning (LTIP) in asset management requires trade-off of investment strategies across a variety of asset types such as bridges versus pavements, etc. The trade-off analysis uses optimization to select the treatment combination (i.e.,investment strategy) that will maximize the objective function. Object functions can include maximizing average asset condition or asset value over the analysis period, minimizing cost for a given asset condition, etc." (MacNaughton et al. 2008).

At the commencement of our current decade, amongst other items, MTO sees asset management as "… a strategy to help allocate available funds and resources amongst

competing asset needs…making the right investment in the right place at the right time…" (MTO 2011).

A trade-off process' level of objectiveness is highly proportional to the level of objectiveness of the medium by which the trade-off is made. Development of an overall performance measure for the highway asset is an approach which is actively being explored. The following is an excerpt from a presentation focused on the matter, made at the 2012 - 9th National Conference on Transportation:

"*Developing a framework to aggregate performance of roadway assets into overall roadway performance measures for cross-asset resource allocation, tradeoff analysis, etc…Performance measures already developed for individual assets…several studies trying to aggregate all different types of performance measures for one asset (e.g. COST method)…Aggregating performance of multiple assets into corridor-level (system-level) performance measures is not yet explicitly addressed…"* (Dehghanisanij 2012).

The need for new methods of highway network program planning as previously expressed by AASHTO's *Transportation Asset Management Guide a Focus on Implementation:*

"Traditional management methods will no longer be sufficient to meet 21st century business and political demands."

Furthermore, it notes the importance of the organizational aspect as it applies to infrastructure asset management:

"The asset management cycle is a sequence of integrated business processes. All transportation agencies have the fundamental business processes required for asset management. However, agencies vary widely in the effectiveness of these processes, particularly the ability to maximize the accomplishment of the agency mission by means of asset management."

In order to develop projected levels of service through the most cost effective manner, it is necessary to align strategies, plans, programs, and budgets within an organization. Lack of this approach will significantly hinder the likelihood of successful delivery (AASHTO 2011).

Provided the use of the term "asset" for the highway network is relatively recent, development of standardized terms and processes is likely necessary for effective implementation of asset management across agencies. Transportation Research Board's NCHRP Synthesis 439: *Use of Transportation Asset Management Principles in State Highway Agencies* provides detail into the current status:

"*Although the emergence of champion agencies using TAM principles is limited, the level of interest among state departments of transportation (DOTs), federal agencies, professional organizations, and the research community has been steadily increasing…Recent Moving Ahead for Progress in the 21st Century Act (MAP-21) performance-based reauthorization…Common terminology for AM functions, practices and processes is needed. The results from the AM state-of-the-practice survey highlighted a few areas where there is no common understanding of the terminology.*"

Organizational structure, data, decision making, performance measures, and risk are all necessary elements of a Transportation Asset Management Plan (TAMP). Three of the five plans received through the synthesis did not satisfy the requirements, however, they were interpreted as complete TAMPs by their respective agencies. (TRB 2013).

Provided trade-off analysis is a subset of highway asset management, a similar standardization of terminology will likely be required for successful implementation. The California Department of Transportation's (Caltrans) *Preliminary Investigation – Application of Cross-Asset Optimization in Transportation Asset Management* provides a sample size insight into current agential interpretations of cross - asset optimization or cross-asset trade-off analysis. The following are summarized points from the report

indicating current and future practice details relating to cross-asset funding allocation processes:

- the level of transportation asset management principle application across departments of transportation is not well understood;
- visualization of varying funding levels and impacts on all asset categories is a future goal;
- projects addressing needs in multiple categories tend to be weighted differently than others during cross-asset optimization;
- new measure – utility approach not most common;
- performance targeting is most common approach;
- identification of optimal pavement and bridge projects over a 25-year period that maximize bridge and pavement condition while meeting budget constraints;
- process will allow for cross-asset optimization at system level for agency's three major asset categories: pavement, bridge and culvert;
- process will be capable of determining if capacity project reducing time delays and accidents has greater cost/benefit than extension of bridge life;
- most difficult challenge is setting value or weighting for a project;
- developed matrix of scores for cross-asset prioritization decision between structure and pavements;
- safety is used to decide among three pavement section with identical repair costs (Caltrans 2012).

The report was completed by a private firm on behalf of Caltrans. The points shown in this list were selected from a larger number based upon their relatively higher degree of relation to cross-asset trade-off analysis provided in this research. It is interesting to note that the most common operational interpretation of cross-asset trade-off analysis is the changing of investment levels and observation of the resulting projected performance across different asset categories. This approach is followed by development of matrix scores, stochastic performance modelling, and "deciding factor" (i.e. safety) development

for trade-off decision making. The most uncommon approach is development of a new measure utility or a unified performance measure for different asset categories.

The report also examined completed and in-process domestic and international research that addresses the current state of the practice in applying cross-asset optimization in transportation asset management. The findings indicate burgeoning interest in cross-asset optimization, but no transportation state department has completed a comprehensive implementation of cross-asset optimization within and across all asset categories at both the system and project levels (Caltrans 2012).

A research project tender put forth by the Transportation Research Board titled "Cross-Asset Resource Allocation and the Impact on System Performance ", NCHRP 08-91 [Pending], 2012; provides a concise summary of the current state of highway asset management with respect to sub-asset integration or cross-asset trade-off analysis, and its shortcomings:

"*The current approaches in transportation asset management contain a significant deficiency in that resource allocation is addressed only within a single asset class with a narrow perspective on performance. They provide little guidance for allocating a fixed funding budget among, for example, pavement resurfacings, culvert replacements, and bridge widening to enhance safety and reliably accommodate traffic. There are no widely accepted approaches for assessing how condition and performance of separate classes of assets interact to influence overall system performance. Research is needed to determine how to align asset-specific performance measures with an agency's system performance targets and how to allocate resources across asset classes to achieve satisfactory performance*." (TRB 2012).

The product is expected to produce a guidebook which is not indented to be an optimization tool, but rather an explanation of principles and procedures that may be adapted and used by a transportation asset management agency to support allocation of public resources across transportation-system asset classes to achieve acceptable system performance.

Scope objectives to be addressed through NCHRP 08-91 include but are not limited to:

- suggest the fundamental dimensions necessary to measure and communicate transportation system performance across asset categories and alternative metrics applicable to each dimension;
- be adaptable for use by any particular DOT or other transportation agencies at various levels of transportation asset management maturity;
- present succinct and easily comprehended exemplary reports of performance implications of resource allocations to specific assets or asset classes;
- be responsive to the accountability, performance measurement and management provisions of MAP-21; and
- be useful as a tool to facilitate communication between stakeholders and transportation-agency officials about the likely impacts of cross-asset resource-allocation decisions. The research should identify data and training requirements for an agency to apply the framework and incorporate its use in cross-asset resource allocation (TRB 2012).

The future direction of roadway infrastructure asset management is further defined in the Transportation Association of Canada (TAC) Pavement Asset Design and Management Guide. Key future research items include:

- Establishing and measuring achievable key performance indicators;

- Developing a comprehensive protocol on the most appropriate valuation method(s) for various types of transportation infrastructure;

- strengthening the existing framework by development of processes and tools for cross-asset comparison and capital planning; and

- providing innovative methods of communicating asset management results to stakeholders (Tighe 2011).

It should be noted that ample academic literature exists on individual sub-asset management systems and processes; however, individual sub-asset management is outside the focus of this research and therefore the literature review. An example of such a system includes the Pavement Management System 2 (PMS2) used by MTO for pavement condition data storage, deterioration modeling, and needs forecasting. In the U.S., the Pontis system "is able to analyze the bridge life-cycle implications of decisions and express the results in a form understandable to a broad audience, including managers and legislators." (Johnson 1998). The BRIDGIT bridge management system "optimizes network performance, it also recommends specific actions for each bridge, consistent with overall network strategy." (Hawk 1998). The goal of this research is to aid the development of a process and / or a system such as the ones mentioned, but for both sub-assets, unified under one performance measure through cross-asset trade-off analysis.

An effort has been put forth over a number of years to separate the sources which aim to explicitly address cross-asset allocation for both sub-assets from those concentrating only on one; or varying funding of one while observing effects on the other. At the time of writing this thesis, the available academic and themed literature is limited. That which is available, has been included into this literature review.

In conclusion, since the formal use of the term "asset" for transportation infrastructure in the mid 1990s the industry has made significant progress in raising awareness and developing strategic and tactical approaches to developing and implementing transportation asset management practices across agencies. Public managing agencies, academia, associations, and the private sector, have all contributed to the creation of an environment where asset management is viewed by all as a natural progression of roadway management; rather than one alternative amongst many future paths to successful infrastructure management.

The literature review defines the necessary strategic and tactical processes, while identifying future needs of operational process development. Hence, the research in this thesis focuses on:

- development of performance measures;
- cross-asset trade-off or optimization; and
- organizational implementation.

The research aims to provide a means of advancing agencies' current cross-asset optimization initiatives through development of a unified performance measure for pavements and bridges. Furthermore, its goal is to provide a preliminary framework for operational implementation within existing organizational structures.

Chapter 3 – Data Sources, Conceptual Structural Integration Factor (CSIF), Organizational Context

This chapter explains the highway network composition, the Conceptual Structural Integration Factor (CSIF), and the organizational implications of Strategic Total Highway Asset Management Integration (STHAMi).

The sources of network data include MTO's pavement and bridge databases. The physical characteristics of the model network are fictional; however, they are modelled after MTO's Central Region network. This ensures any confidential information such as object specific identifiers remain confidential. Conceptually, the proportion of urban along with rural pavement sections represents a region with a localized area of concentrated urbanization and dispersed rural settlements. MTO's Central Region is an example of a region where the southern limits are dominated by the urbanized Greater Toronto Area – north of which a few cities and smaller towns prevail. In comparison, the model network's pavement and bridge networks are 58 % and 45 % of Central Region's existing infrastructure, respectively. The bridge data was used in developing the bridge network deterioration rate. Analysis of rehabilitation history data yielded average years to structure replacements and rehabilitations over the past 100 years.

The highway network is composed of two sub-asset networks: pavements and bridges.

The pavement network in this research is composed of 748 centre lane kilometres and 3,153 lane kilometres. Centre lane kilometres represent the linear length of a roadway segment measured along its centre line. Lane kilometres represent the length of a segment with respect to the number of 3.75 m wide lanes contained within. For example a two-lane roadway measuring 1 km in centre line length equates to 2 lane kilometres. A

percentage breakdown of rural, four lane, six lane and collector / express composition is shown in Table 2.1.

TABLE 3.1: Highway Network Composition Per Cent Breakdown

Lanes in Each Direction	Centre Lane (km)	Per Cent of Total Network (%)	Lane (km)	Per Cent of Total Lane (km) Network (%)
1	344	46	687	22
2	85	11	340	11
3	285	38	1708	54
6	35	5	418	13
Total	**748**	**100**	**3153**	**100**

At 54 %, the majority of the treatable network is composed of three lanes in each direction, followed by one lane, six lanes and two lanes, respectively. The relatively high per cent of three lanes in each direction would be representative of an area containing multiple controlled access freeways serving an urbanized centre, such as the Greater Toronto Area.

Figure 3.1 presents in a graphical form the contents of Table 3.1.

The blue bar represents per cent of network composition with respect to centre lane kilometres. The red bar represents corresponding treatable lane kilometre per cent of total pavement network. A typical pavement section length is ten kilometres.

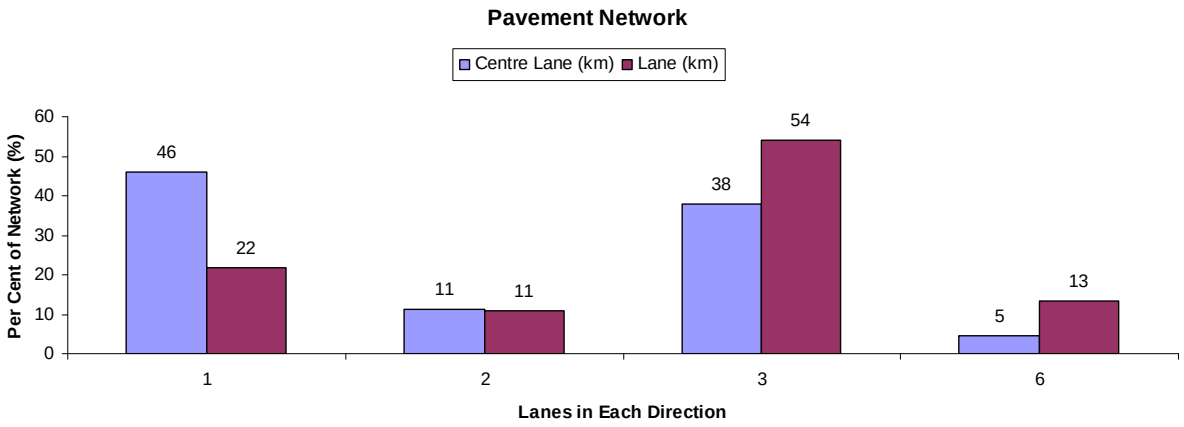


Figure 3.1: Breakdown Highway Network by Lane Number

The bridge network in this research is composed of 466 bridges. A percentage breakdown of rural, four lane, six lane and collector / express bridge network composition is shown in Table 3.2; it represents an over or underpass for a one, two, three and six lane roadway in each direction, respectively.

TABLE 3.2: Breakdown Bridge Network Composition by Lane Number

Lanes in Each Direction	Number of Bridges	Per Cent of Total Network (%)	Individual Deck Area (m^2)	Deck Area (m^2)	Per Cent of Total Area Deck Network (%)
1	87	19	114	9095	5
2	92	20	225	20721	10
3	253	54	526	133167	67
6	34	7	1023	34794	18
Total	**466**	**100**		**197777**	**100**

At 67 %, the majority of treatable deck area of the bridge network is composed of structures supporting three lanes in each direction, followed by six lanes, two lanes and one lane, respectively.

Figure 3.2 presents in a graphical form the contents of Table 3.2. The blue bar represents per cent of network composition with respect to quantity of bridges, while the red bar represents corresponding treatable deck area percentage of total bridge network.

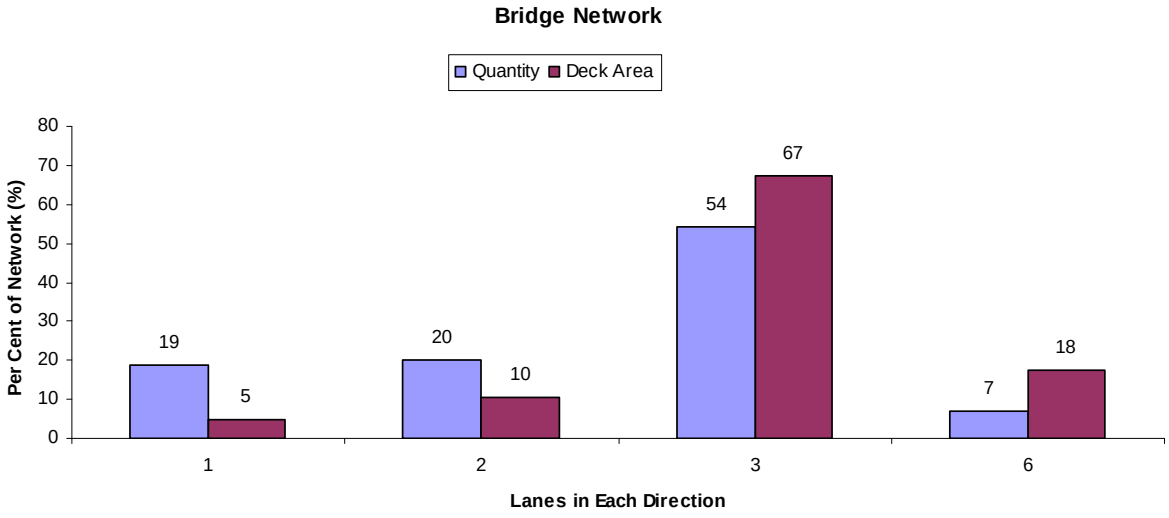


Figure 3.2: Bridge Network Breakdown

For operational purposes agencies typically express performance of pavements and bridges in quantitative terms. A number of standardized pavement performance indicators exist. Use of a specific one is at the discretion of the particular agency. A few examples include: Riding Comfort Index (RCI), International Roughness Index (IRI), and Structural Adequacy Index (SAI) (Tighe 2011). MTO practice and literature review suggest the term "Bridge Condition Index" (BCI) being typically used across agencies to represent the condition of a bridge. For this research, RCI and BCI are assumed to represent pavement and bridge performance for the model network, respectively. The deterioration rate of each is shown in Table 3.3.

TABLE 3.3: Assumed Deterioration Rates

Pavement Deterioration	Bridge Deterioration
0.123 RCI unit / year	1.0 BCI unit / year

The RCI rate of deterioration was developed by approximating the 0 to 7 year slope of an RCI deterioration curve from the Transportation Association of Canada - Pavement Design and Management Guide (TAC 1997). The scale ranges from 0 to 8.73 units, the latter being the highest achievable condition.

Compared to pavement-condition-indices-development, bridge condition index or performance standardization development is relatively recent. Current approaches include a variety of methods (McGee 2002). This is expected provided the peak of "new" construction occurred in the 1960s and 70s; subsequently a significant quantity of bridges is likely within the second half of the designed lifespan. Information sources indicate that "more than 40% of the bridges currently in use in Canada were built over 50 years ago…" (Hammad et al 2007). This is a challenge as an analysis period of 50+ years is necessary in order to obtain a relatively complete data set of bridge behaviour. Adding to the challenge are varying environments, loadings, traffic volumes, materials, and construction methods upon which the bridge deterioration rates are dependant. One of the key challenges is determining the condition relationship between the structural

elements (i.e. abutments, piers, etc.), the structure, and the structural network. Specifically, how the observations at the element level translate to the overall performance of the structure and subsequently to the performance of the overall bridge network. Generally, for long-term highway network planning, bridge network condition and performance are synonymous. In that a part of the network assessed as being in poor condition is highly likely to be viewed as underperforming and therefore requiring investment. This approach is limited with respect to bridges which may be assessed as being in poor condition but are still able to maintain satisfactory performance with respect to transportation of goods. The following Swiss-Canadian research example provides further detail:

"*Condition and performance differ in that the latter is linked to function. For example, although the formation of small surface cracks under 0.5 mm in width on a concrete girder may warrant it being in a new CS [condition state], this may have no discernible effect on the performance of the girder, and therefore no effect on the performance of the structure."*

The explored methodology of advancing bridge funding decision making allows for calculation of structure level costs based on the condition of its elements, through the development of bridge performance states. A single bridge is used as a case study to demonstrate the approach through stochastic modeling and simulation (*Fernando et al 2011).*

In contrast to the project (structure) level method above, an example from Iowa State University approaches the same challenge of advancing bridge investment decision making - but at the bridge network level. Through analysis of historical bridge data, the Classification and Regression Tree (CART) method is used to develop an algorithm for predicting National Bridge Inventory (NBI) values. The approach showed greater accuracy in predicting NBI condition ratings from BMS element data than the NBI Translator legacy system. The conversion of element data to NBI condition ratings is

necessary for securing federal funding (Bektas 2011). The approach of analyzing historical bridge data is used for this research as well.

Without standardized published BCI deterioration rates, a rate of 1.0 BCI per year was assumed. The scale ranges from 0 to 100, the latter being the highest achievable condition. The observed MTO time durations for bridges to reach good, fair, and poor states generally correspond to this rate. With a sample data set of an existing bridge network portion, the assumed BCI rate was calculated through an analysis on the relationship between:

- Years since structure construction;
- Years to first rehabilitation; and
- Years to planned rehabilitation.

Appendix A contains all the raw model network data.
The following section explains the treatment characteristics applied to each sub asset.

Treatment Characteristics

Project or section specific life cycle cost analysis (LCCA) includes a variety of available treatment considerations developed in modern roadway construction over the past century.

A developed long term investment plan, according to optimized treatment alternatives at an individual project level, is highly unlikely to be realized on the network. This is due to certain budgetary restrictions preventing realization of optimal treatment for every section in the network, with respect to timing and treatment choice over a period of 25 years.

Rather than considering each individual section and comparing it to another, the STHAMi method aggregates them into a network through aggregation of all available treatment alternatives into three (TAC 2013):

- routine maintenance;
- preservation; and
- rehabilitation.

This approach considers general structuring of a managing agency, which includes a strategic, tactical, and operational level. Strategic level typically represents an organizational unit with a centralized information base fed by tactical and operational levels. Program planning for an area or corridor of a network is an example of a tactical organizational unit. A project specific organizational unit that typically determines treatment triggers and design criteria, is an operational level example.

While the majority of communication between tactical and operational levels includes specific treatment terms, communication between strategic and operational levels mostly includes terms mentioned above: routine maintenance, preservation, and rehabilitation. Examples of individual section treatment details available under these categories can be found in the Transportation Association of Canada Pavement Asset Design and Management Guide (TAC 2013).

Since long term planning typically occurs at strategic-tactical relation within an organization, the report uses the identical approach of treatment aggregation in development of a 25 year program.

Table 3.4 shows pavement treatment characteristics.

TABLE 3.4: Pavement Treatment Triggers

Treatment	Riding Comfort Index (RCI)	Trigger Value
Routine Maintenance	6.4 to 7.4	< 7.5
Preservation	6.3 to 4.5	< 6.4
Rehabilitation	4.4 to 3.0	< 4.5

Table 3.4 indicates RCI ranges and assumed corresponding appropriate treatments of routine maintenance, preservation and rehabilitation. Assuming available budget, sections become eligible for treatments when RCI values shown in the column labelled "Trigger Value" are surpassed.

The 6th International Conference on Managing Pavements (ICMPA 2004) was used as a relatively loose basis for developing treatment triggers. Specifically, the International Roughness Index (IRI) values from its Pavement Management Investment Analysis Challenge were modified to accommodate an RCI scale, where higher values indicate increased sub-asset performance. It is important to note that due to different environments existing globally, a variety of different performance measures and classification systems exist.

Table 3.5 shows Ontario's 1989 pavement performance rating system.

TABLE 3.5: Ministry of Transportation Ontario Ride Rating Guide (MTO 1989)

RCI	Condition
8 to 10	Excellent
6 to 8	Good
4 to 6	Fair
2 to 4	Poor
0 to 2	Very Poor

The MTO condition rating guide system, as shown in Table 3.5, results in a section treatment strategy where rehabilitation is applied at the lower end of the fair rating. Preservation is applied at the lower end of the good rating; while routine maintenance is applied at the higher end of the good rating. The assumption is that such an approach creates an overall preservation strategy for the network, rather than worst first. For this research, the very poor rating is considered to be part of the poor rating, and is therefore not used explicitly as a condition descriptor in subsequent analysis.

Due to aggregation of all routine maintenance alternatives into one routine maintenance treatment term, it is assumed that the treatment selected is the optimal maintenance treatment for that particular section as determined by an independent and section specific LCCA. The same is assumed for preservation and rehabilitation treatment terms.

Table 3.6 shows minimum condition level acceptable for a pavement section.

TABLE 3.6: Minimum Acceptable Level of Service for Individual Section

Lanes in Each Direction	Minimum RCI
1	3
2	3.25
3	3.5
6	3.75

Sections with lower traffic capacities represented with a lower number of lanes in each direction were allowed to reach lower minimum conditions than sections with higher traffic capacities. A range from 3 to 3.75 RCI is representative of a rural collector or arterial roadway where these would represent the minimum allowed threshold range.

Table 3.7 shows the bridge treatment characteristics developed from analyzing MTO bridge data for a specific region.

TABLE 3.7: Bridge Treatment Triggers

Treatment	Rehabed Previously BCI	Trigger Value	Unrehabed BCI	Trigger Value
Routine Maintenance	59 to 68	< 68	70 to 84	< 84
Preservation	48 to 58	< 58	55 to 69	< 69
Rehabilitation*	34 to 47	< 47	30 to 54	< 54

** replacement*

The bridge asset is divided into two categories: rehabed previously and unrehabed. The categorization of the bridges can be established based upon the sample data set of an existing bridge network portion. However, the BCI condition rating and corresponding treatment selection have been developed independently for the purpose of this research. Categorization of the bridges is necessary so a lower treatment trigger level for structures

allows for an investment strategy that results in increased sensitivity towards the untreated parts of the network, thereby potentially minimizing risk of failure. Depending on agency's bridge assessment procedures, there exists potential for a bridge to be attributed a high overall BCI value but have at the same time one of its elements (i.e. girder) in critical condition. Expert intervention of structural engineers is relied upon in such cases to ensure the structure is programmed for rehabilitation.

Table 3.8 contains associated improvement with each treatment for both sub-assets.

TABLE 3.8: Condition Improvement of Treatment

Treatment	RCI Improvement	BCI Improvement
Routine Maintenance	0.615 units	5 units
Preservation	1.845 units	15 units
Rehabilitation	up to 8.73 units	up to 100 units

For the pavement sub-asset, condition improvement related to routine maintenance is derived at by multiplying deterioration rate of 0.123 RCI units / year by a factor of five. This assumes each section will remain above its pre-treatment condition for the next five years. A preservation treatment is derived by multiplying the deterioration rate by a factor of fifteen, representing a condition higher than the initial for the next fifteen years. A rehabilitation treatment represents an increase to a maximum assumed condition of 8.73 RCI units.

For bridges, maintenance and preservation treatments increase the condition such that time durations of five and fifteen years is required for it to return to its pre-treatment BCI level, respectively. A rehabilitation or replacement treatment causes an assumed increase in condition to a maximum of 100 BCI units.

Tables 3.3 to 3.8, summarize a variety of performance indicators and treatments used by various North American agencies. The intent of this section is not to develop a set of standardized values for investment planning purposes. Such a task is outside the scope of

this thesis. The purpose of introducing these values is to provide a basis for programming long-term investment plans in subsequent sections. In practice, each agency uses performance indicators and treatment options suitable to its environment and organizational capacity.

Generally, a highway agency includes an organizational unit for determining future pavement needs and a separate unit for determining future bridge needs. Subsequently, it is common for the majority of agencies to develop short, mid, and long term investment plans for pavement and bridge sub-assets through mutually exclusive processes. The following section introduces a concept aimed at developing a mutually inclusive process for long-term investment planning, by attempting to integrate bridge sub-asset into an equivalent pavement sub-asset. Subsequently, the intent is to develop one objective performance indicator for both sub-assets.

Conceptual Structural Integration Factor (CSIF)

Bridge and pavement sub-assets are inseparable in allowing for existence of controlled access highway networks in the developed world.

A trade-off analysis in the short-term plan of five years allows for a sufficient level of reliability. For example, if limited budget allows for repair of two bridges or one pavement section; assuming the former yields a higher performance increase for the bridge network and the latter for the pavement network, the option of repairing two bridges will likely be pursued by the agency. However, this approach decreases in reliability as the planning period increases. This is mainly due to increasing uncertainty in predicting future available budgets and asset performance for years 6 to 25. Subsequently, the potential for considering a trade-off analysis situation in a long term investment plan significantly decreases.

The Conceptual Structural Integration Factor (CSIF) aims to allow for reliable long-term trade-off analysis between the two sub-assets.

Given both asset types are made out of engineered materials, which require two different types of engineering expertise related to pavement and structural knowledge, the CSIF concentrates on the value of the three terms common to improving both sub-assets' conditions: routine maintenance, preservation, and rehabilitation.

Integration of a bridge to an equivalent pavement section includes the following steps as shown in Figure 3.3.

The average of three ratios represents CSIF. The deck area of a bridge is multiplied by CSIF to complete the integration. At this stage the bridge is considered an equivalent pavement section. However, in order to be treated as a pavement section in long-term planning, the following steps are necessary:

- BCI division by a factor of ten (10); and
- BCI interpretation as RCI with a 50 % lower deterioration rate for bridges than for pavement sections

The first step allows for proper scaling of the BCI scale of 0 to 100 with the RCI scale of 0 to 10. This avoids the need to develop a separate condition index representing both sub-assets. The 50 % lower deterioration rate for bridges is representative of a 15 year time frame to the first significant rehabilitation of a pavement section, and approximately a 30 year time span of the same for a bridge. The bridge time span is based upon a sample data set from the existing bridge network.

Tables 3.9 and 3.10 show average treatment costs per one square metre of a bridge deck and pavement section, respectively. Costs are based on the 2011 Parametric Estimating Guide published by the Ministry of Transportation of Ontario.

The square meter cost for structures is based on available deck area including 3.75 m wide lanes and 1.2 m sidewalks. Square meter cost for pavements is based on available

pavement area, with assumed 3.75 m wide lanes, 2 m shoulders, and a 3.75 m allowance for concrete barriers where applicable.

TABLE 3.9: Average Structural Treatment Costs

Structural Treatment Type	Cost ($) per squared metre
Routine Maintenance	555
Preservation	1663
Rehabilitation	2998

TABLE 3.10: Average Pavement Treatment Costs

Pavement Treatment Type	Cost ($) per squared metre
Routine Maintenance	31
Preservation	56
Rehabilitation	104

Cost ratios of information contained in the above tables and their average are calculated in Table 3.11.

TABLE 3.11: Structure to Pavement Treatment Cost Ratio

Treatment Type	Unit Cost ($) of Structure to Pavement
Routine Maintenance	18
Preservation	30
Rehabilitation	29
CSIF (average of ratios)	25

The average cost ratios of all treatment types, CSIF is calculated to be 25 when rounding is excluded from the process. The conversion formula for a structure to an equivalent pavement section is as follows:

Equivalent Pavement Section Area = Deck Area of Structure x CSIF (1)

Where:

Equivalent Pavement Section Area (square metres)

Deck Area of Structure (square metres)

CSIF value is the average of the three treatment types determined from Table 3.11 to be 25

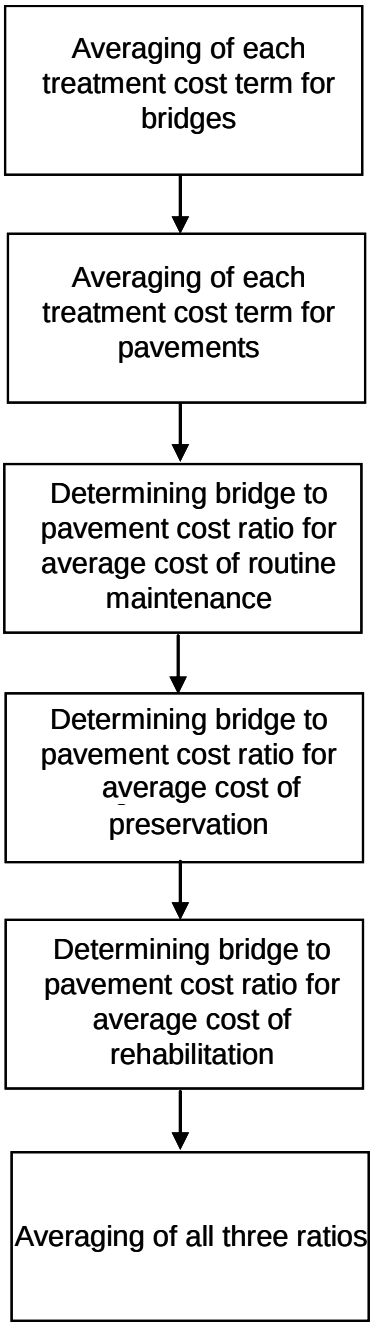


Figure 3.3: Conceptual Structural Integration Factor Development Process

Theoretically, CSIF accounts for material and labour difference of constructing a structure compared to an equivalent pavement section of typical cross sectional characteristic as per agencies design standards for specific site conditions.

The following explores the mechanics of the semi-automatic Microsoft Excel programming used to develop the 25 year investment plans.

Microsoft Excel Semi-Automatic 25 – Year Programming

In order to manipulate 25 years of performance, treatment, and funding data an Excel spreadsheet was developed. Figure 3.4 is a screen capture of the spreadsheet as programmed for the $ 120 M / year scenario for the mutually inclusive approach. In order to explain the programming logic, the screen capture is zoomed in and focused on approximately 5 % of the total spreadsheet area used.

Establishing an automatic relationship between performance, treatment and funding was essential. The three steps noted in purple borders contain the necessary code for this relationship. In step one, the year one treatment column cells check for the condition in year one condition column cells. Depending on where the condition value is with respect to in this case the pavement triggers shown earlier in Table 3.4 - an appropriate treatment is applied provided funding is available. In step two, the funding column cells check the treatment column cells for treatments. If a treatment is applied, the pavement area is multiplied by the corresponding unit cost shown earlier in Table 3.10. A value of three implies a rehabilitative treatment. A value of 1 and 2 represent routine maintenance and preservation, respectively. In case a treatment is not applied, the condition is decreased by 0.123 RCI units, as shown in step three on a different pavement section than the one used for illustration of the first two steps. The condition column checks the previous year's treatment column and updates the condition cell value accordingly.

Strategic implementation of treating high traffic volume pavement sections and bridges first is accomplished by sorting the spreadsheet according to number of lanes and condition, followed by sufficient removal of treatments such that the annual expenditure is below the allowed budget. The screen capture is

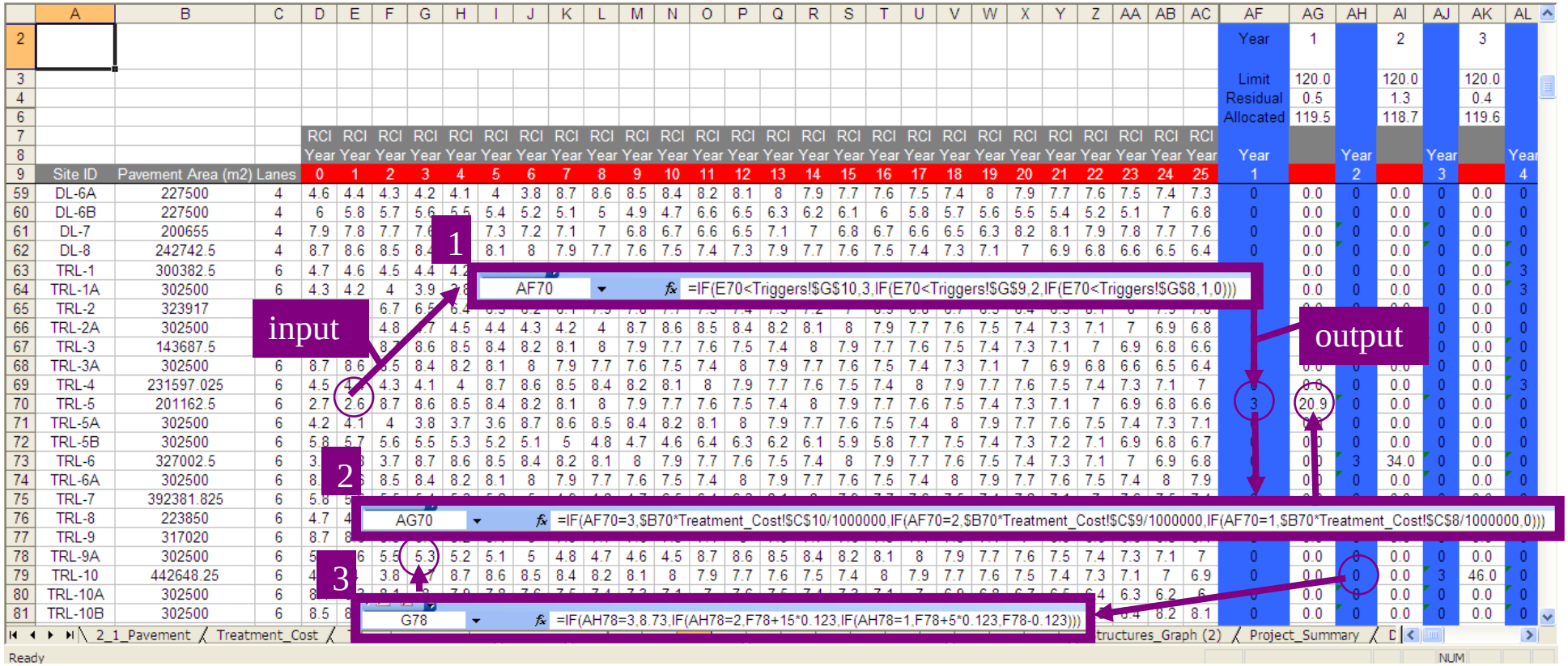


Figure 3.4: Semi-Automatic Microsoft Excel Program

taken after this process as the spreadsheet is sorted back to its original order necessary for efficient extraction of funding and treatment details per sub-asset network for reporting purposes.

Residual funds are not an uncommon occurrence as construction projects include a significant number of inputs from a range of regulatory, administrative and contracting organizations which are subject to varying degrees of uncertainty. In instances where demand of work exceeds capacity in any of the mentioned sectors, the likelihood of unused in year funds increases. Their magnitude and occurrence is also directly proportional to the planned program's reliability, which STHAMi aims to increase.

A regular task addressed by agencies in delivering a multi-year program is appropriate scaling of projects with respect to size such that delivery in design and construction stages can be executed in a timely manner. This challenge is reflected in the excel spreadsheet as there are instances where less urgent needs are addressed prior to higher ones in order to avoid exceeding the budget. In this case the higher priority project's size poses an issue.

Organizational Context – Mutually Inclusive versus Exclusive

This section aims to bring forth the importance of the organization in applying STHAMi. Furthermore, it touches upon the organizational / technological balance necessary for successful implementation of asset management processes. The mutually inclusive versus the mutually exclusive approach to long term investment planning is also explored.

Infrastructure as defined in the *Online Compact Oxford English Dictionary* is "the basic physical and organizational structures and facilities needed for the operation of a society". The 16th and 17th centuries are recognized as the commencement age of charted organizations or companies, which would eventually yield our modern day corporations. The Muscovy Company is the first joint-stock charted company in 1555. The oldest and still active multinational is the Hudson's Bay Company, dating back to 1670 (Micklethwait et al. 2003). For contextual purposes, one of the first crude-oil derived

and plant produced asphalt pavements was laid approximately more than two centuries later in 1907 (Pavement Interactive 2013).

A finite number of positions with a specific goal - is a slight modification of the dictionary's definition of an organization: "an organized group of people with a particular purpose". However, Depending on the network's size, today's managing agencies vary in the number and type of positions contained within. With respect to their goals, it is safe to assume they correspond to the Ministry of Transportation of Ontario's goal of providing a safe, reliable and sustainable transportation network.

In simple terms, the relationship between the asset (highway network) and the agency is one of care; where the agency continuously monitors, maintains, and improves the asset condition such that its societal role is fulfilled. The role being: the means to effectively and efficiently move citizens, goods, and services such that appropriate economic growth and living standard are achieved.

Information flow from the asset to the organization is the means by which this relationship is sustained. Hence, effective implementation of asset management processes will likely occur within the existing information flow. It is important to note that this flow cannot effectively be illustrated through a "silo" view of the organizational structure, as the core of the flow occurs across organizational units. For an asset management system to be effective, the umbrella for the asset management system must incorporate multiple business units and operations to achieve agency objectives (Tighe 2011).

The need to promote cross organizational coordination in an asset management process leads to more effective planning and decision-making. One of the most important starting points for implementing an asset management process is to conduct an organizational assessment (USDOT 2007). The strategic orientation of asset management demands a system that includes channels of communication which transmit the overarching information required by agency executives and front-line practitioners. It

should also supply information and coordinating mechanisms across functions and asset classes within the organization (USDOT 1999).

Figure 3.5 shows the general information flow through the Ministry of Transportation Ontario's organizational units. It was developed through an organizational assessment based upon organizational theory principles. The assessment was inspired by *The Goal* written by the late Dr. Goldratt (1984). The text on top of the boxes indicates the unit where the process is taking place, while the inside of the box indicates the process itself. Notes below the box indicate whether a process is mutually exclusive or inclusive with respect to pavement and bridge needs consideration. The goal of the figure is to illustrate the information flow from the asset to the strategic unit which is responsible for requesting infrastructure funding. Assuming similar size and complexity of network, it is likely that other public managing agencies entail a similar organizational information flow. Agencies with simpler networks likely entail a simplified flow. Steps 1 to 4 include operative units, while steps 5 and 6 include tactical and strategic units respectively. The diagram assumes the network is divided into areas, which aggregate to regions, which when aggregated, constitute the complete network. At step 5 the two different sub-asset needs are within one tactical unit. The term "prioritized" does not necessary mean a specific prioritization method was applied. The method by which prioritization is achieved is at the discretion of the respective agency, and may include optimization or other methods. Step 6 includes funding distribution upon request from the appropriate governmental body or other sources, as well as definition of funding constraints. Key to note is that none of the boxes contain a process where pavements and bridges are optimized as one asset in order to develop a long term investment plan.

STHAMi's "mutual inclusiveness" is directly derived from its implications within the organizational process, which is shown in Figure 3.6. Step 5 includes the integration of the bridge network into the pavement network, thereby providing a homogenous one asset. The subsequent optimization inherently trades-off pavements and bridges such that future condition of the asset is maximized. As in the mutually exclusive process, step 6 contains funding distribution and constraining; however, in this case it is according to a

cross-asset optimized plan. It is important to note that STHAMi can be applied at the area, region, or network level – the figure shows it at the regional level. The 25 year plan developed for this research is at the network level.

It is important to note that STHAMi does not impact how specific projects are delivered, but rather which projects are to be delivered and when. Therefore projects which are in any of the follwing phases are outside STHAMi's scope: Expression of Interest (EOI) preparation, Request for Proposal (RFP) or Request for Quotation (RFQ) preparation, design, tendering and construction. The goal of STHAMi is to provide a 25 year sequence of projects such that the highway network performance is maximized while funding optimized. Practical experience and targeted literature reviews indicate the current organizational processes within managing agencies to be mutually exclusive for long-term planning; because the bridge network needs and performance are determined without considering pavement performance, and vice versa. Furthermore, and most importantly, they do not consider performance maximization of the "highway network" of which both are integral parts. Performances of the bridge and pavement networks are expressed with completely different performance measures without a distinct relation between them, and without a unified performance measure for the highway network.

The following section includes 25 year investment plans for one model highway network developed through two mutually exclusive methods.

In terms of advancing asset management processes such as STHAMi within an agency, promoting on an individual basis rather than via e-mail or memo is recommended. Avoidance of overstating the benefits and concentration on what the process will allow the agency to do rather than what the promoter will do is suggested. Focusing on team collaboration rather than on an asset manager is likely to yield increased result effectiveness (Burns 2010).

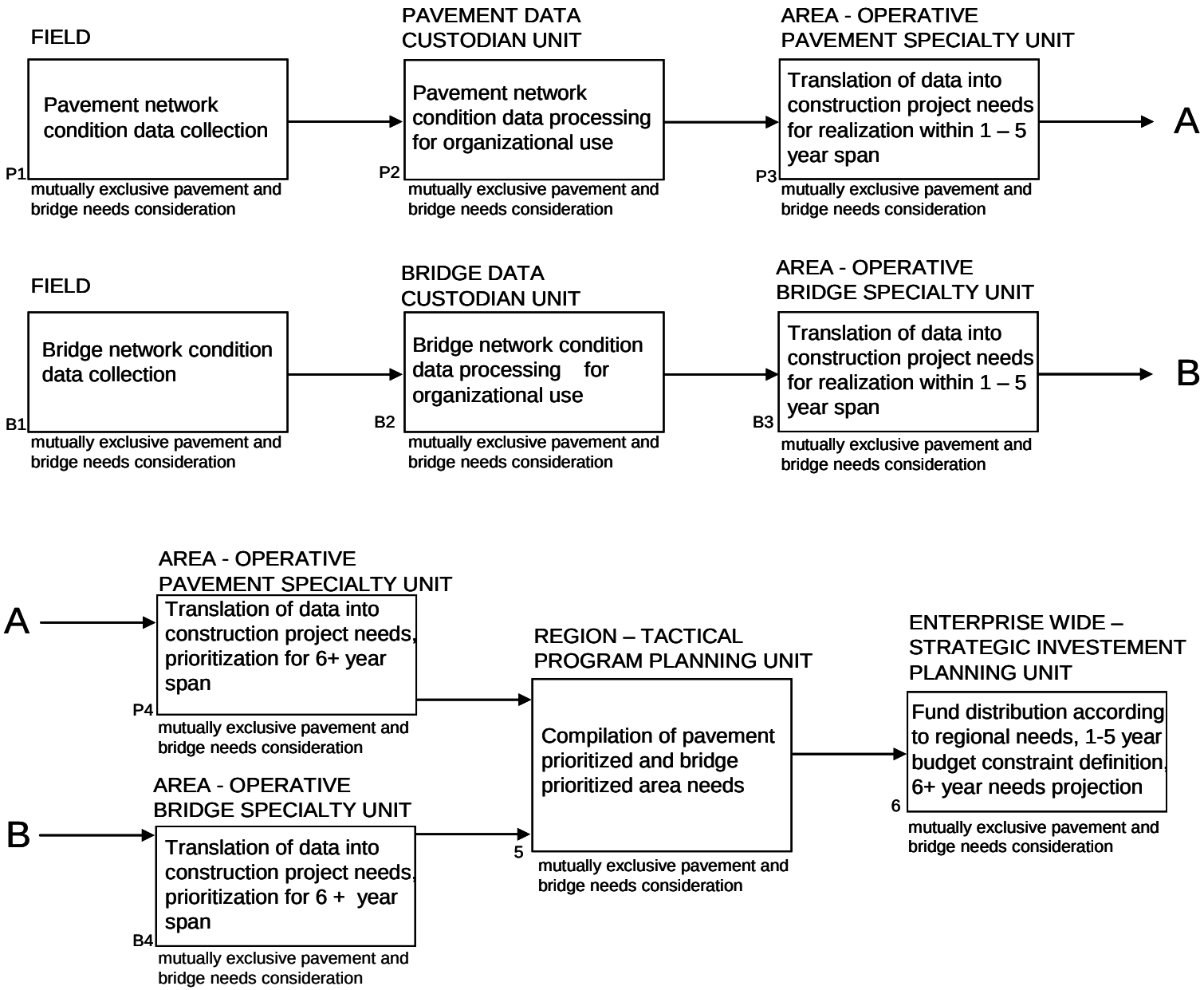


Figure 3.5: Mutually Exclusive Process – Current Pavement and Bridge Sub-asset Investment Planning Process

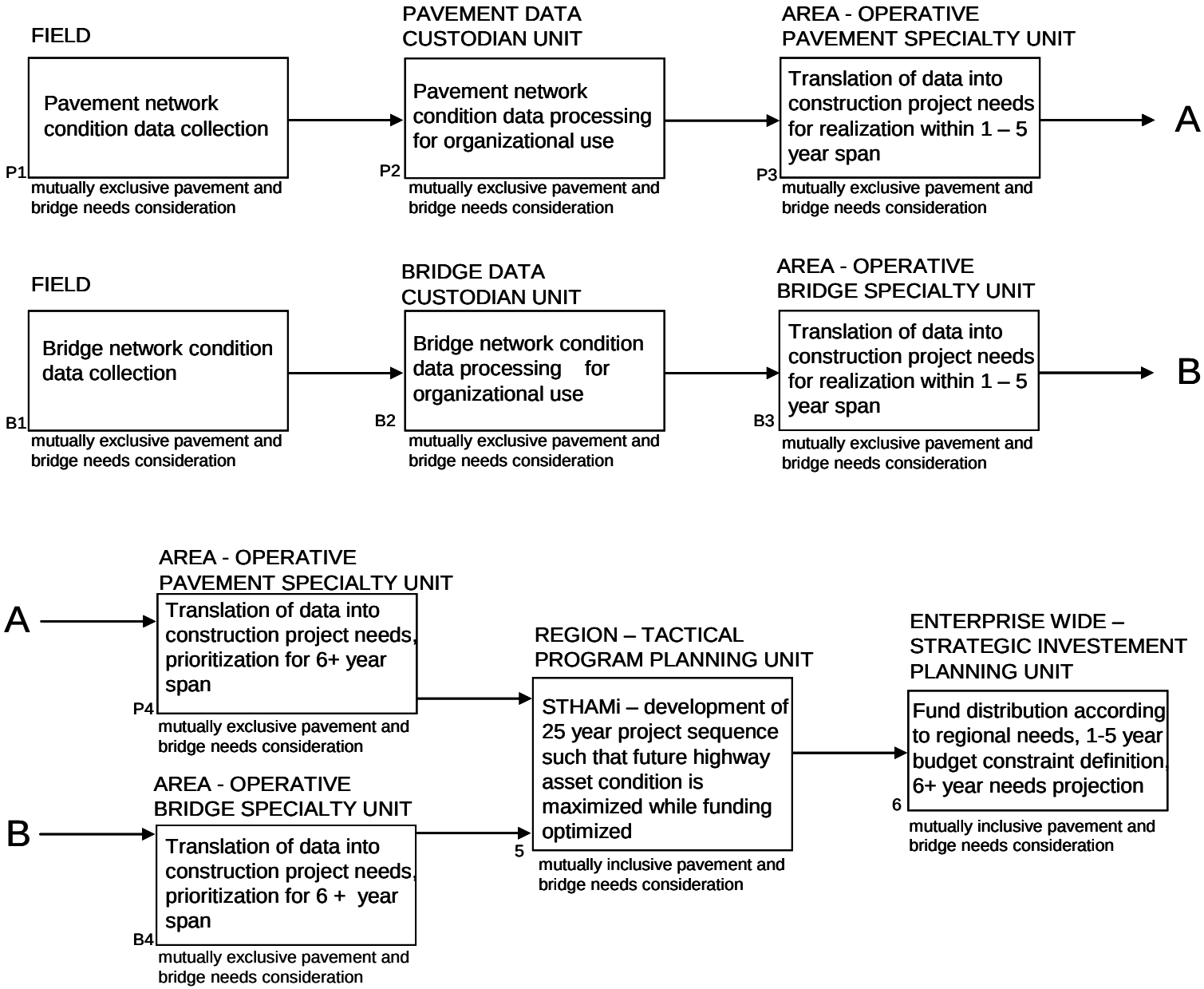


Figure 3.6: Mutually Inclusive Process – Proposed Pavement and Bridge Sub-asset Investment Planning Process

Drawing on experiences from other industries with respect to implantation of new processes - may yield an increased level of efficiency in asset management process implementation. For example, in the early 1990s the automobile industry went through a fundamental shift in its process of managing manufacturing. Emergence of commercial computer systems and their integration into existing organizational processes was assumed to be the way to improve the manufacturing plant's bottom line. Subsequent studies pointed out inconsistencies within the assumption. To reduce production and administrative throughput times, organizations had to create an integrated manufacturing system rather than simply introducing computers within existing organizational process. This was essentially an issue of organizational system design rather than technological system design (Duimering 1993).

Similarly, implementation of STHAMi or new software applications should be approached such that existing organizational processes incur minimal variances of input / output information necessary to fulfil their units' respective goals.

Chapter 4 - Analysis

Generally, a highway agency includes an organizational unit for determining future pavement needs and a separate unit for determining future bridge needs. Subsequently, it is expected that a majority of agencies develop short, mid, and long-term investment plans for the pavement and bridge sub-assets through mutually exclusive processes.

4.1 Mutually Exclusive Allocation of Sub-Asset Funds

This section includes a 25 year investment plan for the model network described in Section 3.0. Each sub-asset was analyzed independently with separate budgets.

Figure 4.1 illustrates the developed 25 year investment plan for the highway asset.

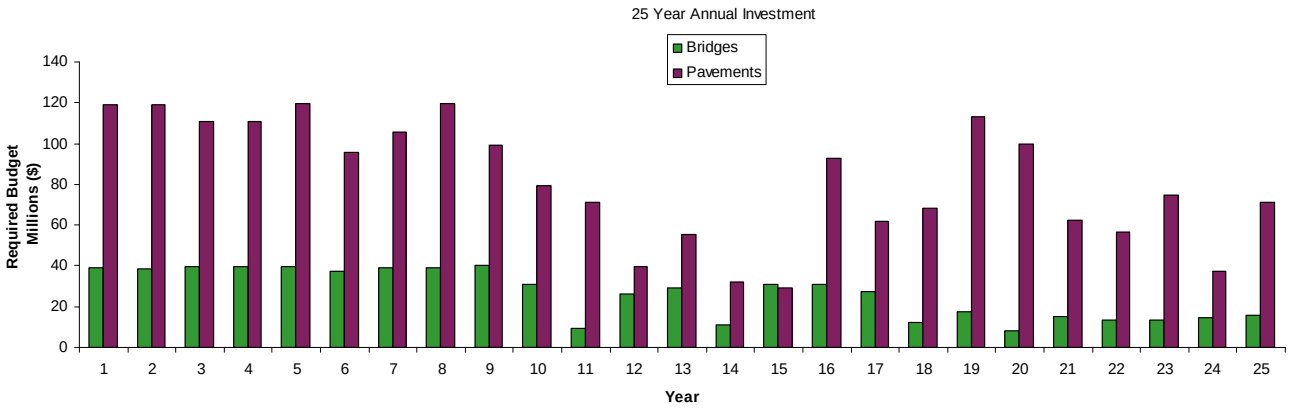


Figure 4.1: 25 Year Investment Plan – Current Practice (Mutually Exclusive)

The annual highway improvement budget spent in a specific Region of Ontario in the year 2011 was used as a starting point. Actual regional network size was compared to the model network.

After considering lower annual budgets through an iterative process, an annual budgetary constraint of $120 M for the pavement asset was determined to be appropriate in order to avoid a significant portion of the network performing below minimum thresholds.

A strategy for treating high traffic volume sections and bridges first was applied. A higher number of lanes in each direction is associated with higher traffic volumes.

Although CSIF was not used in this method for selection of pavement or bridge units for treatment, it played a significant role in determining annual budgetary constraint of $40 M for the bridge sub-asset. Once the entire bridge sub-asset was converted to an equivalent pavement network by using equation Formula (1), the pavement area was determined to be 34 % of the pavement sub-asset. Rounding down to 30 % of the pavement sub-asset's budget constraint was assumed satisfactory.

Present worth value of the budget needs at a 5 % discount rate results in $418 M for the bridge sub-asset with an average 25 year BCI of 71. The BCI is at the middle point of "good" rating category. The initial BCI value of the bridge network was 61.

The present worth value of the budget needs at a 5 % discount rate equals to $1,243 M for the pavement sub-asset with an average 25 year RCI of 7.19. The RCI is at the middle point of "good" rating category. The initial RCI value of the pavement network was 6.

The investment bar graph pattern indicates significant investments in preservation and rehabilitation of the network in the first ten years are required, followed by 15 years of routine maintenance and preservation. Figures 4.2 and 4.3 provide an illustration of this pattern.

The Figure 4.2 was developed using the annual tracking funds spent on each treatment category.

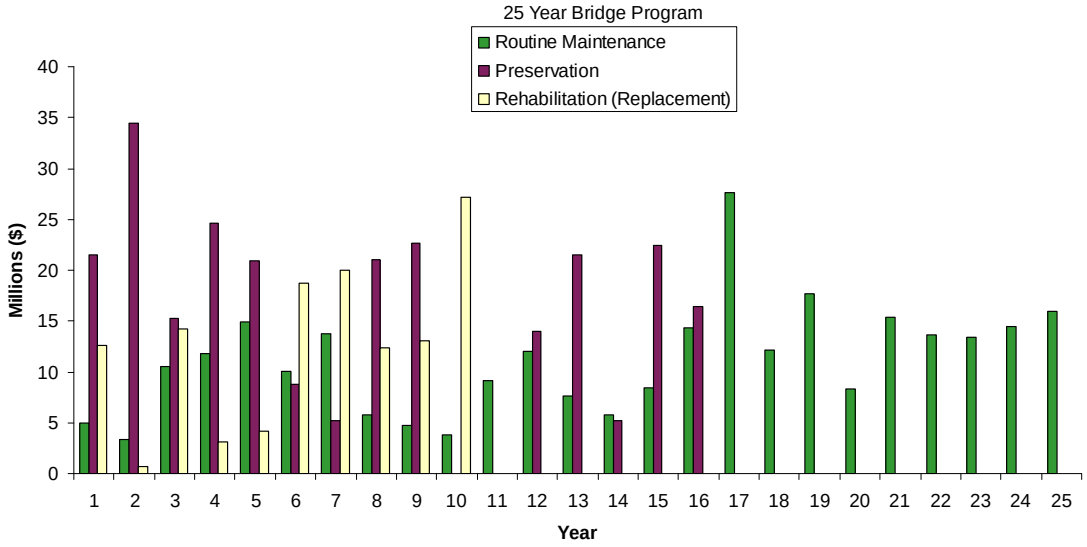


Figure 4.2: Maintenance – Preservation – Rehabilitation Breakdown for Bridge Sub-Asset Current Process (Mutually Exclusive)

Relative to the pavement network, bridge sub-asset includes a greater balance between the three treatments in the 10 to 15 year span. The pavement sub-asset includes a higher focus on rehabilitation treatments in the 10 year span. Drop-off of needed investment to maintain a sustainable network condition around year ten is expected given preservation and rehabilitation treatments yield generally a minimum 10 - 15 year conditional sustainability of the highway network. A ten to fifteen year span includes a mix of maintenance and preservation treatments, with the former dominating.

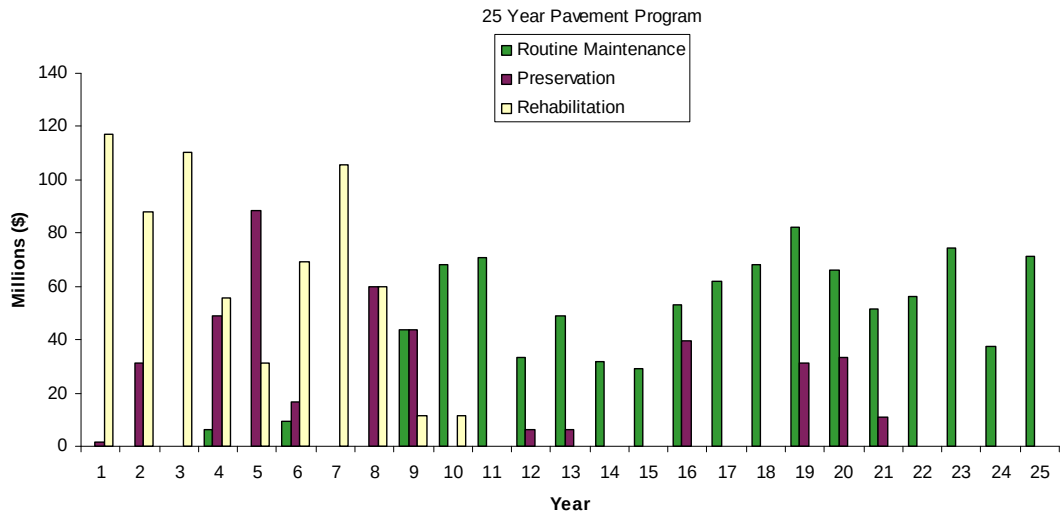


Figure 4.3: Maintenance – Preservation – Rehabilitation Breakdown for Pavement Sub-Asset (Mutually Exclusive)

Appendix B contains data related to the figures shown above.

The investment-needs pattern is representative of historic highway asset deterioration and rehabilitation behaviour, it should be noted that the budgetary allowance of the plan is highly optimistic and inconsiderate of economic uncertainty.

The programming method is semi-automated, with the goal of optimizing allowed budget while maximizing sub-asset performance. Full programming automization is encouraged; however, a thorough manual review of the resulting long-term plan is strongly suggested due to economic value of commitment and magnitude of risk due to potential errors resulting from automization.

Figures 4.4 and 4.5 illustrate average bridge and pavement condition performances, respectively.



Figure 4.4: Bridge Sub Asset – 25 Year Average Performance (mutually exclusive)

The upper half of the "good" average rating of bridge network is reached in year nine (9). Maximum rating of 76.5 BCI is reached in year 18. For pavements, the upper half of the "good" average rating range is reached in year seven (7). The maximum rating of 7.59 RCI is reached in year 12. Performance curves for both sub-assets are considered optimistic due to a relatively stable allowable budget assumption. Variation of annual

budgets and performance targets is encouraged in developing optimal sequence of sections, bridges, and corresponding treatments aimed at maximizing highway asset performance through optimization of available means.



Figure 4.5: Pavement Sub Asset – 25 Year Average Performance (mutually exclusive)

Figures 4.6 and 4.7 show the overall condition distributions for pavements, and bridges; respectively.

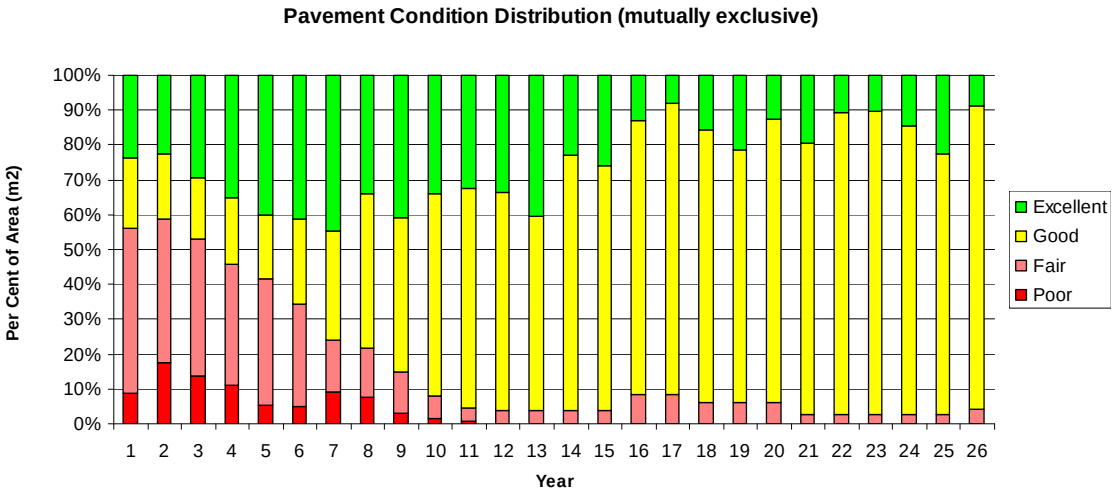


Figure 4.6: Pavement Sub-Asset Condition Distribution (Mutually Exclusive)

As noted Figure 4.6, the poor condition is completely treated or eliminated in year 12, from its maximum amount at approximately 20 % in year two. Less than 10 % of the pavement network is currently performing in the fair condition in year ten, down from its peak in year one at around 50 %. This is maintained below ten per cent for the remainder of the analysis period. From its minimum at around 15 % in year three, good condition rating is above 50 % in year ten. The increasing trend continues in the remaining 15 years with a maximum reach in year 23 at approximately 85 %. The category of pavement in the excellent network condition increases to its maximum in year five to approximately 45 % from there exhibiting a relatively consistent decreasing trend to approximately 20 % in the finishing years of the analysis period.

Overall, the distribution trend corresponds to an aggressive rehabilitation strategy in the first decade as shown in Figure 4.3. This yields the greatest increase in the "excellent" portion of the network initially due to rehabilitation treatment's capability of increasing section's condition to maximum irrelevant of its initial condition.

The poor condition is completely treated or eliminated in year 11, from its maximum amount at approximately 7 to 8 % through out the first eight (8) years.

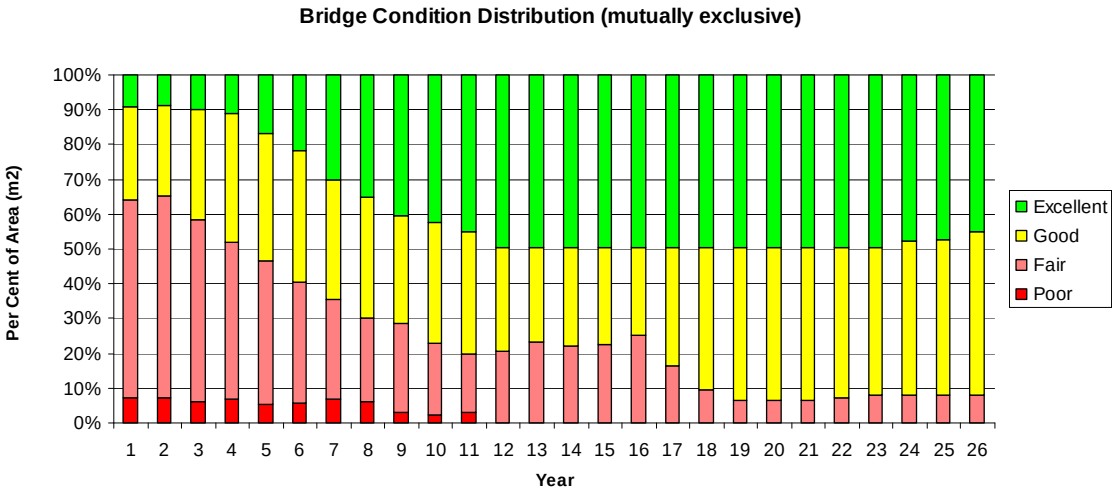


Figure 4.7: Bridge Sub-Asset Condition Distribution (Mutually Exclusive)

From approximately 55 % in year one (1) "fair" condition percentage decreases linearly to approximately 20 % in year 10, remaining around the mark for the next seven years,

decreasing to approximately 10 % in the last eight years. The good condition distribution is relatively consistent for the first 17 years at around 30 %, increasing to 40 % of the network for the last seven years. The excellent network condition increases to its max in year 12, from 10 % in year one to approximately 50 %; remaining consistent over the rest of the analysis period. The distribution trend corresponds to an aggressive rehabilitation strategy in the first decade as shown in Figure 4.2.

Maintaining 50 % of the network in excellent condition for the first 12 years is attributed to two factors. First, this results in a 50 % slower deterioration rate than the pavement sub-asset, and a condition improvement to 100 BCI associated with a rehabilitative treatment. While the deterioration rate is likely within an observable range in the field, the condition improvement assumption is highly optimistic. The implication is that 100 % of all structural projects produce products carrying 100 % effectiveness with respect to agency's related performance provisions. This is not the case with the pavement sub-asset as the maximum RCI level is 8.7. The appropriate level of the BCI improvement associated with a rehabilitative treatment is subject to agency consideration.
Appendix C contains tabular performance information.

Inherit deficiency of this long-term planning approach involves two separate sub-asset networks, with separate budgets, and more importantly, two different performance indices for one highway asset.

Redundant performance indicators yield uncertainty due to lack of an indicator assuring independent sub-asset budget optimization and performance maximization yields an identical result with respect to the one highway asset network.

While conventional sub-asset trade-off analysis has the potential to assure this in the short term, its reliability over long-term is questionable.

The following section reviews a 25 year investment plan results via an integrated sub-asset approach.

4.2 Mutually Inclusive (Integrated) Allocation of Sub-Asset Funds

This section includes a 25 year investment plan for the model network described previously. The bridge sub-asset is integrated into an equivalent pavement sub-asset through the Conceptual Structural Integration Factor (CSIF) described earlier.

Figure 4.8 illustrates the resulting 25 year investment plan for the highway asset.

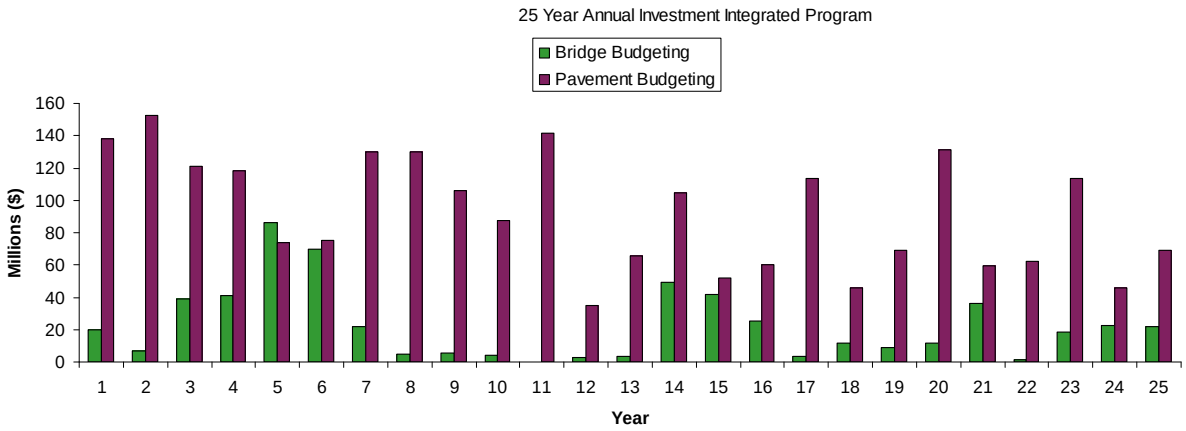


Figure 4.8: 25 Year Investment Plan - Highway Asset (mutually inclusive)

Combining $120 M for pavements and $40 M for bridges a total budgetary allowance of $160 M per year is maintained as per the previous method of 25 year programming. The same strategy of treating high traffic volume sections first was applied. A higher number of lanes in each direction is associated with higher traffic volumes.

The total present worth value at a 5 % discount rate, is $1,734 M, with an average RCI of 7.4. Considering structures as equivalent pavement sections, their present worth value is $344 M of the total value, with $1,390 M allocated to actual pavement sections.

Figure 4.8 is illustrative of the integrated approach's ability to annually balance investment between pavement and bridge sub-assets over time; such that overall asset condition is maximized through budget optimization.

The investment bar graph pattern is indicative of significant investments into preservation and rehabilitation of the network in the first nine years, followed by 16 years of mainly routine maintenance and preservation. Figure 4.9 illustrates this pattern.

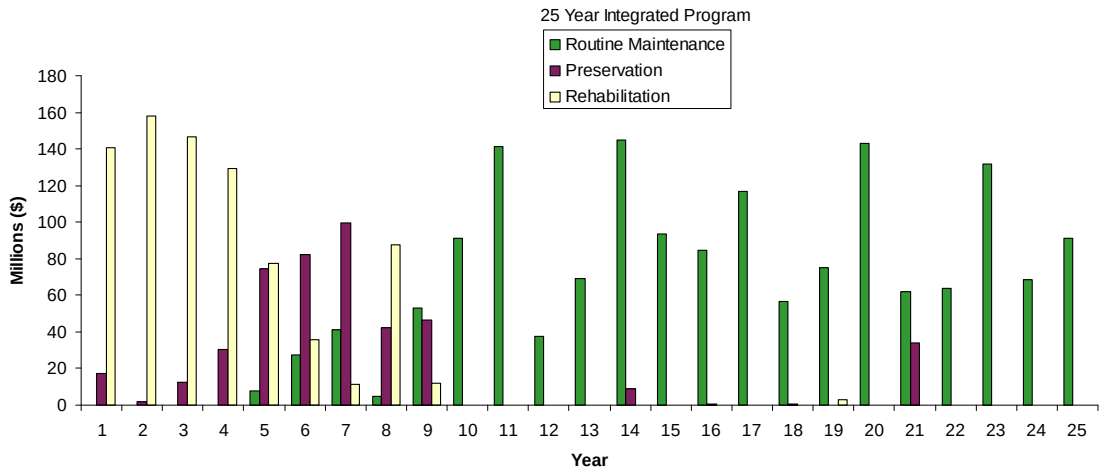


Figure 4.9: Maintenance – Preservation – Rehabilitation Breakdown for Integrated Asset Management (mutually inclusive)

Appendix B contains data related to the figures shown above.

A reduction in the required needed investment to maintain a sustainable network condition around year nine is expected as the preservation and rehabilitation treatments yield generally a minimum 10 - 15 year conditional sustainability of the highway network. The twenty five year span includes a mix of maintenance and preservation treatments, with the former dominating.

The budgetary allowance of the plan is optimistic and does not consider economic uncertainty, while the investment needs pattern is relatively representative of historic highway deterioration and rehabilitation behaviour.

Full programming automization with expert review of the long-term plan is recommended. Review will minimize potential errors due to full automization.

Economic value of commitment and magnitude of risk in case of potential errors associated with automization are significant.

Figure 4.10 illustrates an average highway asset condition. The condition is expressed in terms of RCI which may be considered as representing Highway Condition Index (HCI) due to the integration of the structural network into an equivalent pavement network. This avoids the need for agencies to develop highway condition indices which may likely be subject to variability and subsequently require a period of time for standardization across the industry. The use of RCI or other already developed pavement performance measures would avoid such a process. The industry already uses indices such as the International Roughness Index, Structural Adequacy Index, and Surface Distress Index (Tighe 2011).

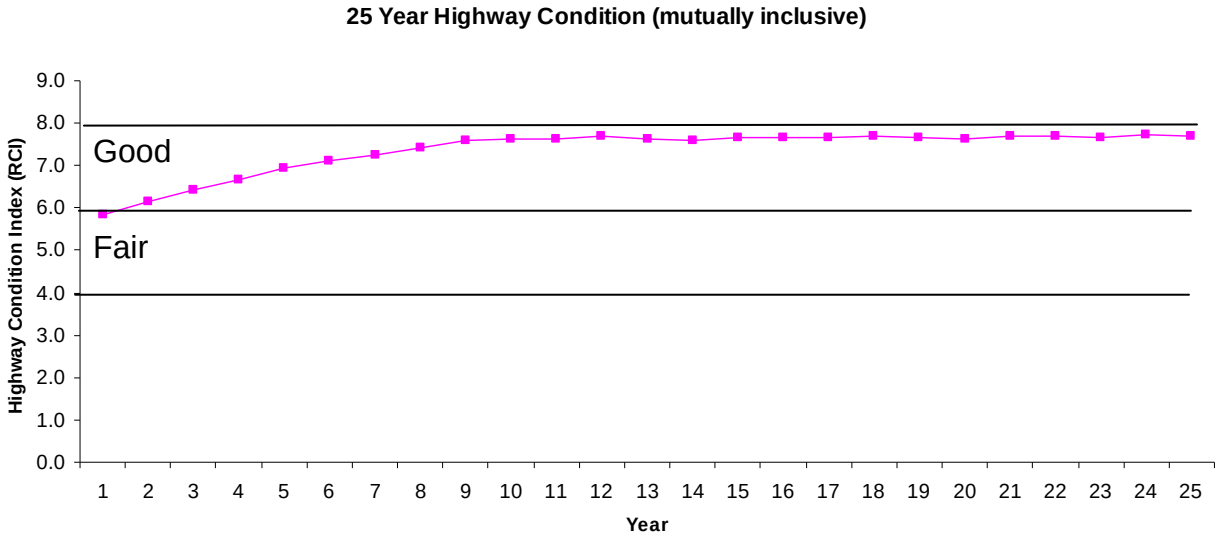


Figure 4.10: Highway Asset – 25 Year Average Performance (mutually inclusive)

The upper half of the good average rating range is reached in year six. A maximum overall rating of 7.7 RCI is achieved in years 22 and 24.

The performance curve is considered optimistic due to a relatively stable allowable budget assumption. Variation of annual budgets and performance targets is encouraged

in developing optimal sequence of sections and corresponding treatments. This flexibility will allow an agency to account for potential variations in forecasted budgets due to economic uncertainty, thereby maximizing highway asset performance through optimization of available funds.

Figures 4.11, 4.12, and 4.13 show resulting condition distributions for pavements, bridges and the highway; respectively.

The poor condition is completely eliminated in year 10, from its maximum level of approximately 20 % in year two. Less than 10 % of the pavement network is in fair condition in year ten, down from its peak in year one at around 50 %; and is subsequently eliminated. From its minimum at around 15 % in year three (3), good condition rating is above 50 % in year ten. The increasing trend continues in the remaining 15 years with a maximum reach in year 20 at approximately 90 %. The excellent network condition increases to its max in year five at approximately 50 %, from there exhibiting a relatively consistent decreasing trend to approximately 20 % in the finishing years of the analysis period.

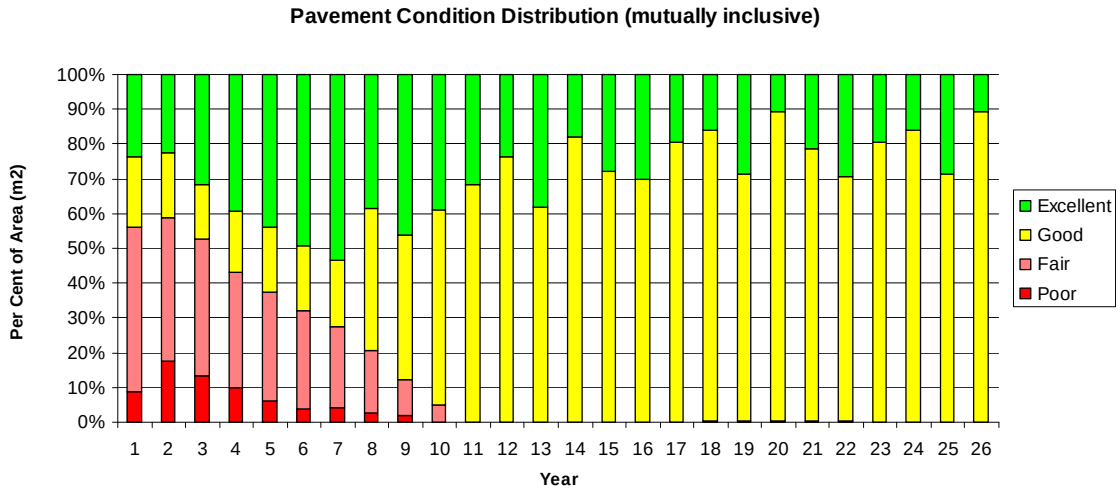


Figure 4.11: Pavement Sub-Asset Condition Distribution (mutually inclusive)

Overall, the distribution trend corresponds to an aggressive rehabilitation strategy in the first decade as shown in Figure 4.9. This yields the greatest increase in the excellent

performance rating portion of the network initially due to rehabilitation treatment's capability of increasing section's condition to maximum irrelevant of its initial condition.

In figure 4.12 the poor condition is completely treated or eliminated in year five, from its maximum amount at approximately 8 % in the first two years. From approximately 55 % in year one the fair condition is eliminated in year eight, with a slight increase in years 16 to 22. A good condition distribution is consistent for the remaining 18 years at approximately 60 %. The excellent network condition increases to its maximum in year 18, from 10 % in year one to approximately 50 %; varying between 20 to 30 % in the last several years of the analysis period.

The distribution trend corresponds to an aggressive rehabilitation strategy in the first decade as shown in Figure 4.9.

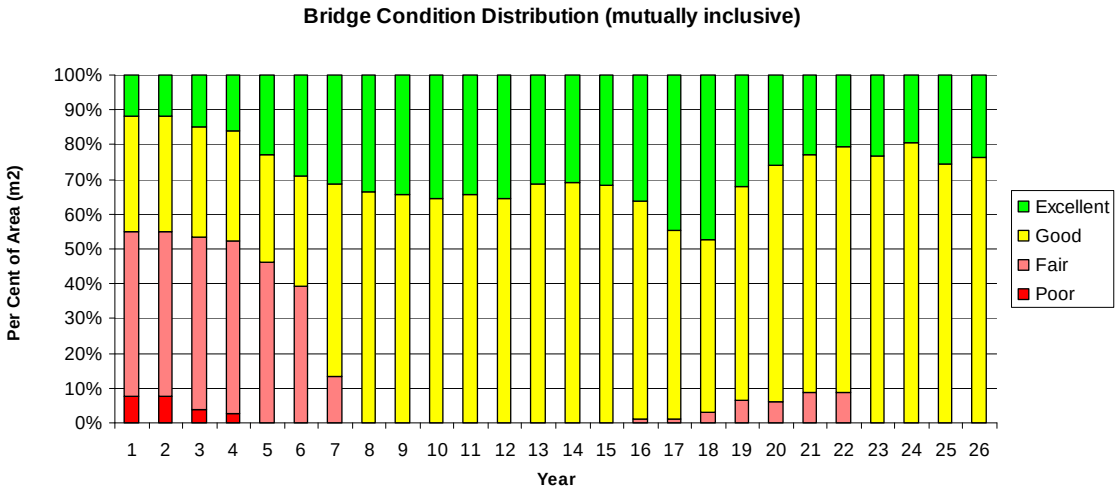


Figure 4.12: Bridge Sub-Asset Condition Distribution (mutually inclusive)

Figure 4.13 is representative of the highway asset condition, where the pavement and bridge sub-asset performance is observed as one. Overall, the poor condition is completely eliminated in year 10, from its maximum amount at approximately 20 % in year two. The fair condition is eliminated in year 11 from its peak in year one at around 50 %.

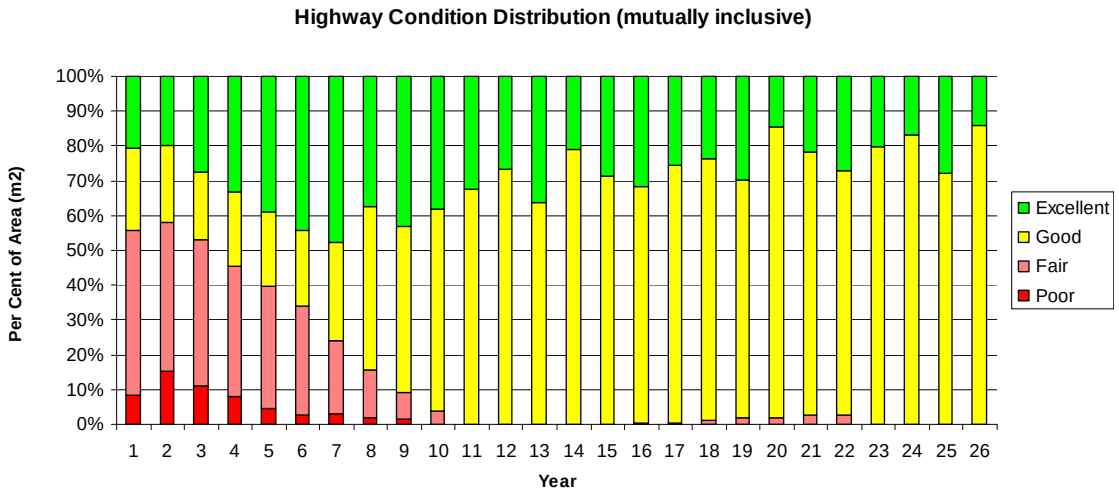


Figure 4.13: Highway Asset Condition Distribution (mutually inclusive)

From its minimum at around 15 % in year three (3), and the good condition rating is above 50 % in year ten. The increasing trend continues in the remaining 15 years with a maximum reach in year 20 at approximately 80 %. The excellent network condition increases to its maximum in year seven at approximately 50 %, from there exhibiting a relatively consistent decreasing trend to approximately 20 to 30 % in the finishing years of the analysis period.

Overall, the distribution trend corresponds to an aggressive rehabilitation strategy in the first decade as shown in Figure 4.9. This yields the greatest increase in the "excellent" portion of the network initially due to rehabilitation treatment's capability of increasing the sections condition to maximum irrelevant of its initial condition.

Appendix C contains tabular performance information.

Inherit deficiency of two separate sub-asset networks, with separate budgets, and most importantly two different performance indices for one highway asset are eliminated through application of CSIF.

Through direct integration of BCI into RCI, developing an independent highway asset condition index is avoided. With the actual pavement sections and the equivalent

pavement sections based on the structural equivalent, the reliability of the long term trade-off analysis is significantly increased due to the consideration of one asset and one performance measure.

The following chapter contains a sensitivity analysis of two methods used to develop two long-term investment plans.

Chapter 5 – Evaluation of Alternatives

The evaluation of the two investment methods includes economic, network performance, and organizational aspects.

Table 5.1 contains a comparison of the methods' respective effectiveness for maximizing the area of network treated by optimization of funds. The present worth value, area of network treated, and resulting "benefit / cost" ratio expressed as area of network treated per one unit of value, are shown in the first five columns of Table 5.1.

STHAMi, or a mutually inclusive planning approach, results in 12.8 % increase in the investment effectiveness when compared to mutually exclusive sub-asset planning, as shown with method B, mutually inclusive one asset approach.

The percentage of increased investment effectiveness is slightly higher at 14 % when the CSIF factor is used to convert to the actual bridge sub-asset from equivalent pavement section representation. The use of actual bridge deck area and corresponding treatment cost application results in a $30 M lower bridge budget of $314 M from $344 M. This conversion is necessary for assessing exact value of the long-term bridge sub-asset program. Actual bridge costs are shown rather than equivalent pavement section costs. This is done by first calculating the equivalent section's "present worth value" to "non-discounted value" ratio, than multiplying the "non-discounted value" of actual bridge costs by the ratio. It is important to note that the 25 - year programs for method B and C are the same, that is the same sequence of bridges is treated.

In addition, for improved investment effectiveness, STHAMi resulted in a slightly higher average asset performance level of 7.36 RCI compared to 7.19 RCI. Figure 5.1 illustrates the performance gap over the long term.

TABLE 5.1: Economic Alternative Comparison

Long Term Planning Method	Pavement PW ($ M)	Bridge PW ($ M)	Total PW ($ M)	Area (meters squared)	Meters Squared / $	Increased Investment Effectivness (%)
(A) Mutually Exclusive Sub-Asset Approach	1,243	418	1,661	45,183,045	27,202	Benchmark
(B) Mutually Inclusive One Asset Approach	1,390	344	1,734	54,089,941	31,198	12.8
(C)Conversion of Equivalent Pavement to Bridge Asset	1,390	314	1,704	54,089,941	31,742	14.3

With the exception of 12 to 15 year range and 19 to 21 time span, the bridge sub-asset years, a mutually exclusive method of investment planning consistently yields a lower annual performance level of the network over time. STHAMi demonstrates a higher level of goal attainment with respect to maximizing network performance by optimization of value.

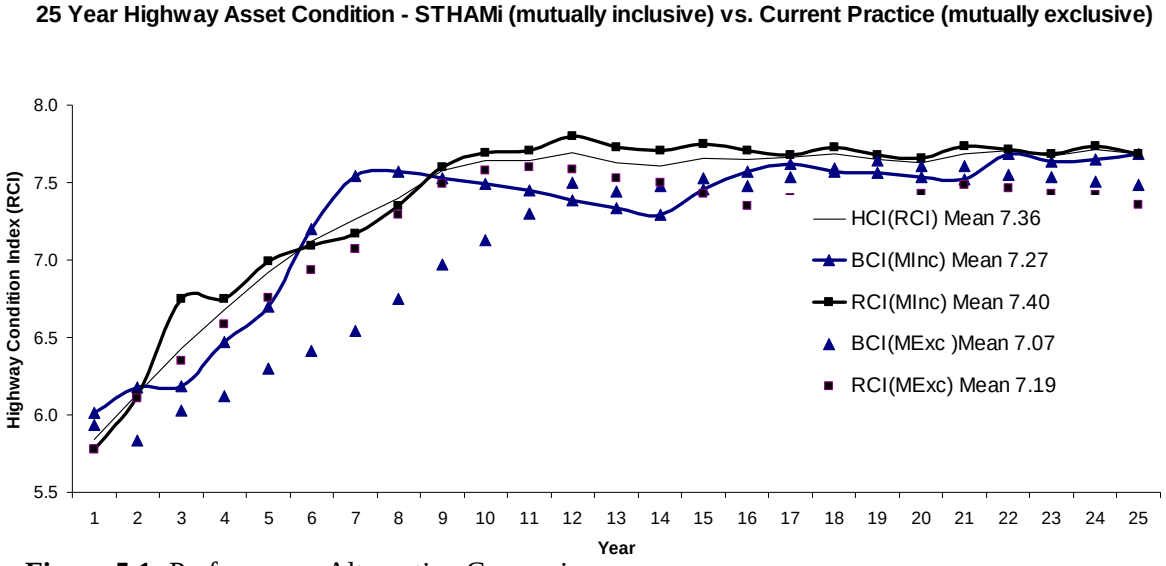


Figure 5.1: Performance Alternative Comparison

A potential explanation of the above pattern is the agencies lack of flexibility in balancing long term budgets between two main sub-assets of bridges and pavements. By treating them as completely separate networks and developing long-term prioritization needs in separate organizational units, the potential for debt incurrence due to unused funds and sub-optimal performance of the highway asset increases.

STHAMi also offers operational advantages to a managing agency, by using CSIF all long-term investment planning can potentially be completed within one organizational unit with one set of expertise. It is important to note that this does not entail an impact on the existing processes of the pavement and bridge units - where the majority of the focus is on the operational or project delivery level. Rather, a potential opportunity exists to

increase the agencies' ability to develop reliable sequences of projects over the 6 to 25 year planning horizon. In Canada 70 % of provincial agencies use a planning horizon of 3-5 years, while 15 % use a planning horizon of greater than 10 years (Tighe 2011). Assuming the term "planning horizon" entails a projected lump sum value of future needs, STHAMi has the potential to interpret it as an optimal sequence of projects over the same period. STHAMi allows for this sequence development process to occur within one organizational unit. Assuming current practice for the 15 % of agencies with a planning horizon greater than 10 years involves a bridge and pavement organizational unit, STHAMi would theoretically increases an agency's operational efficiency related to long-term planning by 100%. Furthermore, it has the potential to provide the other 70 % of agencies with an effective means of expanding their 3-5 year planning horizons to 25 years. It is important to note that STHAMi's epicentre is at the strategic and tactical positions of an organization, the continued need for bridge and pavement expertise at the project level or operational level would not be impacted.

Another advantage of STHAMi is the ability to express highway asset condition with one performance indicator. This allows optimization of highway asset performance with "one objective" function. Equally important, is that this indicator is not a new term with which the industry would have to familiarize itself with, but rather BCI can be integrated into existing pavement performance indicators of agency's choice, such as RCI. Subsequent to integration, the RCI may be interpreted as being the Highway Condition Index (HCI).

Based on the analysis, maximized network performance, maximized optimization of funds, and significantly improved organizational efficiency, STHAMi has been shown to outperform the method of treating bridge and pavement sub-assets as separate networks in long term planning development.

Chapter 6 – Sensitivity Analysis – 75 % of Original Annual Budget

This chapter contains a sensitivity analysis of the two 25 year investment plans by lowering the annual budget to 75 % of the original. Subsequently the mutually exclusive plan includes $ 30 M / year and $ 90 M / year for the bridge and pavement networks, respectively. STHAMi's mutually inclusive plan includes an annual budget restriction of $ 120 M which is 75 % of the original $ 160 M / year. The following section contains a sensitivity analysis of the mutually exclusive programming process currently applied in the industry. It is important to note that a focus is placed on comparing the performance of each program's distribution curve relative to the other, rather than on the corresponding percent distribution values.

6.1 Mutually Exclusive Allocation of Sub-Asset Funds – Sensitivity Analysis

Figure 6.1 is an illustration of the annual pavement and bridge investments showing the original and the 75 % annual budget scenarios for the mutually exclusive approach. The curved dotted lines will represent the original $ 160 M annual budgeting trends through out the sensitivity graphs of this chapter; while the solid straight lines represent the $ 120 M annual budgeting restriction.

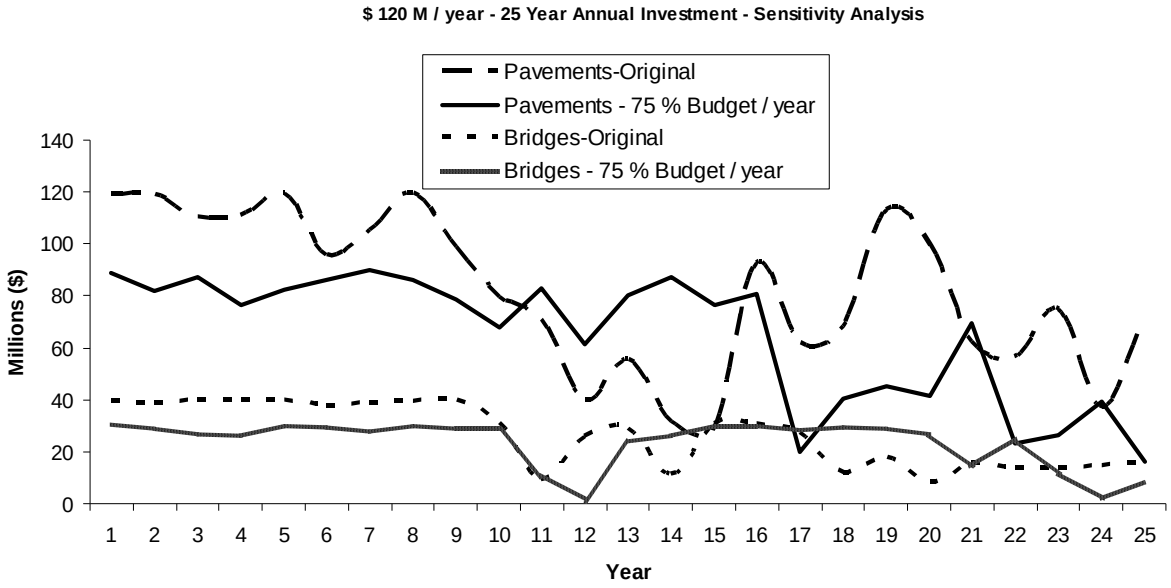


Figure 6.1: 25 Year Investment Plan – Current Practice (mutually exclusive) – Sensitivity Analysis

The top curved and dashed line shows the result of the sensitivity analysis in the original funding trend for the pavement network. The top solid line shows the impact of 75 % of the original budget for the pavement funding trend. The original scenario hovers around the maximum mark of $ 120 M / year for the first nine years, while the 75 % scenario hovers around its maximum of $ 90 M / year for 16 years. The additional seven years is the time required for the second scenario to address pavement needs which the original scenario was able to address earlier due to a 25 % higher funding allowance. The bridge funding trend is maximized for the first 9 and 10 years of the original budget scenario and 75 % funding scenario, respectively. Maximized bridge funding is continued from year 13 to 20 for the 75 % funding scenario, while the original budget scenario remains below maximum for the remainder of the analysis period. As with the pavement network, this is likely representative of the original scenario's ability to address needs earlier due to greater budget allowance.

Figure 6.2 shows sensitivity analysis results with respect to the excellent and good bridge network distributions.

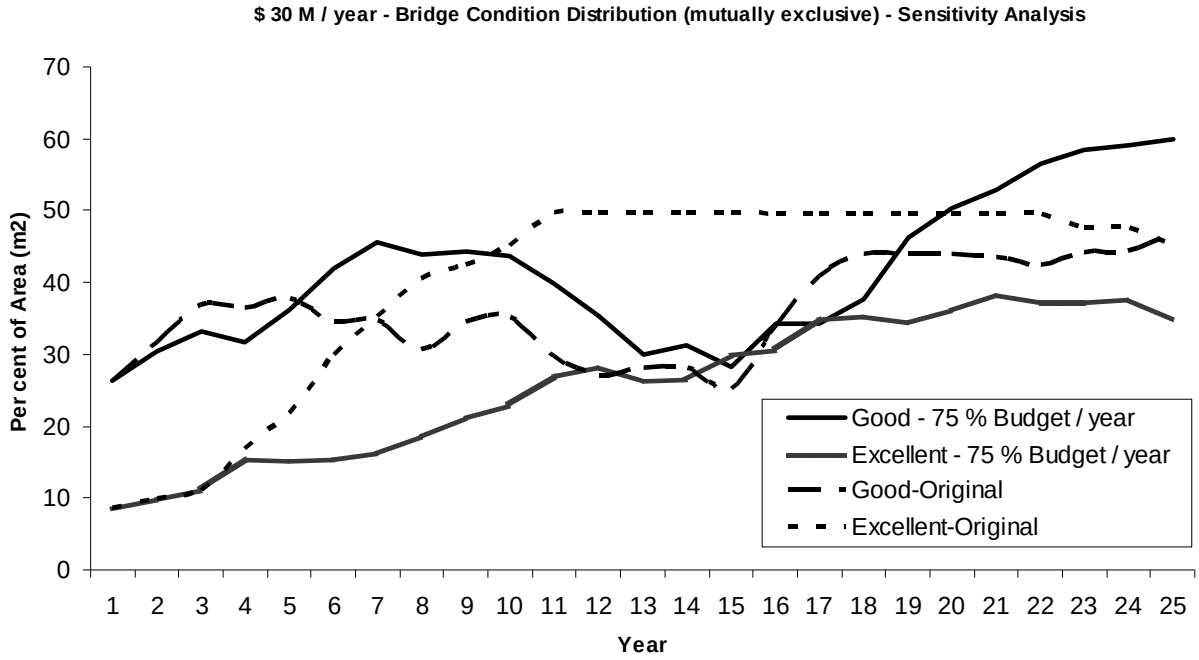


Figure 6.2: Excellent and Good Bridge Sub-Asset Condition Distribution (mutually exclusive) – Sensitivity Analysis

Both scenarios share increasing excellent condition trends over the majority of the analysis period. While the original funding scenario attains a peak of approximately 50 % excellent bridge area network condition in year 11, the second scenario achieves its peak of approximately 38 % in year 21. Complimenting this trend are the good condition - bridge network area distribution curves. The 75 % scenario exhibits a higher good condition percentage over the majority of the analysis period, this is mainly due to exhibiting a lower excellent condition as previously mentioned.

Figure 6.3 shows sensitivity analysis results with respect to the fair and poor bridge network distributions.

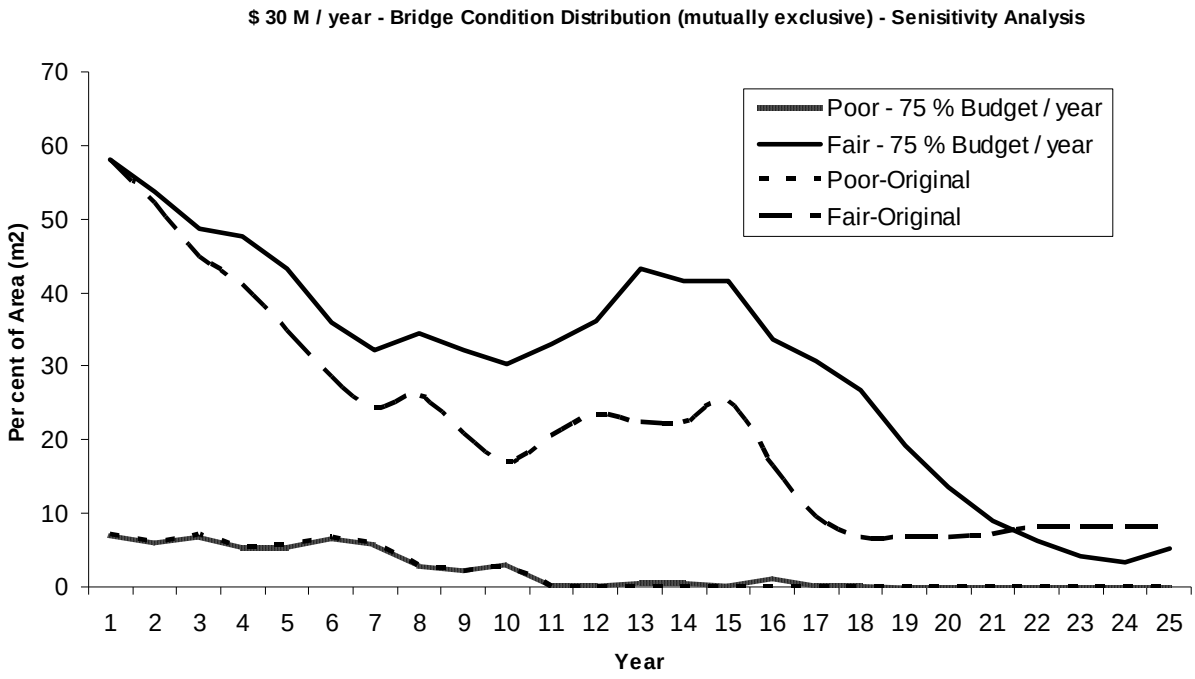


Figure 6.3: Fair and Poor Bridge Sub-Asset Condition Distribution (mutually exclusive) – Sensitivity Analysis

The poor condition curve is almost identical for both scenarios, however, the poor condition in the original scenario is eliminated in year 11; while the same occurs in year 19 for the second scenario. The general decreasing of fair condition is observed for both funding scenarios; however, other than the last four years, the original funding scenario exhibits a lower percentage of fair bridge network area.

Figure 6.4 shows sensitivity analysis results with respect to the excellent and good pavement network distributions.

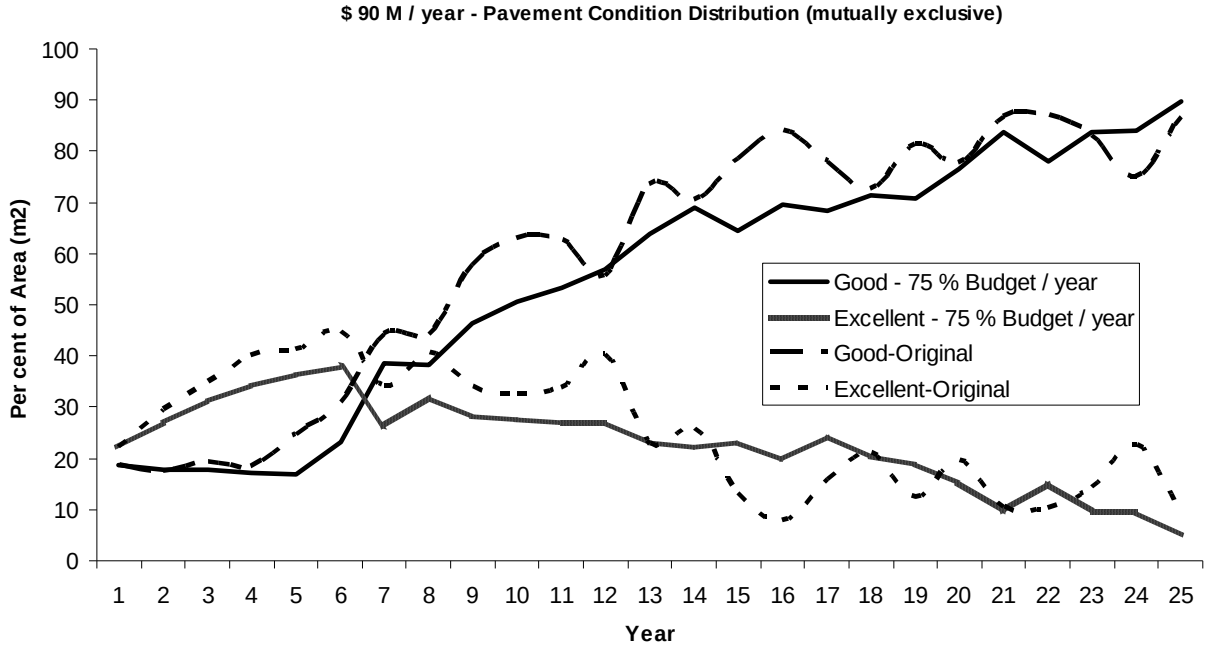


Figure 6.4: Excellent and Good Pavement Sub-Asset Condition Distribution (mutually exclusive) – Sensitivity Analysis

Both scenarios share decreasing excellent and increasing good condition percentages over the majority of the analysis period. The original funding scenario exhibits higher good condition distributions over the analysis period, with the exception of the last two years. Same trend is observed with respect to the excellent condition for the first 14 years, after which the 75 % scenario exhibits greater or equal excellent condition untill year 20.

Figure 6.5 shows sensitivity analysis results with respect to the fair and poor pavement network distributions

The fair and poor condition curves follow very similar trends for both scenarios; however, the original $ 160 M / year funding allocation is - as expected able to decrease both at a higher rate over the 25 year period.

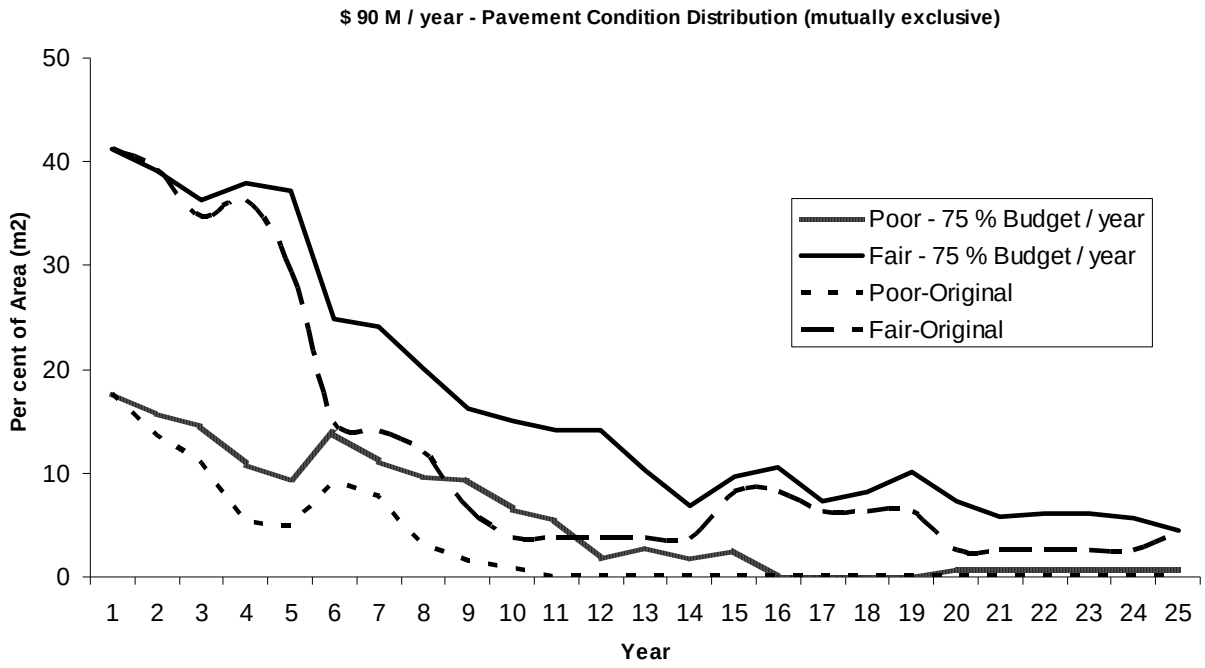


Figure 6.5: Fair and Poor Pavement Sub-Asset Condition Distribution (mutually exclusive) – Sensitivity Analysis

Figure 6.6 shows the average bridge sub-asset performance sensitivity analysis.

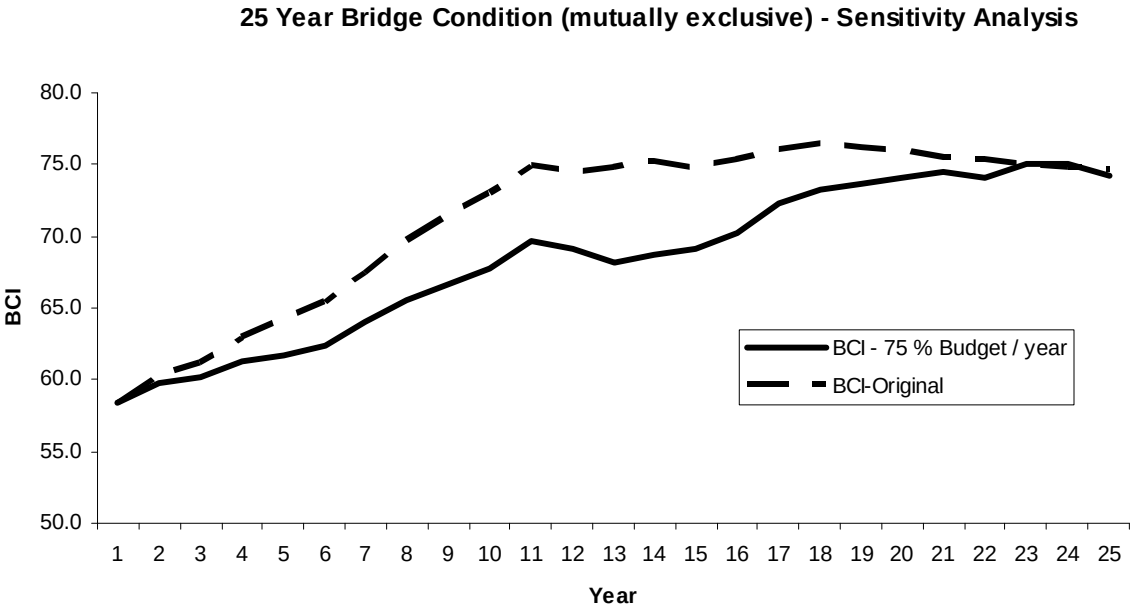


Figure 6.6: Bridge Sub Asset – 25 Year Average Performance (mutually exclusive) – Sensitivity Analysis

As expected the original higher budget yields increased performance of the bridge network over the analysis period with the year specific BCI averages overlapping only in year one and 23 to 25. The 25 – year average condition is 68 and 71 BCI for the original and 75 % funding scenarios, respectively.

Figure 6.7 illustrates the pavement condition over the analysis period for the two scenarios.

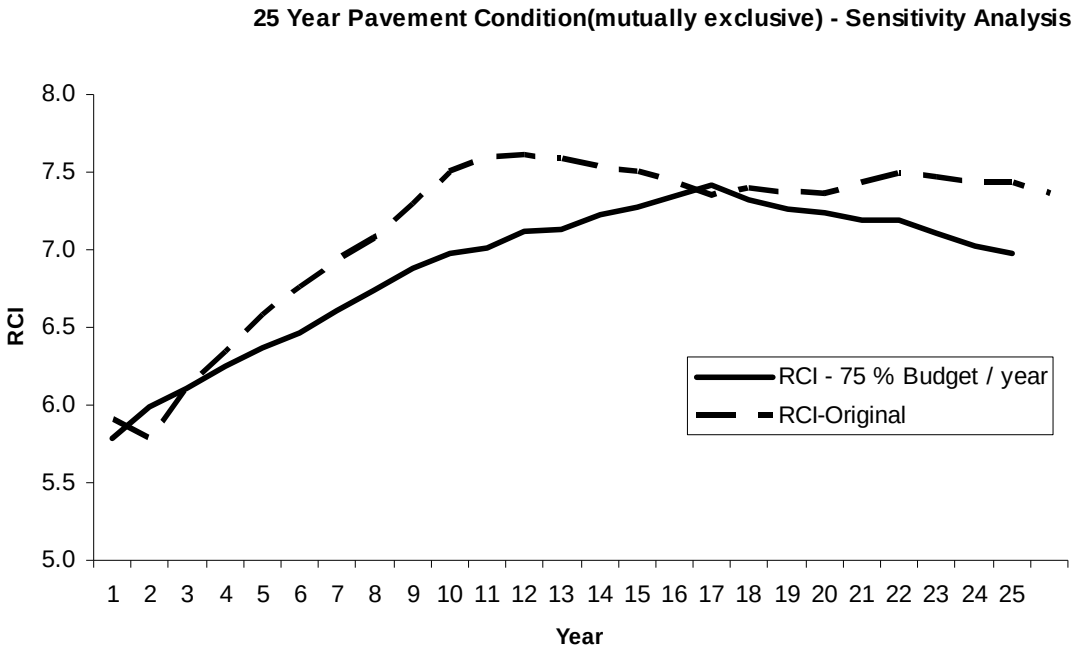


Figure 6.7: Pavement Sub Asset – 25 Year Average Performance (mutually exclusive) – Sensitivity Analysis

While the original scenario outperforms, it is interesting to note that peaks between the two are offset by approximately six years. This is again likely representative of the original scenario's increased capacity to address needs earlier. Other than year two and 17, the original funding scenario yields greater pavement network performance over the analysis period. The 25 year average conditions are 6.8 and 7.1 RCI for the original and 75 % funding scenarios, respectively. It is interesting to note that the 75 % scenario curve resembles a horizontally stretched version of the original curve. In general, the

behaviour of the curves observed in Figures 6.2 to 6.7 supports the intuitive expectation of increased network performance with increased funding.

The next section contains the mutually inclusive sensitivity analysis.

6.2 Mutually Inclusive Allocation of Sub-Asset Funds – Sensitivity Analysis

Figure 6.8 is an illustration of the annual pavement and bridge investments showing the original and the 75 % annual budget scenarios for the mutually inclusive approach.

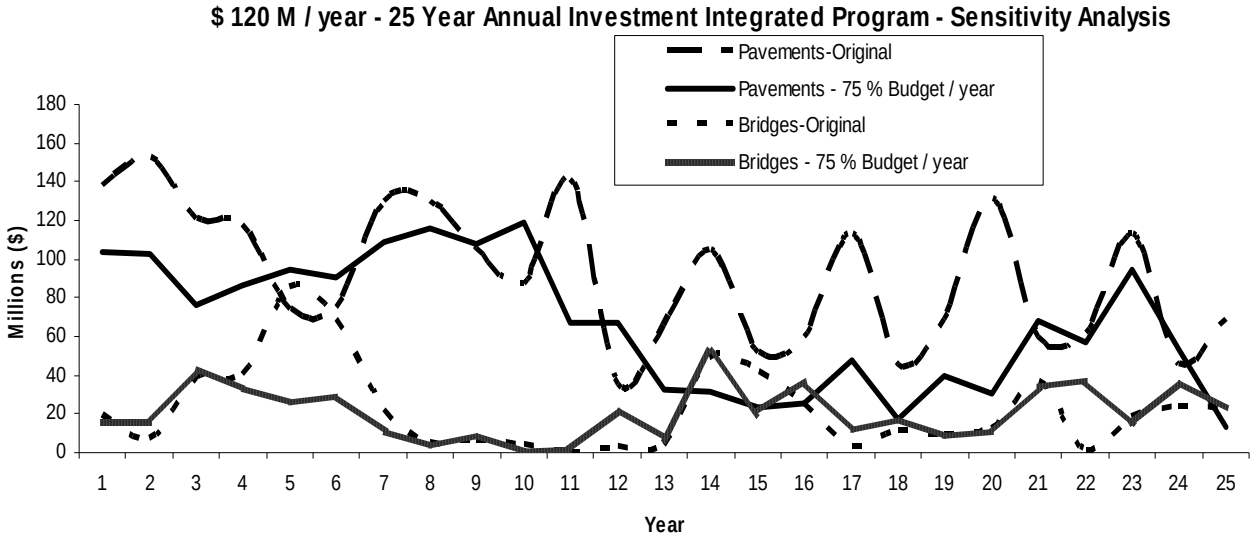


Figure 6.8: 25 Year Investment Plan - Highway Asset (mutually inclusive) – Sensitivity Analysis

The top curved and dashed line shows the original budget scenario which is a mutually inclusive funding trend for the pavement network. From its maximum in the initial years it consistently decreases to approximately 50 % in years five and six. It then rebounds to approximately $ 120 M until year 12, fluctuating around $ 80 M for the remainder of the analysis period. The 75 % scenario pavement curve remains on average at approximately $ 110 M for the first 10 years, subsequently decreasing consistently until year 12, fluctuating on average at approximately $ 40 M for the remainder of the analysis period. Years 20 to 23 do exhibit a consistent increase to approximately $ 100 M followed by a sharp drop in the last two years.

The original $ 160 M mutually inclusive funding curve for the bridge sub-asset reaches its peak of approximately $ 90 M in year five, decreasing to below $ 20 M from year eight to 13; fluctuating at approximately $ 20 M for the remainder of the analysis period. The 75 % funding scenario sees the peak occur in year 14, other than years five and six - it generally resembles the original scenario's allocation curve. It is interesting to note that the original bridge funding exceeds pavement funding in year five, while the same occurs nine years later in the 75 % annual funding scenario. As in the mutually exclusive sensitivity analysis, this is likely representative of the $ 160 M / year alternative's ability to address needs with greater capacity in a shorter period of time. Given a homogenous network of actual and equivalent pavement sections, both the original and the 75 % funding scenario bring upon a year where the funding for bridges is greater than for pavements.

This illustrates a pattern suggesting repeatability of the mutually inclusive process of programming. Figure 6.9 shows sensitivity analysis results with respect to the excellent and good bridge network distributions.

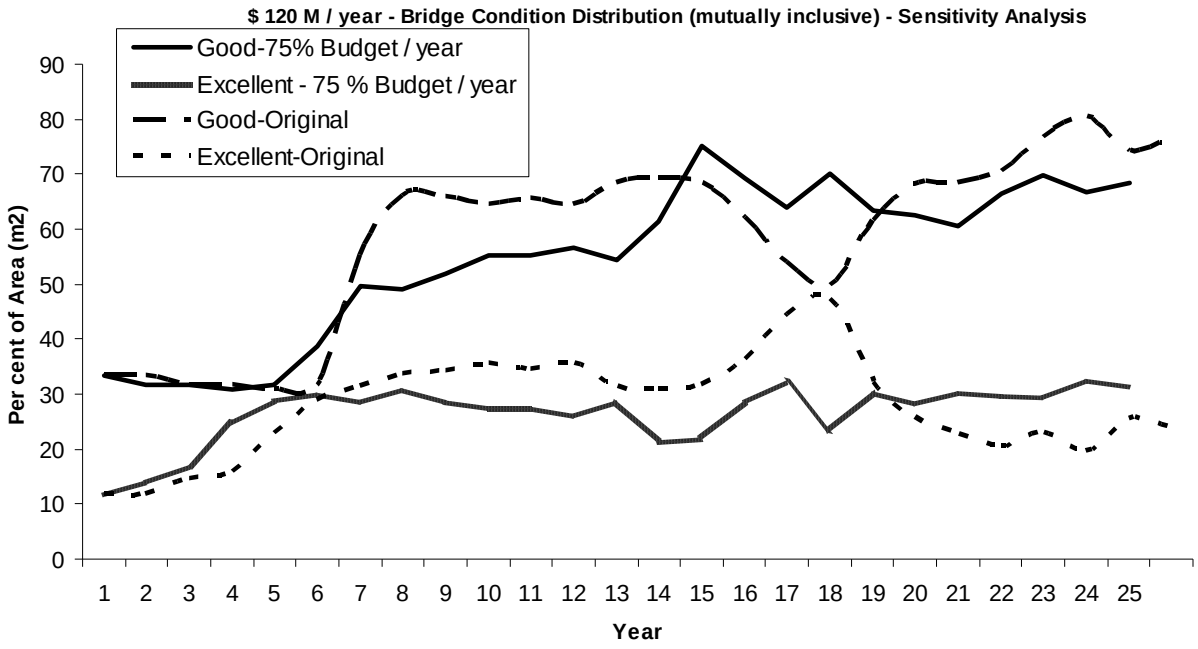


Figure 6.9: Excellent and Good Bridge Sub-Asset Condition Distribution (mutually inclusive) – Sensitivity Analysis

Both scenarios share increasing excellent and good condition trends up to year eight, without any mirroring effect of the excellent and good curves. This is likely due to the increased portions of the bridge network being upgraded to those categories from the fair and poor ratings as treatment occurs. Past year eight, a mirroring affect for both conditions occurs over the analysis period. This is representative of the condition distributions alternating between the excellent and good categories, for both programs. Indicative of the higher annual funding, the original program exhibits relatively greater percentages of excellent and good bridge network condition over the analysis period.

Figure 6.10 shows the fair and poor area network percentage curves over the 25 year period for the bridge network.

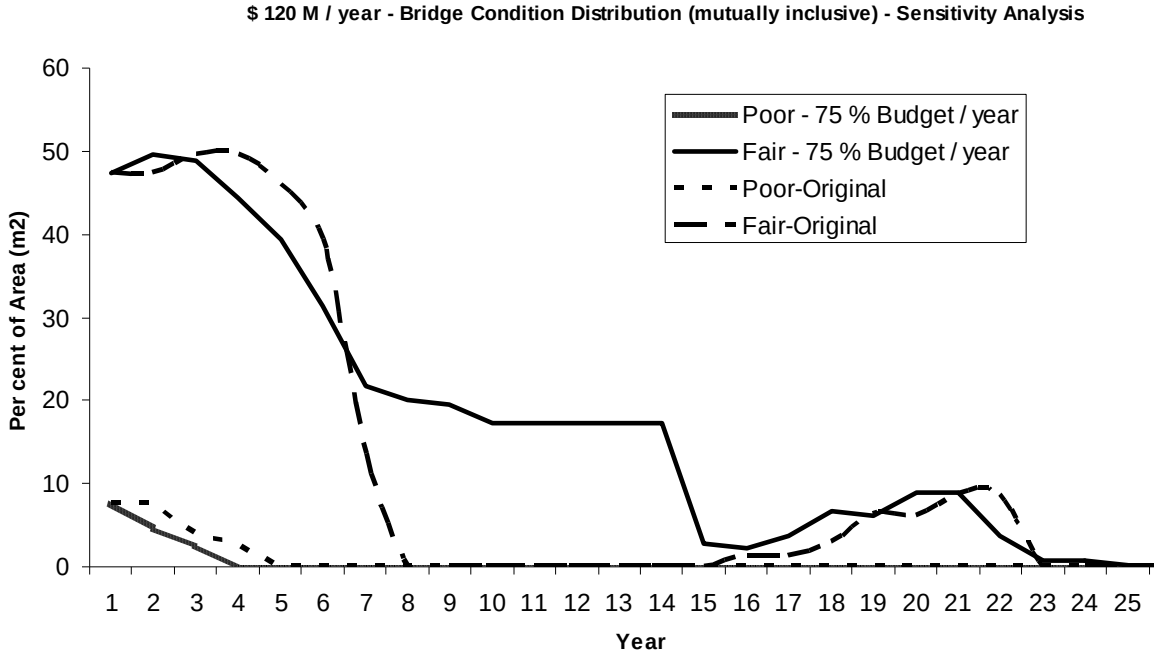


Figure 6.10: Fair and Poor Bridge Sub-Asset Condition Distribution (mutually inclusive) – Sensitivity Analysis

Both programs eliminate the poor performance condition within the first five years, with the 75 % funding program which performs slightly better than the original. While, in years four to six the results show the same level of performance for the fair condition curve. Overall, the majority of the remaining years show higher effectiveness of the

original program with respect to minimizing the fair condition portions of the bridge network.

Figure 6.11 shows sensitivity analysis results with respect to the excellent and good pavement network distributions.

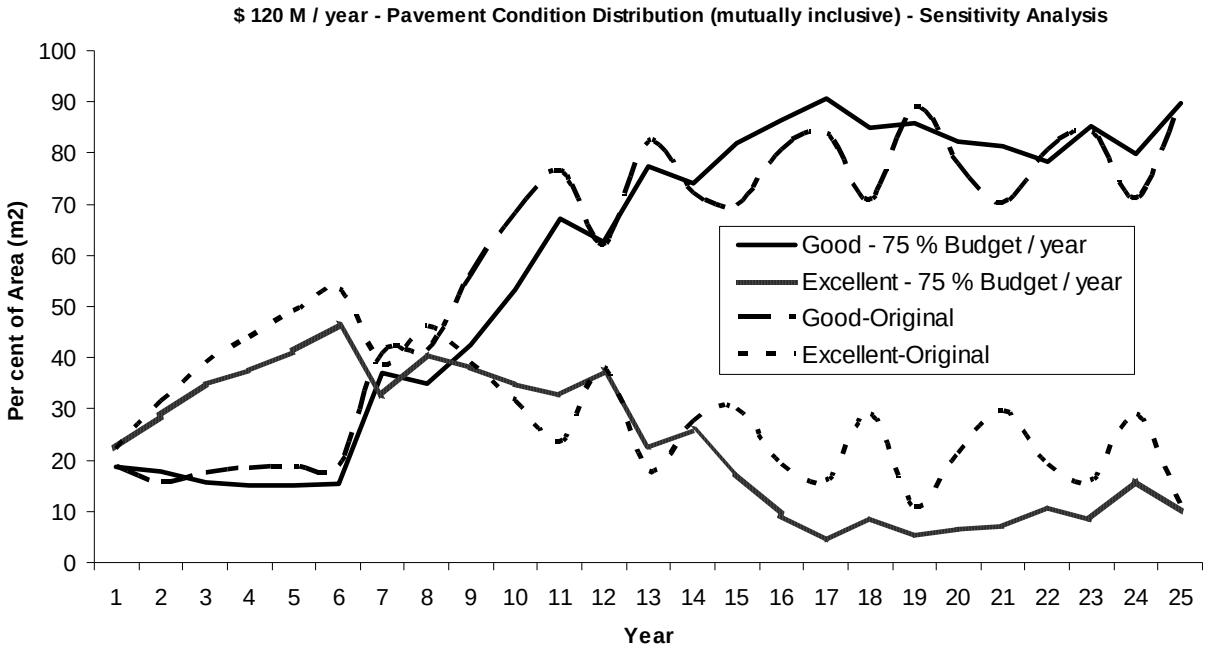


Figure 6.11: Excellent and Good Pavement Sub-Asset Condition Distribution (mutually inclusive) – Sensitivity Analysis

In the first six years, the excellent performance curves increase due to the majority of the investment concentrated on rehabilitative treatments of the poor pavement network areas. This subsequently causes immediate upgrades of areas from poor to excellent rating. In the first 14 years, the original programming alternative generally exhibits greater effectiveness in maximizing pavement network areas of good rating compared to the 75 % funding alternative; the trend is reversed from year 15 and on. The trend reversal is explained through generally higher excellent condition percentages attributed to the original funding budget for the same time period.

The excellent and good curves exhibit the mirroring effect throughout, its symmetry increases especially after year 12. The increase can be attributed to the elimination of the poor condition and relatively slight resurgence of the fair condition to approximately 10 % for the 75 % funding scenario, as illustrated in Figure 6.12.

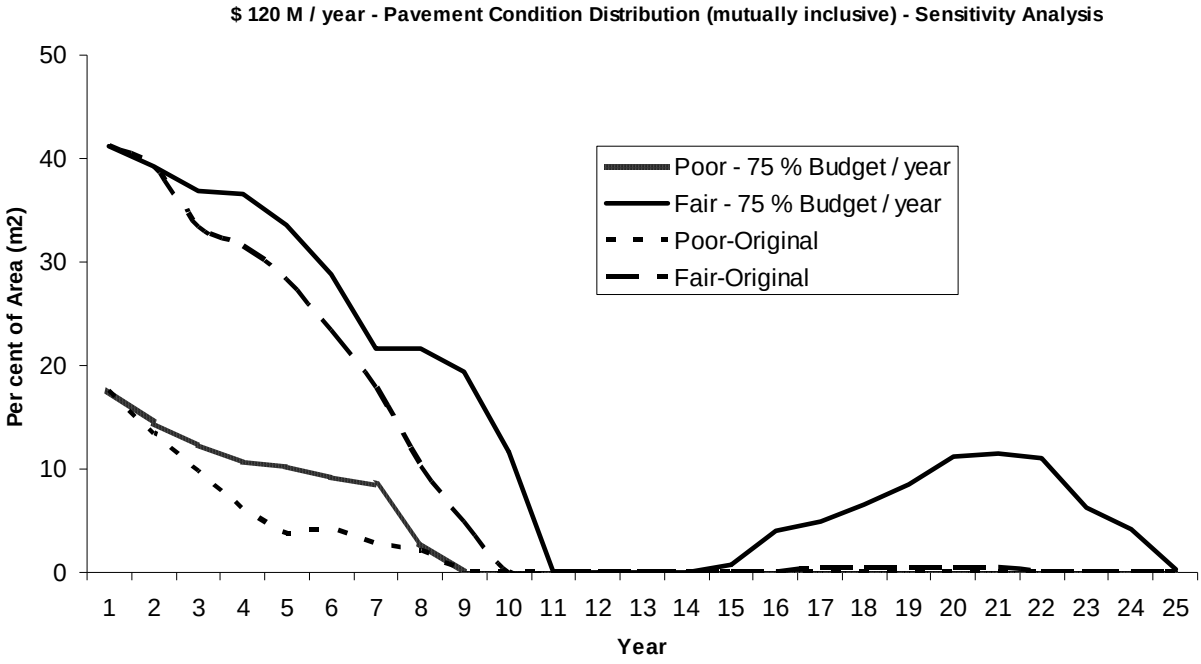


Figure 6.12: Fair and Poor Pavement Sub-Asset Condition Distribution (mutually inclusive) – Sensitivity Analysis

Figure 6.12 illustrates the corresponding fair and poor condition curves. The decreasing pattern of both conditions carries a high degree of similarity for both program alternatives for the first 14 years, as both conditions steadily decrease to zero between years nine and 11. Poor condition is eliminated for the remainder of the analysis, with the fair resurging in year 15. After which the original program exhibits greater effectiveness in minimizing the fair percentage of total bridge area network.

Figure 6.13 shows sensitivity analysis results with respect to the excellent and good unified highway asset network distributions. Given that it represents both sub-assets, the trends exhibit a high degree of resemblance to the individual sub-asset distribution curves previously shown in Figures 6.9 and 6.11.

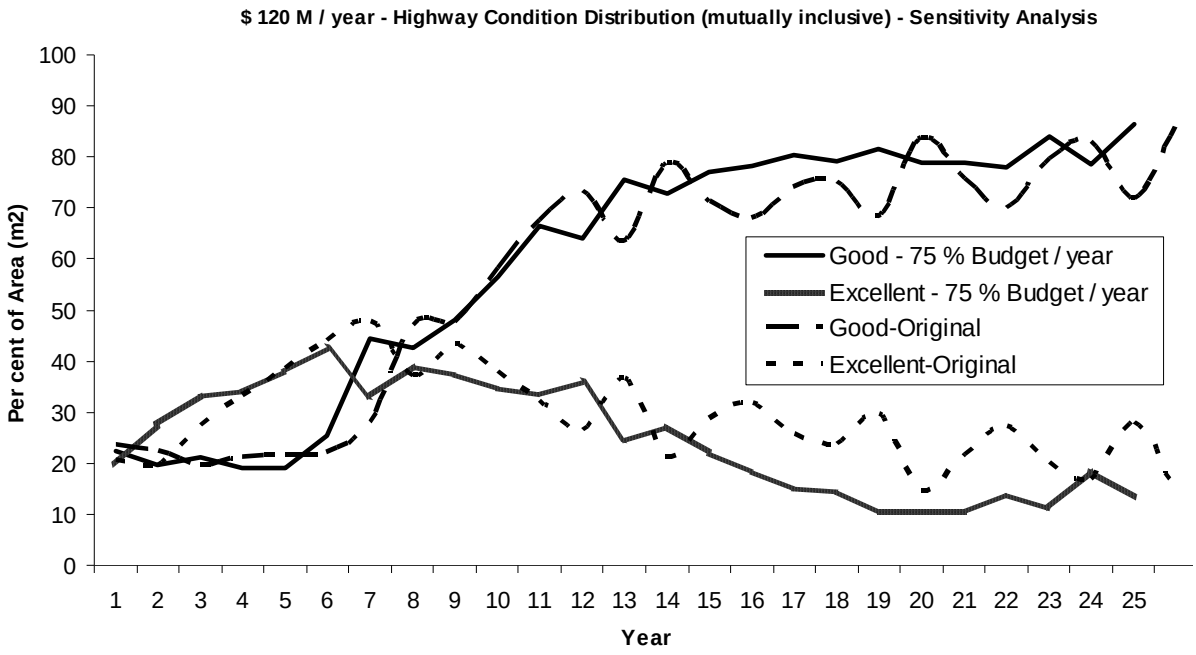


Figure 6.13: Excellent and Good Highway Asset Condition Distribution (mutually inclusive) – Sensitivity Analysis

For the first six years the excellent performance level of network increases steadily for the 75 % funding program, the same occurs for an extra year in the original program. The trend is likely due to the fact that the majority of the investment concentrated on rehabilitative treatments of the poor pavement network areas, subsequently causing immediate upgrades of areas from poor performance to an excellent performance rating. In the first 14 years, the original programming alternative generally exhibits equal level effectiveness in maximizing pavement network areas of good rating compared to the 75 % funding alternative; which exhibits higher performance from year 15 and on. This is explained through generally higher excellent condition percentages attributed to the original funding budget for the same time period. The excellent and good curves exhibit the mirroring effect throughout, its symmetry increases especially after year 12.

Figure 6.14 illustrates the corresponding fair and poor condition curves for the unified highway asset.

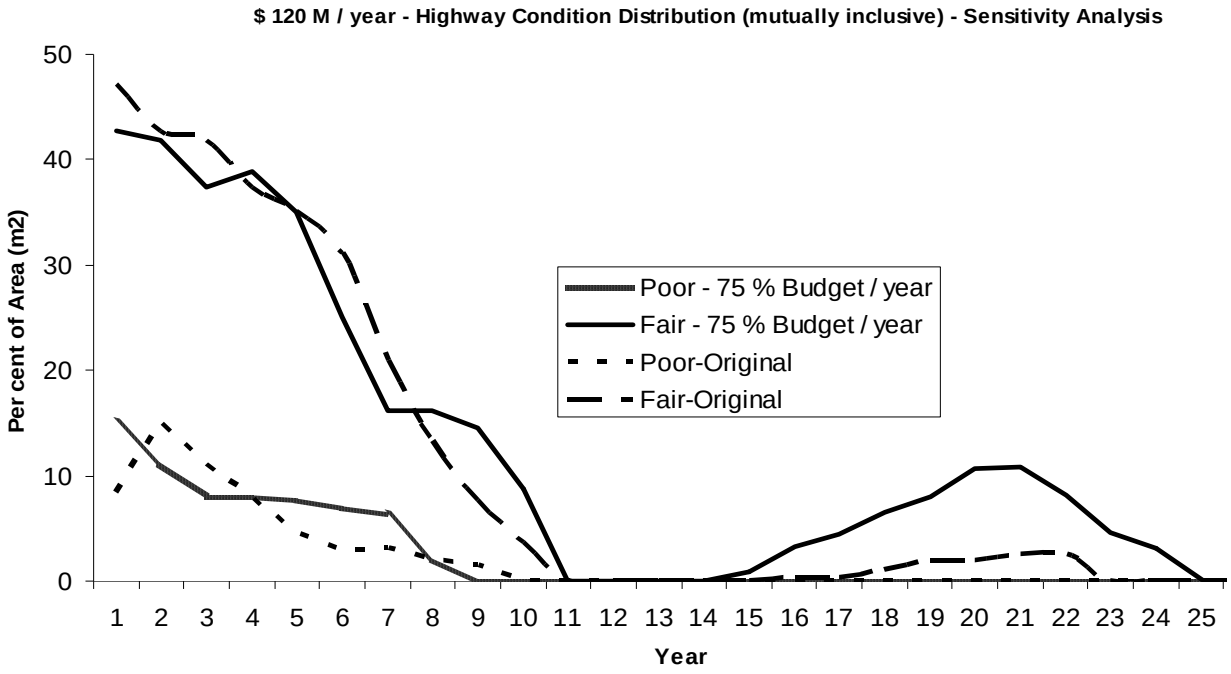


Figure 6.14: Fair and Poor Highway Asset Condition Distribution (mutually inclusive) – Sensitivity Analysis

The decreasing pattern of both conditions carries a high degree of similarity for both program alternatives in the first 14 years, as both conditions steadily decrease to zero between years nine and 11. Poor condition is eliminated for the remainder of the analysis, with the fair resurging in year 15. After which the original program exhibits greater effectiveness in minimizing the fair percentage of the highway asset network area.

Figure 6.15 illustrates the average highway condition index for the two programming alternatives. Expectedly, the original funding program of $ 160 M / year yields higher highway asset performance over the analysis period. The overall average of the original program is 7.36 HCI while the $ 120 M / year alternative yields 7.01 HCI. The original program curve shown has not been formatted to appear as a smoothed line in Microsoft Excel – implying a relatively higher degree of condition fluctuation under the 75 % funding scenario as observed in years three, 11 and 21. In general, the behaviour of the curves in Figures 6.9 to 6.15 supports the intuitive expectation of increased network performance with increased funding, assuming appropriate allocation.

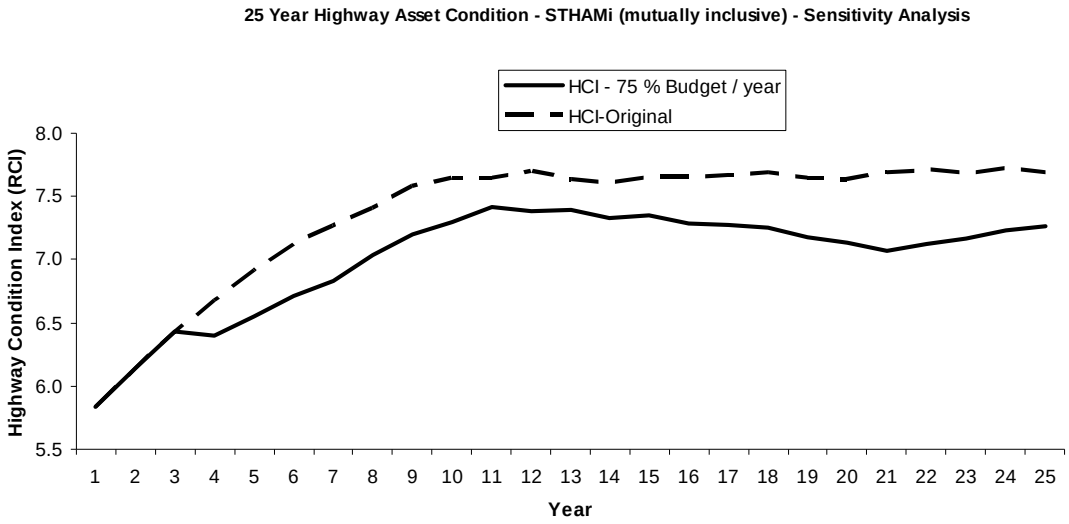


Figure 6.15: Highway Asset – 25 Year Average Performance (mutually inclusive) – Sensitivity Analysis

Table 6.1 contains the sensitivity analysis' economic summary comparison. The $ 120 M / year (75 % Budget / year of original) program expectedly yielded lower present worth investment values for the bridge and pavement sub-assets across both programming approaches when compared to the original $ 160 M / year funding restriction. Lower pavement and higher bridge investment in the mutually exclusive approach is consistent in both budget scenarios. However, unlike in the original budget scenario, the total present worth is slightly higher at $ 1,347 M for the mutually exclusive approach in the 75 % of original budget scenario.

Table 6.2 shows the resulting treated area, treated area per unit of value, and resulting investment effectiveness. Given lesser capacity, the 75 % budget / year yielded a lower treated area, treated area per unit of value, and investment effectiveness. A decrease of 8.7 % from 14.3 % to 5.6 % may imply the possibility of decreased STHAMi effectiveness with lower budgets.

TABLE 6.1: Economic Alternative Comparison – Sensitivity Analysis *

Long Term Planning Method	Pavement PW ($ M)	Pavement PW ($ M) 75 % Budget / Year	Bridge PW ($ M)	Bridge PW ($ M) 75 % Budget / Year	Total PW ($ M)	Total PW ($ M) 75 % Budget / Year
Mutually Exclusive Sub-Asset Approach	1,243	1,001	418	346	1,661	1,347
Mutually Inclusive Sub-Asset Approach	1,390	1,048	314	293	1,704	1,341

** bridge cost is actual rather than equivalent pavement section as shown in Appendix B*

TABLE 6.2: Investment Effectiveness Alternative Comparison – Sensitivity Analysis

Long Term Planning Method	Treated Area (metres squared)	Treated Area (meters squared) 75 % Budget / Year	Treated Meters Squared / $ M	Treated Meters Squared / $ M 75 % Budget / Year	Increased Investment Effectiveness (%)	Increased Investment Effectiveness (%) 75 % Budget / Year
Mutually Exclusive Sub-Asset Approach	45,183,045	27,767,335	27,202	20,620	Benchmark	Benchmark
Mutually Inclusive Sub-Asset Approach	54,089,941	29,296,683	31.,742	21,839	14.3	5.6

Although the overall economic indicators are necessary for investment analysis, they alone are likely insufficient for a comprehensive comparison within the sensitivity analysis, because they consider mutually exclusive and inclusive approaches. For example, independent of the investment effectiveness value of 5.6 %, the mutually inclusive approach within the 75 % budget / year scenario yields generally higher highway network performance compared to the mutually exclusive approach; as shown in Figure 6.16.

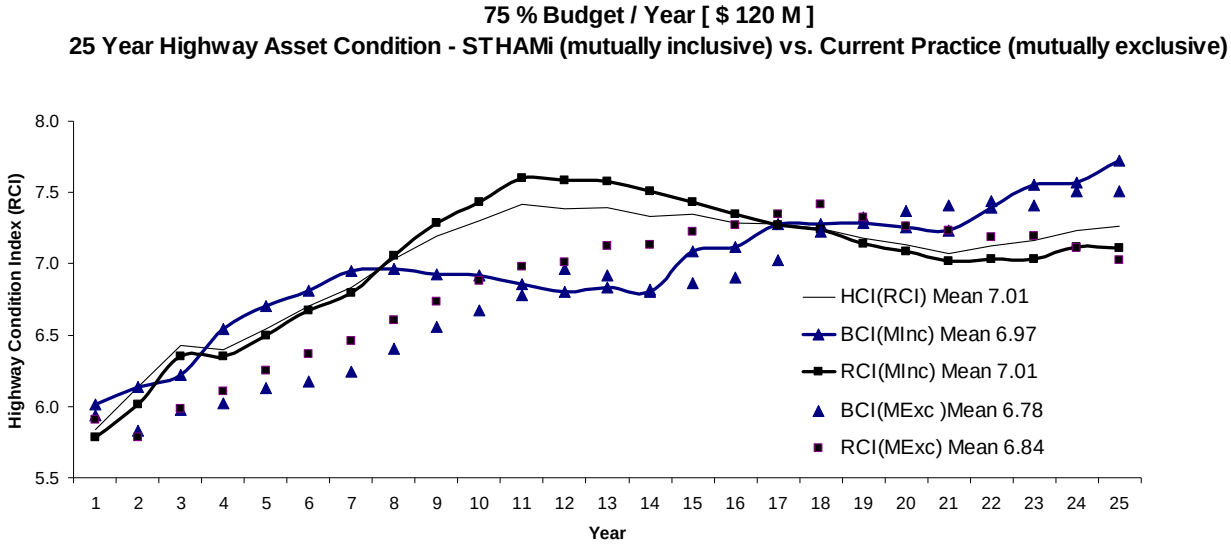


Figure 6.16: 75 % Budget / Year ($ 120 M) - Performance Alternative Comparison

The 25 year average condition values for the mutually inclusive approach are higher for both sub-assets, including the unified HCI value. Other than years 20 and 21 the BCI value is consistently higher in the mutually inclusive approach. Other than years 17, 19, 22, and 23 the pavement network condition is consistently higher for the inclusive approach of programming. The unified highway asset condition is also greater than both mutually exclusive sub-asset conditions for approximately two thirds of the analysis period.

The sensitivity analysis has:

- demonstrated STHAMi’s repeatability;
- highlighted direct relationship between available funding and asset performance; and
- provided a framework for the highway network management which considers: condition distribution and investment effectiveness analysis for comparing the mutually exclusive approach to STHAMi.

Chapter 7 – Conclusions and Recommendations

Summary

In order to properly manage a significant quantity of aging roadway infrastructure with minimal cost to the public, agencies are faced with the challenge of developing reliable long term plans focused on maximizing network performance.

This research included information obtained through a review of relevant transportation asset management literature and five years of work experience within a managing agency.

The literature review includes published material from academia, associations, managing agencies, individuals, and private firms. It spans a period from 1984 to 2013. The work experience includes positions at strategic, tactical and operational positions. Related knowledge of organizational structure and information flow was learned through daily task completion carried within each position.

Significant knowledge was drawn upon from organizational theory and operational analysis publications as well as from related undergraduate instruction at the University of Waterloo.

Available historical and cost estimating data was used to develop a Conceptual Structural Integration Factor (CSIF), which allows for integration of the bridge network into the pavement network as equivalent pavement sections (EPS). After conversion of the Bridge Condition Index (BCI) into an equivalent Riding Comfort Index (RCI), a homogeneous highway network consisting of actual and equivalent pavement sections was used to develop a mutually inclusive 25 year investment plan. Subsequently, a unified

performance measure for the highway network was introduced, i.e. the RCI pavement performance measure, by which cross-asset trade-off between pavements and bridges was achieved.

The resulting mutually inclusive 25 year plan yielded greater area treated per unit of value when compared to a 25 year plan where pavements and bridges were considered as distinct asset categories.

Conclusions

A preliminary implementation framework was introduced for this integrated approach of highway asset management.

Along with increased sub-asset trade-off reliability, STHAMi has the potential to provide significant increases in organizational efficiency regarding long term highway asset planning. One performance measure for the one highway asset opens potential for long term bridge sub-asset planning execution within a pavement engineering oriented organizational unit.

The STHAMi process is subject to limitations with respect to investment strategies applied, investment effectiveness measure, CSIF flexibility, BCI integration, and the highway network's operational and safety needs.

Recommendations

The approach of ensuring that a minimum acceptable level of service or condition of individual sections is satisfied for determining appropriate annual budgetary restrictions has significant potential for improvement. This was applied due to semi-automated programming of the network. Significant improvements can be derived from full programming automization leading to investment strategy development according to a target level of service for the average network condition.

The CSIF is an average ratio of three treatment options; this aggregation may lead to over estimation of costs for a number of sections, and under estimation of costs for a number of other sections. This will especially affect highway networks that cover a large region subject to varying economic environments. A possible remedy is assigning separate CSIF factors to each economic environment.

Due to a variety of BCI interpretations and development methods existing in industry and academia; the most appropriate one for STHAMi should be considered after maximized exploration of existing approaches. Perhaps a top-to-bottom approach with respect to data analysis may lead to increased consensus in BCI development.

While the economic performance measure of the area treated / unit of value ratio is an important indicator for assessing an alternative's fund optimization ability, it is insufficient for comparing alternatives on their own. Considering it along with average asset performance and distribution curves significantly increases sensitivity analysis reliability. An inherit draw back of the investment effectiveness factor is its inability to communicate performance of the treated area. Analyzing overall average performance and yearly condition distribution charts significantly aids in determining an optimal investment program. The determination process is however subject to bias over the order of importance of each indicator. Without a direct link between the investment effectiveness measure and performance, the objectivity and reliability of the sensitivity analysis and mutually exclusive and inclusive comparisons are subject to risk. In order to minimize it, future development of a single value such as a hybrid measure of traffic, area, condition, and value is suggested.

Finally, the greatest limitation of STHAMi is its lack of sensitivity for operational and safety needs of the network. It is not unusual for a roadway segment or corridor to need rehabilitation or expansion due to traffic demand or safety issues. Currently the process does not account for these scenarios. A potential approach that may solve this is integration of operational and safety performance measures into a unified performance

measure. This yields the possibility for developing a roadway infrastructure asset management system that can be optimized through a single object function that will accommodate pavement, bridge, operational and safety needs of a roadway network. Development of an implementation process for such a system, such that daily business turbulence is minimized through an optimal organizational / technological balance is also a potential element of future work.

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Appendix A: Model Network

Bridge ID	Lanes in Each Direction	Length of Bridge Deck (m)	Area of Bridge Deck (m2)	BCI	Year Built	Year Last Rehabilitated
431	1	11.5	113.85	25	1937	0
429	1	11.5	113.85	27	1939	0
426	1	11.5	113.85	28	1940	0
391	1	11.5	113.85	29	1941	0
423	1	11.5	113.85	30	1942	0
389	1	11.5	113.85	39	1951	0
388	1	11.5	113.85	41	1953	0
387	1	11.5	113.85	42	1954	0
381	1	11.5	113.85	44	1956	0
365	1	11.5	113.85	47	1959	0
366	1	11.5	113.85	47	1959	0
360	1	11.5	113.85	48	1960	0
346	1	11.5	113.85	50	1962	0
340	1	11.5	113.85	51	1963	0
335	1	11.5	113.85	52	1964	0
336	1	11.5	113.85	52	1964	0
324	1	11.5	113.85	53	1965	0
326	1	11.5	113.85	53	1965	0
327	1	11.5	113.85	53	1965	0
316	1	11.5	113.85	55	1967	0
298	1	11.5	113.85	57	1969	0
300	1	11.5	113.85	57	1969	0
293	1	11.5	113.85	58	1970	0
294	1	11.5	113.85	58	1970	0
295	1	11.5	113.85	58	1970	0
290	1	11.5	113.85	59	1971	0
281	1	11.5	113.85	60	1972	0
282	1	11.5	113.85	60	1972	0
283	1	11.5	113.85	60	1972	0
284	1	11.5	113.85	60	1972	0
276	1	11.5	113.85	61	1973	0
277	1	11.5	113.85	61	1973	0
274	1	11.5	113.85	62	1974	0
266	1	11.5	113.85	63	1975	0
244	1	11.5	113.85	66	1978	0
245	1	11.5	113.85	66	1978	0
228	1	11.5	113.85	67	1979	0
229	1	11.5	113.85	67	1979	0
230	1	11.5	113.85	67	1979	0
231	1	11.5	113.85	67	1979	0
232	1	11.5	113.85	67	1979	0
233	1	11.5	113.85	67	1979	0
235	1	11.5	113.85	67	1979	0
205	1	11.5	113.85	68	1980	0
206	1	11.5	113.85	68	1980	0
210	1	11.5	113.85	68	1980	0
211	1	11.5	113.85	68	1980	0
212	1	11.5	113.85	68	1980	0
213	1	11.5	113.85	68	1980	0
214	1	11.5	113.85	68	1980	0
178	1	11.5	113.85	70	1982	0
164	1	11.5	113.85	71	1983	0
151	1	11.5	113.85	72	1984	0
152	1	11.5	113.85	72	1984	0
153	1	11.5	113.85	72	1984	0
154	1	11.5	113.85	72	1984	0
155	1	11.5	113.85	72	1984	0
141	1	11.5	113.85	73	1985	0
144	1	11.5	113.85	73	1985	0
145	1	11.5	113.85	73	1985	0
136	1	11.5	113.85	74	1986	0
137	1	11.5	113.85	74	1986	0

Bridge ID	Lanes in Each Direction	Length of Bridge Deck (m)	Area of Bridge Deck (m2)	BCI	Year Built	Year Last Rehabilitated
131	1	11.5	113.85	75	1987	0
116	1	11.5	113.85	77	1989	0
105	1	11.5	113.85	78	1990	0
106	1	11.5	113.85	78	1990	0
107	1	11.5	113.85	78	1990	0
90	1	11.5	113.85	80	1992	0
77	1	11.5	113.85	82	1994	0
71	1	11.5	113.85	83	1995	0
62	1	11.5	113.85	85	1997	0
59	1	11.5	113.85	86	1998	0
52	1	11.5	113.85	87	1999	0
53	1	11.5	113.85	87	1999	0
54	1	11.5	113.85	87	1999	0
40	1	11.5	113.85	88	2000	0
41	1	11.5	113.85	88	2000	0
42	1	11.5	113.85	88	2000	0
35	1	11.5	113.85	89	2001	0
36	1	11.5	113.85	89	2001	0
29	1	11.5	113.85	90	2002	0
26	1	11.5	113.85	91	2003	0
27	1	11.5	113.85	91	2003	0
17	1	11.5	113.85	92	2004	0
19	1	11.5	113.85	92	2004	0
20	1	11.5	113.85	92	2004	0
13	1	11.5	113.85	94	2006	0
8	2	22.8	225.225	95	2007	0
9	2	22.8	225.225	95	2007	0
10	2	22.8	225.225	95	2007	0
4	2	22.8	225.225	96	2008	0
432	2	22.8	225.225	1	1913	1988
433	2	22.8	225.225	20	1932	1996
862	2	22.8	225.225	25	1937	2006
925	2	22.8	225.225	29	1941	1977
869	2	22.8	225.225	30	1942	2000
921	2	22.8	225.225	33	1945	1982
883	2	22.8	225.225	42	1954	2000
911	2	22.8	225.225	42	1954	1993
937	2	22.8	225.225	44	1956	1989
942	2	22.8	225.225	44	1956	1986
887	2	22.8	225.225	45	1957	2001
567	2	22.8	225.225	58	1970	1998
639	2	22.8	225.225	58	1970	1993
672	2	22.8	225.225	58	1970	1991
737	2	22.8	225.225	58	1970	1987
746	2	22.8	225.225	58	1970	1986
792	2	22.8	225.225	58	1970	1982
807	2	22.8	225.225	58	1970	1979
823	2	22.8	225.225	58	1970	1976
532	2	22.8	225.225	59	1971	2002
534	2	22.8	225.225	59	1971	2002
569	2	22.8	225.225	59	1971	1999
578	2	22.8	225.225	59	1971	1998
703	2	22.8	225.225	59	1971	1990
704	2	22.8	225.225	59	1971	1990
705	2	22.8	225.225	59	1971	1990
706	2	22.8	225.225	59	1971	1990
791	2	22.8	225.225	59	1971	1983
550	2	22.8	225.225	60	1972	2002
552	2	22.8	225.225	60	1972	2002
715	2	22.8	225.225	60	1972	1990
716	2	22.8	225.225	60	1972	1990
717	2	22.8	225.225	60	1972	1990
718	2	22.8	225.225	60	1972	1990
733	2	22.8	225.225	60	1972	1989

Bridge ID	Lanes in Each Direction	Length of Bridge Deck (m)	Area of Bridge Deck (m2)	BCI	Year Built	Year Last Rehabilitated
735	2	22.8	225.225	60	1972	1989
531	2	22.8	225.225	61	1973	2004
568	2	22.8	225.225	61	1973	2001
613	2	22.8	225.225	61	1973	1997
732	2	22.8	225.225	61	1973	1990
700	2	22.8	225.225	62	1974	1993
930	2	22.8	225.225	62	1974	2008
931	2	22.8	225.225	62	1974	2008
601	2	22.8	225.225	63	1975	2000
602	2	22.8	225.225	63	1975	2000
668	2	22.8	225.225	63	1975	1996
524	2	22.8	225.225	64	1976	2008
525	2	22.8	225.225	64	1976	2008
529	2	22.8	225.225	65	1977	2008
530	2	22.8	225.225	65	1977	2008
600	2	22.8	225.225	65	1977	2002
630	2	22.8	225.225	65	1977	2000
631	2	22.8	225.225	65	1977	2000
780	2	22.8	225.225	65	1977	1990
754	2	22.8	225.225	67	1979	1994
756	2	22.8	225.225	67	1979	1994
825	2	22.8	225.225	67	1979	1984
826	2	22.8	225.225	67	1979	1984
834	2	22.8	225.225	68	1980	1984
805	2	22.8	225.225	69	1981	1990
651	2	22.8	225.225	70	1982	2004
763	2	22.8	225.225	72	1984	1998
775	2	22.8	225.225	73	1985	1998
832	2	22.8	225.225	73	1985	1989
855	2	22.8	225.225	73	1985	1986
829	2	22.8	225.225	74	1986	1990
814	2	22.8	225.225	77	1989	1996
815	2	22.8	225.225	77	1989	1996
819	2	22.8	225.225	77	1989	1996
853	2	22.8	225.225	87	1999	2000
854	2	22.8	225.225	93	2005	2006
843	2	22.8	225.225	95	2007	2009
308	2	22.8	225.225	56	1968	0
309	2	22.8	225.225	56	1968	0
299	2	22.8	225.225	57	1969	0
234	2	22.8	225.225	67	1979	0
7	2	22.8	225.225	95	2007	0
726	2	22.8	225.225	69	1981	1998
727	2	22.8	225.225	69	1981	1998
765	2	22.8	225.225	69	1981	1995
648	2	22.8	225.225	70	1982	2004
649	2	22.8	225.225	70	1982	2004
777	2	22.8	225.225	70	1982	1995
857	2	22.8	225.225	70	1982	1983
752	2	22.8	225.225	71	1983	1998
787	2	22.8	225.225	71	1983	1995
816	2	22.8	225.225	71	1983	1990
817	2	22.8	225.225	71	1983	1990
422	3	30.3	526.35	35	1947	0
390	3	30.3	526.35	38	1950	0
384	3	30.3	526.35	43	1955	0
377	3	30.3	526.35	45	1957	0
378	3	30.3	526.35	45	1957	0
369	3	30.3	526.35	46	1958	0
370	3	30.3	526.35	46	1958	0
371	3	30.3	526.35	46	1958	0
372	3	30.3	526.35	46	1958	0
364	3	30.3	526.35	47	1959	0
359	3	30.3	526.35	48	1960	0

Bridge ID	Lanes in Each Direction	Length of Bridge Deck (m)	Area of Bridge Deck (m2)	BCI	Year Built	Year Last Rehabilitated
349	3	30.3	526.35	49	1961	0
350	3	30.3	526.35	49	1961	0
351	3	30.3	526.35	49	1961	0
352	3	30.3	526.35	49	1961	0
353	3	30.3	526.35	49	1961	0
343	3	30.3	526.35	50	1962	0
344	3	30.3	526.35	50	1962	0
345	3	30.3	526.35	50	1962	0
341	3	30.3	526.35	51	1963	0
325	3	30.3	526.35	53	1965	0
328	3	30.3	526.35	53	1965	0
329	3	30.3	526.35	53	1965	0
320	3	30.3	526.35	54	1966	0
321	3	30.3	526.35	54	1966	0
322	3	30.3	526.35	54	1966	0
315	3	30.3	526.35	55	1967	0
272	3	30.3	526.35	62	1974	0
273	3	30.3	526.35	62	1974	0
264	3	30.3	526.35	63	1975	0
265	3	30.3	526.35	63	1975	0
267	3	30.3	526.35	63	1975	0
261	3	30.3	526.35	64	1976	0
248	3	30.3	526.35	65	1977	0
249	3	30.3	526.35	65	1977	0
250	3	30.3	526.35	65	1977	0
251	3	30.3	526.35	65	1977	0
252	3	30.3	526.35	65	1977	0
253	3	30.3	526.35	65	1977	0
207	3	30.3	526.35	68	1980	0
208	3	30.3	526.35	68	1980	0
209	3	30.3	526.35	68	1980	0
215	3	30.3	526.35	68	1980	0
196	3	30.3	526.35	69	1981	0
197	3	30.3	526.35	69	1981	0
198	3	30.3	526.35	69	1981	0
199	3	30.3	526.35	69	1981	0
176	3	30.3	526.35	70	1982	0
177	3	30.3	526.35	70	1982	0
179	3	30.3	526.35	70	1982	0
180	3	30.3	526.35	70	1982	0
181	3	30.3	526.35	70	1982	0
182	3	30.3	526.35	70	1982	0
183	3	30.3	526.35	70	1982	0
184	3	30.3	526.35	70	1982	0
185	3	30.3	526.35	70	1982	0
165	3	30.3	526.35	71	1983	0
166	3	30.3	526.35	71	1983	0
167	3	30.3	526.35	71	1983	0
168	3	30.3	526.35	71	1983	0
169	3	30.3	526.35	71	1983	0
156	3	30.3	526.35	72	1984	0
142	3	30.3	526.35	73	1985	0
143	3	30.3	526.35	73	1985	0
129	3	30.3	526.35	75	1987	0
130	3	30.3	526.35	75	1987	0
120	3	30.3	526.35	76	1988	0
115	3	30.3	526.35	77	1989	0
108	3	30.3	526.35	78	1990	0
96	3	30.3	526.35	79	1991	0
98	3	30.3	526.35	79	1991	0
89	3	30.3	526.35	80	1992	0
83	3	30.3	526.35	81	1993	0
84	3	30.3	526.35	81	1993	0
85	3	30.3	526.35	81	1993	0

Bridge ID	Lanes in Each Direction	Length of Bridge Deck (m)	Area of Bridge Deck (m2)	BCI	Year Built	Year Last Rehabilitated
75	3	30.3	526.35	82	1994	0
76	3	30.3	526.35	82	1994	0
78	3	30.3	526.35	82	1994	0
69	3	30.3	526.35	83	1995	0
70	3	30.3	526.35	83	1995	0
65	3	30.3	526.35	84	1996	0
66	3	30.3	526.35	84	1996	0
61	3	30.3	526.35	85	1997	0
60	3	30.3	526.35	86	1998	0
43	3	30.3	526.35	88	2000	0
44	3	30.3	526.35	88	2000	0
45	3	30.3	526.35	88	2000	0
30	3	30.3	526.35	90	2002	0
25	3	30.3	526.35	91	2003	0
18	3	30.3	526.35	92	2004	0
14	3	30.3	526.35	93	2005	0
3	3	30.3	526.35	96	2008	0
1	3	30.3	526.35	97	2009	0
875	3	30.3	526.35	27	1939	1992
889	3	30.3	526.35	27	1939	1983
863	3	30.3	526.35	28	1940	2005
866	3	30.3	526.35	29	1941	2002
924	3	30.3	526.35	29	1941	1977
876	3	30.3	526.35	35	1947	1999
958	3	30.3	526.35	36	1948	1968
913	3	30.3	526.35	38	1950	1989
915	3	30.3	526.35	38	1950	1988
936	3	30.3	526.35	38	1950	1983
943	3	30.3	526.35	38	1950	1980
905	3	30.3	526.35	39	1951	1992
912	3	30.3	526.35	39	1951	1990
916	3	30.3	526.35	39	1951	1989
917	3	30.3	526.35	39	1951	1988
918	3	30.3	526.35	39	1951	1988
945	3	30.3	526.35	39	1951	1980
947	3	30.3	526.35	39	1951	1980
873	3	30.3	526.35	40	1952	2008
886	3	30.3	526.35	40	1952	1997
919	3	30.3	526.35	40	1952	1989
882	3	30.3	526.35	42	1954	2000
898	3	30.3	526.35	42	1954	1996
944	3	30.3	526.35	42	1954	1984
574	3	30.3	526.35	43	1955	1983
895	3	30.3	526.35	43	1955	1997
929	3	30.3	526.35	43	1955	1990
566	3	30.3	526.35	46	1958	1987
622	3	30.3	526.35	46	1958	1982
629	3	30.3	526.35	46	1958	1982
934	3	30.3	526.35	46	1958	1992
935	3	30.3	526.35	46	1958	1992
517	3	30.3	526.35	47	1959	1992
537	3	30.3	526.35	47	1959	1990
646	3	30.3	526.35	47	1959	1982
647	3	30.3	526.35	47	1959	1982
879	3	30.3	526.35	47	1959	2008
940	3	30.3	526.35	47	1959	1990
941	3	30.3	526.35	47	1959	1990
482	3	30.3	526.35	48	1960	1998
597	3	30.3	526.35	48	1960	1986
565	3	30.3	526.35	49	1961	1990
662	3	30.3	526.35	49	1961	1983
665	3	30.3	526.35	49	1961	1983
888	3	30.3	526.35	49	1961	2005
496	3	30.3	526.35	50	1962	1997

Bridge ID	Lanes in Each Direction	Length of Bridge Deck (m)	Area of Bridge Deck (m2)	BCI	Year Built	Year Last Rehabilitated
858	3	30.3	526.35	50	1962	1992
861	3	30.3	526.35	50	1962	1965
923	3	30.3	526.35	50	1962	1998
939	3	30.3	526.35	50	1962	1994
952	3	30.3	526.35	50	1962	1985
542	3	30.3	526.35	51	1963	1994
599	3	30.3	526.35	51	1963	1989
723	3	30.3	526.35	51	1963	1981
724	3	30.3	526.35	51	1963	1981
884	3	30.3	526.35	51	1963	2009
885	3	30.3	526.35	51	1963	2009
891	3	30.3	526.35	51	1963	2005
892	3	30.3	526.35	51	1963	2005
899	3	30.3	526.35	51	1963	2005
959	3	30.3	526.35	51	1963	1982
960	3	30.3	526.35	51	1963	1981
961	3	30.3	526.35	51	1963	1981
504	3	30.3	526.35	52	1964	1998
541	3	30.3	526.35	52	1964	1995
544	3	30.3	526.35	52	1964	1995
556	3	30.3	526.35	52	1964	1994
558	3	30.3	526.35	52	1964	1994
559	3	30.3	526.35	52	1964	1994
606	3	30.3	526.35	52	1964	1989
722	3	30.3	526.35	52	1964	1982
725	3	30.3	526.35	52	1964	1982
813	3	30.3	526.35	52	1964	1972
628	3	30.3	526.35	53	1965	1989
663	3	30.3	526.35	53	1965	1987
664	3	30.3	526.35	53	1965	1987
674	3	30.3	526.35	53	1965	1986
680	3	30.3	526.35	53	1965	1986
681	3	30.3	526.35	53	1965	1986
682	3	30.3	526.35	53	1965	1986
694	3	30.3	526.35	53	1965	1985
709	3	30.3	526.35	53	1965	1984
710	3	30.3	526.35	53	1965	1984
745	3	30.3	526.35	53	1965	1981
747	3	30.3	526.35	53	1965	1981
750	3	30.3	526.35	53	1965	1981
751	3	30.3	526.35	53	1965	1981
859	3	30.3	526.35	53	1965	1986
860	3	30.3	526.35	53	1965	1984
897	3	30.3	526.35	53	1965	2007
908	3	30.3	526.35	53	1965	2005
910	3	30.3	526.35	53	1965	2004
953	3	30.3	526.35	53	1965	1987
676	3	30.3	526.35	54	1966	1987
695	3	30.3	526.35	54	1966	1986
749	3	30.3	526.35	54	1966	1982
762	3	30.3	526.35	54	1966	1981
786	3	30.3	526.35	54	1966	1979
894	3	30.3	526.35	54	1966	2008
909	3	30.3	526.35	54	1966	2005
914	3	30.3	526.35	54	1966	2004
954	3	30.3	526.35	54	1966	1987
955	3	30.3	526.35	54	1966	1986
956	3	30.3	526.35	54	1966	1986
596	3	30.3	526.35	55	1967	1993
614	3	30.3	526.35	55	1967	1991
758	3	30.3	526.35	55	1967	1982
760	3	30.3	526.35	55	1967	1982
761	3	30.3	526.35	55	1967	1982
772	3	30.3	526.35	55	1967	1981

Bridge ID	Lanes in Each Direction	Length of Bridge Deck (m)	Area of Bridge Deck (m2)	BCI	Year Built	Year Last Rehabilitated
790	3	30.3	526.35	55	1967	1979
487	3	30.3	526.35	56	1968	2004
499	3	30.3	526.35	56	1968	2002
519	3	30.3	526.35	56	1968	2000
521	3	30.3	526.35	56	1968	2000
641	3	30.3	526.35	56	1968	1991
686	3	30.3	526.35	56	1968	1988
687	3	30.3	526.35	56	1968	1988
689	3	30.3	526.35	56	1968	1988
785	3	30.3	526.35	56	1968	1981
589	3	30.3	526.35	57	1969	1996
605	3	30.3	526.35	57	1969	1994
607	3	30.3	526.35	57	1969	1994
611	3	30.3	526.35	57	1969	1994
615	3	30.3	526.35	57	1969	1993
620	3	30.3	526.35	57	1969	1993
625	3	30.3	526.35	57	1969	1993
642	3	30.3	526.35	57	1969	1992
713	3	30.3	526.35	57	1969	1987
794	3	30.3	526.35	57	1969	1981
951	3	30.3	526.35	57	1969	1992
963	3	30.3	526.35	57	1969	1981
553	3	30.3	526.35	58	1970	2000
554	3	30.3	526.35	58	1970	2000
633	3	30.3	526.35	58	1970	1993
634	3	30.3	526.35	58	1970	1993
637	3	30.3	526.35	58	1970	1993
655	3	30.3	526.35	58	1970	1992
707	3	30.3	526.35	58	1970	1989
720	3	30.3	526.35	58	1970	1988
721	3	30.3	526.35	58	1970	1988
734	3	30.3	526.35	58	1970	1987
738	3	30.3	526.35	58	1970	1987
594	3	30.3	526.35	64	1976	2002
767	3	30.3	526.35	64	1976	1990
768	3	30.3	526.35	64	1976	1990
593	3	30.3	526.35	66	1978	2004
667	3	30.3	526.35	66	1978	1999
729	3	30.3	526.35	66	1978	1995
730	3	30.3	526.35	66	1978	1995
755	3	30.3	526.35	66	1978	1993
764	3	30.3	526.35	70	1982	1996
766	3	30.3	526.35	70	1982	1996
799	3	30.3	526.35	70	1982	1992
811	3	30.3	526.35	70	1982	1990
838	3	30.3	526.35	76	1988	1991
846	3	30.3	526.35	78	1990	1992
845	3	30.3	526.35	80	1992	1994
828	3	30.3	526.35	82	1994	1998
836	3	30.3	526.35	84	1996	2000
306	6	52.8	1023.35	56	1968	0
307	6	52.8	1023.35	56	1968	0
301	6	52.8	1023.35	57	1969	0
292	6	52.8	1023.35	58	1970	0
121	6	52.8	1023.35	76	1988	0
122	6	52.8	1023.35	76	1988	0
123	6	52.8	1023.35	76	1988	0
103	6	52.8	1023.35	78	1990	0
104	6	52.8	1023.35	78	1990	0
97	6	52.8	1023.35	79	1991	0
31	6	52.8	1023.35	90	2002	0
457	6	52.8	1023.35	51	1963	2005
962	6	52.8	1023.35	55	1967	1982
467	6	52.8	1023.35	56	1968	2008

Bridge ID	Lanes in Each Direction	Length of Bridge Deck (m)	Area of Bridge Deck (m2)	BCI	Year Built	Year Last Rehabilitated
523	6	52.8	1023.35	56	1968	2000
588	6	52.8	1023.35	56	1968	1995
619	6	52.8	1023.35	56	1968	1992
659	6	52.8	1023.35	56	1968	1990
673	6	52.8	1023.35	56	1968	1989
677	6	52.8	1023.35	56	1968	1989
708	6	52.8	1023.35	56	1968	1987
736	6	52.8	1023.35	56	1968	1985
739	6	52.8	1023.35	56	1968	1985
744	6	52.8	1023.35	56	1968	1984
773	6	52.8	1023.35	56	1968	1982
793	6	52.8	1023.35	56	1968	1980
536	6	52.8	1023.35	57	1969	2000
562	6	52.8	1023.35	57	1969	1998
621	6	52.8	1023.35	57	1969	1993
656	6	52.8	1023.35	57	1969	1991
782	6	52.8	1023.35	57	1969	1982
783	6	52.8	1023.35	57	1969	1982
795	6	52.8	1023.35	57	1969	1981
638	6	52.8	1023.35	58	1970	1993

Pavement Section ID	Lanes in Each Direction	Centre Lane (km)	Lane (km)	Area (m2)	RCI
SL-1	1	9.4853	18.9706	109080.95	4.7
SL-2	1	2.277	4.554	26185.5	8.1
SL-3	1	3.047	6.094	35040.5	8.0
SL-4	1	2.09	4.18	24035	4.2
SL-5	1	11.77	23.54	135355	7.1
SL-6	1	1.76	3.52	20240	8.2
SL-7	1	0.88	1.76	10120	3.7
SL-8	1	2.31	4.62	26565	7.5
SL-9	1	5.83	11.66	67045	2.5
SL-10	1	7.7	15.4	88550	8.6
SL-11	1	12.71	25.42	146165	4.3
SL-11A	1	10	20	115000	5.7
SL-11B	1	10	20	115000	3.1
SL-12	1	14.1	28.2	162150	3.0
SL-13	1	15.41	30.82	177215	8.7
SL-14	1	9.753	19.506	112159.5	4.7
SL-14A	1	10	20	115000	7.0
SL-15	1	14.3	28.6	164450	5.5
SL-16	1	0.22	0.44	2530	5.5
SL-17	1	6.046	12.092	69529	8.7
SL-17A	1	10	20	115000	6.0
SL-18	1	6.4	12.8	73600	6.0
SL-18A	1	10	20	115000	2.7
SL-19	1	14.04	28.08	161460	7.1
SL-19A	1	10	20	115000	5.1
SL-19B	1	10	20	115000	5.0
SL-19C	1	10	20	115000	4.6
SL-20	1	15.46	30.92	177790	4.4
SL-20A	1	10	20	115000	5.3
SL-20B	1	10	20	115000	6.1
SL-20C	1	10	20	115000	4.7
SL-21	1	1.21	2.42	13915	8.7
SL-22	1	10.02	20.04	115230	5.7
SL-23	1	12.69	25.38	145935	4.1
SL-23B	1	10	20	115000	4.8
SL-23C	1	10	20	115000	5.8
SL-24	1	6.51	13.02	74865	5.8
SL-25	1	13.21	26.42	151915	6.0
SL-26	1	2.64	5.28	30360	6.5
SL-27	1	1.32	2.64	15180	4.5
SL-28	1	1.76	3.52	20240	8.4
SL-29	1	5.61	11.22	64515	6.9
SL-30	1	3.08	6.16	35420	6.5

Pavement Section ID	Lanes in Each Direction	Centre Lane (km)	Lane (km)	Area (m2)	RCI
DL-1	2	3.5046	14.0184	79729.65	8.7
DL-2	2	8.49	33.96	193147.5	2.7
DL-3	2	7.05	28.2	160387.5	8.7
DL-4	2	5.61	22.44	127627.5	8.7
DL-5	2	7.07	28.28	160842.5	8.7
DL-6	2	13.68	54.72	311220	6.2
DL-6A	2	10	40	227500	4.6
DL-6B	2	10	40	227500	6.0
DL-7	2	8.82	35.28	200655	7.9
DL-8	2	10.67	42.68	242742.5	8.7
TRL-1	3	9.93	59.58	300382.5	4.7
TRL-1A	3	10	60	302500	4.3
TRL-2	3	10.708	64.248	323917	6.9
TRL-2A	3	10	60	302500	5.0
TRL-3	3	4.75	28.5	143687.5	2.2
TRL-3A	3	10	60	302500	8.7
TRL-4	3	7.6561	45.9366	231597.025	4.5
TRL-5	3	6.65	39.9	201162.5	2.7
TRL-5A	3	10	60	302500	4.2
TRL-5B	3	10	60	302500	5.8
TRL-6	3	10.81	64.86	327002.5	3.9
TRL-6A	3	10	60	302500	8.7
TRL-7	3	12.9713	77.8278	392381.825	5.8
TRL-8	3	7.4	44.4	223850	4.7
TRL-9	3	10.48	62.88	317020	8.7
TRL-9A	3	10	60	302500	5.7
TRL-10	3	14.633	87.798	442648.25	4.1
TRL-10A	3	10	60	302500	8.4
TRL-10B	3	10	60	302500	8.5
TRL-10C	3	10	60	302500	5.0
TRL-10D	3	10	60	302500	8.7
TRL-11	3	15.154	90.924	458408.5	4.1
TRL-11A	3	10	60	302500	8.7
TRL-11B	3	10	60	302500	4.1
TRL-12	3	10.02	60.12	303105	7.0
TRL-13	3	8.734	52.404	264203.5	5.0
TRL-14	3	13.574	81.444	410613.5	6.3
TRL-15	3	1.21	7.26	36602.5	8.7
TRL-16	3	10.02	60.12	303105	6.4
CLTX-1	6	14.868	178.416	293643	4.8
CLTX-1A	6	10	120	197500	4.3
CLTX-1B	6	10	120	197500	7.5

Appendix B: Investment Breakdown Tables

Table B1: Bridge Investment Breakdown (mutually exclusive) Year 1 to 12 - $ 40 M / year

	Treat / Year	1	2	3	4	5	6	7	8	9	10	11	12
Investment per Treatment ($ M)	Maint.	4.97	3.40	10.49	11.85	14.87	10.04	13.70	5.75	4.72	3.82	9.13	12.01
	Preserv.	21.46	34.48	15.25	24.58	20.88	8.75	5.25	21.00	22.61	0.00	0.00	14.00
	Rehab.	12.63	0.68	14.20	3.16	4.17	18.72	20.06	12.41	13.09	27.16	0.00	0.00
Deck Area Treated (m2)	Maint.	8947.95	6135.05	18901.20	21345.45	26798.10	18084.58	24691.40	10353.28	8503.98	6885.45	16448.13	21639.28
	Preserv.	12906.75	20739.75	9172.45	14786.93	12558.98	5263.50	3158.10	12632.40	13599.30	0.00	0.00	8421.60
	Rehab.	4213.28	225.23	4737.15	1052.70	1391.78	6245.25	6690.75	4139.85	4367.55	9061.80	0.00	0.00
Number of Structures	Maint.	17.00	13.00	42.00	42.00	86.00	37.00	74.00	24.00	36.00	17.00	40.00	54.00
	Preserv.	20.00	30.00	37.00	23.00	26.00	10.00	6.00	24.00	43.00	0.00	0.00	16.00
	Rehab.	14.00	1.00	9.00	2.00	4.00	15.00	15.00	11.00	13.00	18.00	0.00	0.00
Bridge Investement	i=	0.05											
	Value ($)	39.05	38.56	39.94	39.59	39.92	37.51	39.01	39.16	40.02	30.98	9.13	26.01
Total PW ($ M) = 418	PW ($)	37.19	34.97	34.50	32.57	31.28	27.99	27.72	26.50	25.80	19.02	5.34	14.48

Table B2: Bridge Investment Breakdown (mutually exclusive) Year 13 to 25 - $ 40 M / year

	Treat / Year	13	14	15	16	17	18	19	20	21	22	23	24	25
Investment per Treatment ($ M)	Maint.	7.61	5.79	8.45	14.32	27.60	12.11	17.70	8.29	15.35	13.67	13.37	14.40	15.95
	Preserv.	21.49	5.25	22.43	16.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Deck Area Treated (m2)	Maint.	13707.48	10437.78	15226.53	25803.40	49725.55	21811.93	31893.43	14942.28	27665.63	24623.53	24092.45	25951.78	28735.33
	Preserv.	12923.63	3158.10	13494.38	9883.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Number of Structures	Maint.	36.00	24.00	34.00	69.00	123.00	58.00	83.00	44.00	55.00	54.00	52.00	69.00	77.00
	Preserv.	40.00	6.00	20.00	15.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bridge Investement	i=	0.05												
	Value ($)	29.09	11.04	30.89	30.75	27.60	12.11	17.70	8.29	15.35	13.67	13.37	14.40	15.95
Total PW ($ M) = 418	PW ($)	15.43	5.58	14.86	14.09	12.04	5.03	7.00	3.13	5.51	4.67	4.35	4.47	4.71

Table B3: Pavement Investment Breakdown (mutually exclusive) Year 1 to 12 - $ 120 M / year

	Treat / Year	1	2	3	4	5	6	7	8	9	10	11	12
Investment per Treatment ($ M)	Maint.	0.00	0.00	0.00	6.21	0.00	9.52	0.00	0.00	43.82	67.99	70.94	33.50
	Preserv.	1.69	31.09	0.00	48.94	88.29	16.89	0.00	59.69	43.65	0.00	0.00	6.41
	Rehab.	117.28	88.07	110.59	55.55	31.24	69.20	105.57	59.80	11.66	11.61	0.00	0.00
Pavement Area Treated (m2)	Maint.	0.00	0.00	0.00	197500.00	0.00	302500.00	0.00	0.00	1392671.00	2160562.50	2254503.65	1064478.00
	Preserv.	30360.00	557846.50	0.00	878168.50	1584218.83	303105.00	0.00	1071025.00	783150.00	0.00	0.00	115000.00
	Rehab.	1127647.50	846815.75	1063408.50	534097.03	300382.50	665385.00	1015070.00	575000.00	112159.50	111610.95	0.00	0.00
Number of Sections	Maint.	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	11.00	11.00	14.00	18.00
	Preserv.	1.00	2.00	0.00	3.00	6.00	1.00	0.00	8.00	7.00	0.00	0.00	1.00
	Rehab.	7.00	4.00	3.00	2.00	1.00	4.00	6.00	5.00	1.00	2.00	0.00	0.00
Pavement Investement	i=	0.05											
	Value ($)	118.97	119.16	110.59	110.70	119.53	95.61	105.57	119.49	99.13	79.59	70.94	39.90
Total PW ($ M) = 1,243	PW ($)	113.30	108.08	95.54	91.08	93.66	71.35	75.02	80.88	63.90	48.86	41.48	22.22

Table B4: Pavement Investment Breakdown (mutually exclusive) Year 13 to 25 - $ 120 M / year

	Treat / Year	13	14	15	16	17	18	19	20	21	22	23	24
Investment per Treatment ($ M)	Maint.	48.80	31.86	28.91	52.92	61.76	68.24	82.02	66.31	51.48	56.42	74.68	37.25
	Preserv.	6.42	0.00	0.00	39.74	0.00	0.00	31.09	33.26	11.01	0.00	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pavement Area Treated (m2)	Maint.	1550802.50	1012415.75	918835.00	1681887.03	1962699.65	2168675.50	2606677.50	2107382.50	1635994.50	1792892.98	2373313.15	1183917.00
	Preserv.	115230.00	0.00	0.00	713113.50	0.00	0.00	557846.50	596748.00	197500.00	0.00	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Number of Sections	Maint.	12.00	7.00	6.00	9.00	15.00	11.00	15.00	15.00	9.00	11.00	16.00	8.00
	Preserv.	1.00	0.00	0.00	2.00	0.00	0.00	2.00	2.00	1.00	0.00	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pavement Investement	i=												
	Value ($)	55.22	31.86	28.91	92.67	61.76	68.24	113.11	99.57	62.49	56.42	74.68	37.25
Total PW ($ M) = 1,243	PW ($)	29.28	16.09	13.91	42.45	26.95	28.36	44.76	37.53	22.43	19.29	24.31	11.55

Table B5: Highway Investment Breakdown (mutually inclusive) Year 1 to 12 - $ 160 M / year

	Treat / Year	1	2	3	4	5	6	7	8	9	10	11	12
Investment per Treatment ($ M)	Maint.	0.00	0.00	0.00	0.00	7.89	27.26	41.03	4.68	52.78	91.43	141.35	37.73
	Preserv.	17.35	1.69	12.68	30.12	74.54	82.04	99.70	42.48	46.58	0.00	0.00	0.00
	Rehab.	140.73	157.67	146.81	129.30	77.53	35.62	11.34	87.41	11.96	0.00	0.00	0.00
Pavement Area Treated (m2)	Maint.	0.00	0.00	0.00	0.00	250656.82	866385.39	1303893.20	148606.15	1677399.30	2905518.01	4492002.15	1199005.48
	Preserv.	311220.00	30360.00	227500.00	540386.00	1337455.35	1471974.08	1788853.83	762267.15	835778.60	0.00	0.00	0.00
	Rehab.	1353144.70	1516072.75	1411598.30	1243235.68	745502.10	342500.00	109080.95	840470.00	115000.00	0.00	0.00	0.00
Number of Sections	Maint.	0.00	0.00	0.00	0.00	11.00	79.00	65.00	11.00	45.00	43.00	27.00	19.00
	Preserv.	1.00	1.00	1.00	40.00	99.00	110.00	6.00	8.00	14.00	0.00	0.00	0.00
	Rehab.	23.00	16.00	40.00	15.00	11.00	2.00	1.00	6.00	1.00	0.00	0.00	0.00
Bridge Investement PW ($ M) = 344	Value ($)	19.78	7.03	38.77	41.17	85.85	69.52	21.89	4.84	5.66	4.12	0.00	2.56
Pavement Investement PW ($ M) = 1390	Value ($)	138.29	152.34	120.71	118.25	74.11	75.40	130.18	129.73	105.66	87.31	141.35	35.17
	i=	0.05											
	Value ($)	158.07	159.36	159.49	159.41	159.96	144.92	152.07	134.57	111.32	91.43	141.35	37.73
Total PW ($ M) = 1,734	PW ($)	150.55	144.55	137.77	131.15	125.33	108.14	108.07	91.08	71.76	56.13	82.64	21.01

Table B6: Highway Investment Breakdown (mutually inclusive) Year 13 to 25 - $ 160 M / year

	Treat / Year	13	14	15	16	17	18	19	20	21	22	23
Investment per Treatment ($ M)	Maint.	69.28	145.02	93.63	84.34	116.75	56.83	75.10	143.10	61.75	63.63	131.89
	Preserv.	0.00	9.04	0.00	0.75	0.00	0.65	0.00	0.00	34.22	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	2.73	0.00	0.00	0.00	0.00
Pavement Area Treated (m2)	Maint.	2201686.65	4608754.93	2975559.47	2680368.02	3710383.88	1805953.63	2386577.31	4547792.34	1962247.03	2022149.11	4191295.72
	Preserv.	0.00	162115.80	0.00	13509.65	0.00	11688.60	0.00	0.00	613986.00	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	26265.98	0.00	0.00	0.00	0.00
Number of Sections	Maint.	21.00	114.00	110.00	83.00	27.00	44.00	27.00	50.00	30.00	16.00	79.00
	Preserv.	0.00	12.00	0.00	1.00	0.00	4.00	0.00	0.00	41.00	0.00	0.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Bridge Investement PW ($ M) = 344	Value ($)	3.57	49.20	41.55	24.98	3.49	11.53	8.69	11.80	36.16	1.19	18.62
Pavement Investement PW ($ M) = 1390	Value ($)	65.70	104.86	52.08	60.12	113.26	45.95	69.14	131.30	59.80	62.44	113.26
	i=											
	Value ($)	69.28	154.06	93.63	85.10	116.75	57.48	77.83	143.10	95.96	63.63	131.89
Total PW ($ M) = 1,734	PW ($)	36.74	77.81	45.04	38.98	50.94	23.88	30.80	53.93	34.45	21.75	42.94

Table B7: Bridge Investment Breakdown (mutually exclusive) Year 1 to 12 - $ 30 M / year

	Treat / Year	1	2	3	4	5	6	7	8	9	10	11	12
Investment per Treatment ($ M)	Maint.	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	1.59	0.00
	Preserv.	17.37	27.67	12.30	22.65	25.61	10.50	7.57	17.35	15.81	1.44	9.43	0.88
	Rehab.	12.63	0.68	14.20	3.16	4.17	18.72	20.06	12.41	13.09	27.16	0.00	0.00
Deck Area Treated (m2)	Maint.	0.00	0.00	0.00	0.00	0.00	0.00	113.85	0.00	0.00	0.00	2859.45	0.00
	Preserv.	10447.55	16646.35	7398.60	13626.40	15405.10	6316.20	4552.35	10438.95	9509.78	867.90	5672.45	526.35
	Rehab.	4213.28	225.23	4737.15	1052.70	1391.78	6245.25	6690.75	4139.85	4367.55	9061.80	0.00	0.00
Number of Structures	Maint.	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	7.00	0.00
	Preserv.	18.00	26.00	36.00	24.00	36.00	12.00	11.00	17.00	24.00	4.00	7.00	1.00
	Rehab.	14.00	1.00	9.00	2.00	4.00	15.00	15.00	11.00	13.00	18.00	0.00	0.00
Bridge Investement	i=	0.05											
	Value ($)	30.00	28.35	26.50	25.81	29.78	29.22	27.69	29.76	28.50	28.61	11.02	0.88
Total PW ($ M) = 346	PW ($)	28.57	25.71	22.89	21.23	23.34	21.81	19.68	20.15	18.37	17.56	6.44	0.49

Table B8: Bridge Investment Breakdown (mutually exclusive) Year 13 to 25 - $ 30 M / year

	Treat / Year	13	14	15	16	17	18	19	20	21	22	23	24	25
Investment per Treatment ($ M)	Maint.	0.00	7.13	0.00	0.00	6.17	0.00	0.61	6.49	1.13	6.29	0.65	1.50	4.84
	Preserv.	17.73	17.10	14.41	0.00	10.45	27.42	28.10	19.69	12.69	2.63	1.06	0.00	3.50
	Rehab.	6.13	1.58	15.34	29.63	11.48	1.58	0.00	0.00	0.00	16.12	9.72	0.00	0.00
Deck Area Treated (m2)	Maint.	0.00	12845.60	0.00	0.00	11111.10	0.00	1095.60	11687.53	2029.50	11339.98	1166.55	2710.13	8715.30
	Preserv.	10666.43	10283.50	8666.60	0.00	6285.68	16491.98	16903.30	11842.88	7632.08	1579.05	640.20	0.00	2105.40
	Rehab.	2046.70	526.35	5116.75	9883.25	3828.83	526.35	0.00	0.00	0.00	5377.35	3242.60	0.00	0.00
Number of Structures	Maint.	0.00	41.00	0.00	0.00	36.00	0.00	6.00	29.00	5.00	36.00	3.00	10.00	28.00
	Preserv.	38.00	20.00	11.00	0.00	18.00	36.00	43.00	25.00	17.00	3.00	2.00	0.00	4.00
	Rehab.	2.00	1.00	5.00	15.00	17.00	1.00	0.00	0.00	0.00	11.00	6.00	0.00	0.00
Bridge Investement	i=													
	Value ($)	23.87	25.80	29.75	29.63	28.09	29.00	28.71	26.18	13.81	25.04	11.43	1.50	8.34
Total PW ($ M) = 346	PW ($)	12.66	13.03	14.31	13.57	12.26	12.05	11.36	9.87	4.96	8.56	3.72	0.47	2.46

Table B9: Pavement Investment Breakdown (mutually exclusive) Year 1 to 12 - $ 90 M / year

	Treat / Year	1	2	3	4	5	6	7	8	9	10	11	12
Investment per Treatment ($ M)	Maint.	3.62	0.00	8.31	6.21	0.00	0.00	0.00	0.00	15.83	33.60	0.00	6.21
	Preserv.	0.85	16.37	0.00	0.00	51.41	0.00	34.91	49.65	16.89	13.95	0.00	0.00
	Rehab.	83.46	65.47	79.13	70.12	31.24	86.20	55.12	40.78	42.67	20.60	72.30	46.62
Pavement Area Treated (m2)	Maint.	115000.00	0.00	264203.50	197500.00	0.00	0.00	0.00	0.00	503155.00	1067887.50	0.00	197500.00
	Preserv.	15180.00	293643.00	0.00	0.00	922381.83	0.00	626417.00	890785.00	303105.00	250355.00	0.00	0.00
	Rehab.	802542.50	629502.50	760908.50	674245.28	300382.50	828850.00	530000.00	392150.00	410320.00	198030.00	695155.45	448270.00
Number of Sections	Maint.	1.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	2.00	4.00	0.00	1.00
	Preserv.	1.00	1.00	0.00	0.00	3.00	0.00	2.00	4.00	1.00	2.00	0.00	0.00
	Rehab.	5.00	2.00	2.00	2.00	1.00	3.00	2.00	3.00	5.00	2.00	7.00	6.00
Pavement Investement	i=	0.05											
	Value ($)	88.78	81.83	87.45	76.34	82.65	86.20	90.03	85.99	78.62	67.62	82.81	61.64
Total PW ($ M) = 1,001	PW ($)	84.55	74.23	75.54	62.80	64.76	64.32	63.98	58.20	50.68	41.52	48.42	34.32

Table B10: Pavement Investment Breakdown (mutually exclusive) Year 13 to 25 - $ 90 M / year

	Treat / Year	13	14	15	16	17	18	19	20	21	22	23	24	25
Investment per Treatment ($ M)	Maint.	35.12	67.75	21.56	21.22	20.14	40.51	16.68	28.58	39.61	15.75	21.87	14.94	0.00
	Preserv.	9.86	3.41	0.00	16.86	0.00	0.00	28.53	12.68	29.06	7.54	3.60	21.79	16.29
	Rehab.	39.10	17.10	58.02	42.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pavement Area Treated (m2)	Maint.	1115972.50	2153082.15	685319.00	674245.28	640090.00	1287258.50	530000.00	908105.00	1258936.00	500530.00	695155.45	474835.00	0.00
	Preserv.	176985.00	61226.00	0.00	302500.00	0.00	0.00	511875.00	227500.00	521417.00	135355.00	64515.00	391050.00	292215.00
	Rehab.	375935.00	164450.00	557846.50	410613.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Number of Sections	Maint.	6.00	14.00	5.00	2.00	3.00	4.00	2.00	3.00	11.00	3.00	7.00	7.00	0.00
	Preserv.	3.00	2.00	0.00	1.00	0.00	0.00	2.00	1.00	2.00	1.00	1.00	2.00	2.00
	Rehab.	3.00	1.00	2.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pavement Investement	i=													
	Value ($)	80.00	87.35	76.39	80.78	20.14	40.51	45.21	41.25	69.65	23.13	26.18	39.40	16.29
Total PW ($ M) = 1,001	PW ($)	42.43	44.12	36.75	37.01	8.79	16.83	17.89	15.55	25.00	7.91	8.52	12.22	4.81

Table B11: Highway Investment Breakdown (mutually inclusive) Year 1 to 12 - $ 120 M / year

	Treat / Year	1	2	3	4	5	6	7	8	9	10	11	12
Investment per Treatment ($ M)	Maint.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	67.09	66.37
	Preserv.	0.00	0.00	0.00	30.12	25.60	66.88	22.77	16.89	83.63	75.43	1.46	21.87
	Rehab.	119.53	118.67	119.56	89.60	94.38	52.54	96.89	102.18	32.14	43.42	0.00	0.00
Pavement Area Treated (m2)	Maint.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2132020.00	2109217.33
	Preserv.	0.00	0.00	0.00	540386.00	459328.10	1200065.90	408468.78	303105.00	1500465.63	1353430.00	26265.98	392381.83
	Rehab.	1149364.65	1141072.25	1149627.25	861498.83	907500.00	505213.15	931667.35	982489.30	308999.30	417500.00	0.00	0.00
Number of Sections	Maint.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.00	73.00
	Preserv.	0.00	0.00	0.00	40.00	34.00	38.00	27.00	1.00	42.00	9.00	1.00	1.00
	Rehab.	15.00	22.00	42.00	5.00	0.00	3.00	23.00	9.00	5.00	2.00	0.00	0.00
Bridge Investement PW ($ M) = 283	Value ($)	15.46	15.57	42.99	32.93	25.60	28.51	10.68	2.81	8.02	0.00	1.46	21.08
Pavement Investement PW ($ M) = 1,049	Value ($)	104.08	103.10	76.57	86.79	94.38	90.92	108.98	116.26	107.74	118.85	67.09	67.16
	i=	0.05											
	Value ($)	119.53	118.67	119.56	119.71	119.98	119.43	119.66	119.07	115.76	118.85	68.55	88.24
Total PW ($ M) = 1,332	PW ($)	113.84	107.64	103.28	98.49	94.01	89.12	85.04	80.59	74.62	72.96	40.08	49.13

Table B12: Highway Investment Breakdown (mutually inclusive) Year 13 to 25 - $ 120 M / year

	Treat / Year	13	14	15	16	17	18	19	20	21	22	23	24	25
Investment per Treatment ($ M)	Maint.	35.98	33.87	40.38	15.28	37.14	30.26	33.90	38.63	22.76	25.67	26.69	18.44	19.99
	Preserv.	2.93	48.94	2.93	46.17	21.28	3.44	11.18	1.46	79.55	68.09	82.47	71.17	0.65
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	2.73	0.00	0.00	0.00	0.00	0.00	0.00
Pavement Area Treated (m2)	Maint.	1143404.76	1076255.58	1283213.91	485566.13	1180411.65	961682.63	1077251.30	1227806.17	723427.95	815828.43	848306.45	585938.69	635177.98
	Preserv.	52531.97	878127.25	52531.97	828437.59	381902.95	61685.98	200655.00	26185.50	1427253.35	1221690.55	1479711.90	1276955.05	11688.60
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	26265.98	0.00	0.00	0.00	0.00	0.00	0.00
Number of Sections	Maint.	12.00	15.00	45.00	16.00	20.00	42.00	26.00	29.00	16.00	27.00	15.00	28.00	24.00
	Preserv.	2.00	65.00	2.00	53.00	4.00	2.00	1.00	1.00	45.00	39.00	23.00	56.00	4.00
	Rehab.	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Bridge Investement PW ($ M) = 283	Value ($)	6.78	51.61	20.14	36.47	10.71	16.25	8.48	10.05	33.89	36.73	14.51	35.97	20.64
Pavement Investement PW ($ M) = 1,049	Value ($)	32.13	31.19	23.17	24.98	47.72	17.45	39.34	30.05	68.42	57.03	94.65	53.63	0.00
	i=													
	Value ($)	38.91	82.81	43.31	61.45	58.43	33.70	47.81	40.09	102.31	93.76	109.16	89.61	20.64
Total PW ($ M) = 1,332	PW ($)	20.63	41.82	20.83	28.15	25.49	14.00	18.92	15.11	36.72	32.05	35.54	27.78	6.09

Appendix C: Network Distribution Performance Tables

Table C1: Network Distribution Performance - Bridges (mutually exclusive) - $ 40 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	7.1	7.1	6.1	7.0	5.5	5.6	6.7	5.9	2.9	2.1	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	56.9	58.0	52.3	44.9	41.1	34.9	28.7	24.2	25.9	21.0	16.9	20.6	23.4	22.3	22.4	25.2	16.4	9.5	6.6	6.6	6.6	7.1	8.2	8.2	8.2	8.2
Good (%)	26.8	26.3	31.7	36.9	36.5	37.7	34.5	34.6	30.7	34.5	35.1	29.7	26.9	28.0	28.0	25.2	34.1	41.0	43.9	43.9	43.9	43.4	42.3	44.2	44.3	46.7
Excellent (%	9.2	8.6	9.9	11.2	17.0	21.8	30.1	35.3	40.5	42.4	45.2	49.7	49.7	49.7	49.6	49.6	49.5	49.5	49.5	49.5	49.5	49.5	49.5	47.6	47.5	45.1

Table C2: Network Distribution Performance - Pavements (mutually exclusive) - $ 120 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	8.8	17.7	13.7	11.1	5.2	4.9	9.3	7.7	3.0	1.5	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	47.1	41.2	39.3	34.7	36.2	29.3	14.8	14.0	12.0	6.7	3.7	3.7	3.7	3.7	3.7	8.3	8.3	6.3	6.3	6.3	2.6	2.6	2.6	2.6	2.6	4.3
Good (%)	20.4	18.8	17.5	19.2	18.5	24.6	31.1	44.3	44.3	57.9	63.1	62.6	55.8	73.5	70.5	78.6	83.9	77.9	72.5	81.3	77.8	86.7	87.1	83.0	74.9	86.7
Excellent (%)	23.7	22.3	29.6	35.0	40.0	41.2	44.7	34.0	40.7	34.0	32.5	33.8	40.5	22.9	25.9	13.1	7.9	15.8	21.2	12.4	19.6	10.7	10.4	14.4	22.5	9.0

Table C3: Network Distribution Performance - Bridges (mutually inclusive) - $ 160 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	7.6	7.6	3.9	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	47.3	47.3	49.6	49.6	46.0	39.3	13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	2.9	6.3	6.1	8.7	8.7	0.0	0.0	0.0	0.0
Good (%)	33.4	33.4	31.8	31.8	31.0	31.8	55.1	66.2	65.8	64.5	65.6	64.5	68.5	69.1	68.3	62.4	54.1	49.9	61.6	68.1	68.5	70.7	76.9	80.4	74.4	76.2
Excellent (%	11.7	11.7	14.7	16.0	23.0	28.9	31.4	33.8	34.2	35.5	34.4	35.5	31.5	30.9	31.7	36.3	44.6	47.3	32.1	25.8	22.7	20.5	23.1	19.6	25.6	23.8

Table C4: Network Distribution Performance - Pavements (mutually inclusive) - $ 160 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	8.8	17.7	13.5	9.9	6.1	3.7	4.2	2.7	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	47.1	41.2	39.3	33.4	31.5	28.4	23.4	17.9	10.3	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
Good (%)	20.4	18.8	15.6	17.6	18.4	18.7	19.0	40.8	41.7	56.1	68.3	76.5	61.9	82.2	72.3	69.8	80.7	83.6	70.7	88.7	78.1	70.1	80.7	84.1	71.2	89.2
Excellent (%)	23.7	22.3	31.6	39.2	44.0	49.2	53.3	38.5	46.0	39.0	31.7	23.5	38.1	17.8	27.7	30.2	19.3	15.9	28.8	10.8	21.4	29.4	19.3	15.9	28.8	10.8

Table C5: Network Distribution Performance - Highway (mutually inclusive) – 160 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	8.5	15.1	11.1	8.0	4.6	2.8	3.2	2.1	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	47.2	42.8	41.9	37.4	35.1	31.1	20.9	13.4	7.7	3.7	0.0	0.0	0.0	0.0	0.0	0.3	0.3	1.1	2.0	1.9	2.6	2.6	0.0	0.0	0.0	0.0
Good (%)	23.7	22.4	19.7	21.2	21.5	22.0	28.1	47.2	47.7	58.2	67.6	73.5	63.6	78.9	71.3	67.9	74.0	75.1	68.4	83.6	75.7	70.2	79.7	83.2	72.0	85.9
Excellent (%	20.7	19.7	27.4	33.4	38.8	44.1	47.8	37.3	43.1	38.1	32.4	26.5	36.4	21.1	28.7	31.7	25.7	23.8	29.6	14.5	21.7	27.2	20.3	16.8	28.0	14.1

Table C6: Network Distribution Performance - Bridges (mutually exclusive) - $ 30 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	7.1	7.1	6.0	7.0	5.4	5.5	6.7	5.9	2.9	2.4	3.2	0.3	0.3	0.5	0.5	0.3	1.3	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	56.9	58.0	53.7	48.8	47.5	43.2	35.9	32.2	34.4	32.2	30.2	33.1	36.2	43.3	41.7	41.5	33.7	30.6	26.8	19.3	13.5	8.9	6.2	4.3	3.4	5.3
Good (%)	26.8	26.3	30.4	33.1	31.7	36.1	42.0	45.6	44.0	44.3	43.8	39.7	35.3	29.9	31.2	28.3	34.3	34.3	37.6	46.2	50.3	52.9	56.5	58.5	59.0	59.9
Excellent (%	9.2	8.6	9.9	11.2	15.3	15.2	15.4	16.3	18.7	21.1	22.8	26.9	28.3	26.3	26.6	29.9	30.7	34.8	35.3	34.5	36.2	38.2	37.3	37.2	37.6	34.8

Table C7: Network Distribution Performance - Pavements (mutually exclusive) - $ 90 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	8.8	17.7	15.8	14.7	10.8	9.4	13.8	11.1	9.6	9.3	6.6	6.2	2.5	3.6	1.8	2.5	0.0	0.0	0.0	0.0	0.8	0.8	0.8	0.8	0.8	0.8
Fair (%)	47.1	41.2	39.2	36.4	37.9	37.2	24.9	24.1	20.1	19.6	17.2	17.2	17.2	17.2	17.2	2.8	2.3	3.7	6.7	6.2	9.0	9.0	3.8	0.7	0.7	0.2
Good (%)	20.4	18.8	17.8	17.8	17.1	16.9	23.3	38.5	38.3	46.3	48.6	51.4	55.7	62.5	66.9	61.7	66.8	65.5	69.4	68.7	74.4	83.8	78.2	83.7	84.7	90.4
Excellent (%	23.7	22.3	27.2	31.2	34.2	36.6	38.0	26.3	31.9	27.4	26.9	26.2	26.4	22.3	21.6	22.5	19.2	23.6	19.7	18.3	14.7	8.8	14.2	8.7	8.9	4.4

Table C8: Network Distribution Performance - Bridges (mutually inclusive) - $ 120 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	7.6	7.6	4.7	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	47.3	47.3	49.6	48.8	44.4	39.3	31.3	21.8	20.1	19.6	17.2	17.2	17.2	17.2	17.2	2.8	2.3	3.7	6.7	6.2	9.0	9.0	3.8	0.7	0.7	0.2
Good (%)	33.4	33.4	31.8	31.8	31.0	31.8	38.7	49.7	49.1	51.8	55.3	55.3	56.7	54.3	61.4	75.3	69.2	64.0	70.0	63.4	62.6	60.7	66.4	69.7	66.7	68.4
Excellent (%	11.7	11.7	13.9	16.8	24.6	28.9	30.0	28.6	30.8	28.6	27.5	27.5	26.1	28.5	21.4	21.9	28.5	32.3	23.2	30.4	28.4	30.3	29.8	29.5	32.6	31.4

Table C9: Network Distribution Performance - Pavements (mutually inclusive) - $ 120 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	8.8	17.7	14.5	12.4	10.7	10.3	9.3	8.5	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	47.1	41.2	39.3	36.9	36.5	33.6	28.9	21.7	21.7	19.4	11.7	0.0	0.0	0.0	0.0	3.3	6.6	9.6	11.1	13.1	15.8	18.0	17.5	8.2	4.2	0.2
Good (%)	20.4	18.8	17.7	15.7	15.0	15.0	15.3	37.1	35.0	42.5	53.4	67.2	62.6	80.1	76.8	79.2	84.0	86.0	82.3	83.4	77.6	75.9	74.8	85.4	82.1	91.3
Excellent (%	23.7	22.3	28.5	34.9	37.8	41.1	46.5	32.7	40.6	38.1	34.9	32.8	37.4	19.9	23.2	17.4	9.5	4.4	6.6	3.5	6.6	6.0	7.7	6.4	13.7	8.5

Table C10: Network Distribution Performance - Highway (mutually inclusive) – $ 120 M / year

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Poor (%)	8.5	15.1	11.1	8.0	8.0	7.7	7.0	6.4	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair (%)	47.2	42.8	41.9	37.4	38.9	35.0	25.0	16.2	16.2	14.5	8.7	0.0	0.0	0.0	0.0	2.8	5.3	7.9	9.9	11.4	14.1	15.7	13.1	6.2	3.1	0.2
Good (%)	23.7	22.4	19.7	21.2	19.0	19.2	25.3	44.4	42.7	48.0	56.5	66.5	64.1	77.3	74.6	75.0	76.5	76.9	77.1	79.6	75.3	74.6	75.3	84.2	80.2	87.5
Excellent (%)	20.7	19.7	27.4	33.4	34.1	38.1	42.7	33.0	39.0	37.5	34.8	33.5	35.9	22.7	25.4	22.2	18.3	15.2	13.0	9.1	10.6	9.7	11.6	9.7	16.7	12.4