Application of Probabilistic Life Cycle Cost Analysis in Pavement Management

By

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ABSTRACT

Transportation agencies seek to optimize their public budget to finance the construction and maintenance of pavements, and management tools that allow evaluating the efficiency of pavements and their economic benefits are needed. Life Cycle Cost Analysis (LCCA) is a decision support tool that allows agencies to contrast and optimize infrastructure design alternatives based on agency, user and environmental costs of the asset over its lifetime, including initial construction and future maintenance and rehabilitation activities.

This thesis developed statistical distributions for discount rate, treatment activity timing and agency costs based on agency historical data of the provincial network of the Province of Manitoba and the municipal network of the City of Winnipeg. The distributions were used to study the variability associated with each LCCA input. A case study was used to compare the results from the deterministic and the probabilistic computational approaches using the Federal Highway Administration RealCost software. Additionally, the inclusion of the variability of minor maintenance and rehabilitation treatments was studied. The results demonstrated that a probabilistic LCCA provides reliability levels for the evaluation of the present value of the total project cost. It provides a distribution of all possible values with their respective probabilities of occurrence, which allows for analyzing the risk associated with each alternative and avoiding cost overruns. It was also demonstrated that the inclusion of the variability of the timing of minor treatments has an effect on the distribution of the net present value and the risk associated with each alternative. It is recommended that transportation agencies consider probabilistic life cycle cost analyses as part of their decision-making process to minimize total costs and guarantee the quality of the assets in the long term.

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CHAPTER 1 - INTRODUCTION

Given the need of public budget optimization to finance the construction and maintenance of pavements, it is essential to calculate the economic benefits that could be obtained from estimating the life cycle cost of the pavements, which would not only benefit transportation agencies but also the road users by providing high levels of service. Life cycle cost analysis (LCCA) considers initial and future costs resulting from agency costs, road user costs and environmental impact. Nevertheless, user and environmental costs are still not been fully considered by many transportation agencies due to the complexity of their calculation. According to Morges et al. (2017) “In Canada, most provincial agencies use LCCA as a primary decision tool for selecting pavement design and/or rehabilitation alternatives” (Morges et al. 2017).

Another important aspect to take into account during the process is the life expectancy of the pavements. Pavement life is affected by the materials used during construction, the design method, subgrade soil, type of drainage system, external agents such as temperature changes, freeze and thaw cycles, salts used for defrosting, etc. As a result, pavement life is uncertain as well as the timing of the activities to extend it. Data management systems are useful tools to store data, but the objective of storing data is to learn from experience. Historical data can be used to analyze pavement performance and asset management practices.

LCCA inputs such as unit cost and discount rate are dependent on the economy, the timing of maintenance and rehabilitation (M&R) activities is dependent on budget, pavement condition, and road use. As a result, the variability of the inputs should be considered when analyzing the life cycle cost of pavements. This type of analysis is achieved by applying the probabilistic computational approach that also helps to evaluate the risks associated with each pavement alternative.

Research on the application of probabilistic LCCA of pavements has increased since the publication of the FHWA LCCA Technical Bulletin in 1998. Table 1 shows some studies where some sources of variations were accounted for the development of life cycle cost analysis on pavements. One common application of probabilistic LCCA of pavements is for the comparison of two different structural materials. Akbarian et al. (2017) compared asphalt versus concrete pavements, Swei, Gregory, & Kirchain (2012) compared Joint Plain Concrete Pavement (JPCP) versus Hot Mix Asphalt (HMA), and Cheng and Hicks (2012) compared Rubberized Hot Mix Asphalt (RHMA) versus HMA. Probabilistic LCCA is also used to evaluate design alternatives of the same material, for example, various overlay thicknesses as in Whiteley, Tighe, & Zhang (2005).

These studies considered some of the LCCA inputs as probabilistic to study their effect on the output. Additionally, the frequency and type of maintenance and rehabilitation activities came from existing standards and their associated variability was not considered. Pittenger et al. (2012) studied probabilistic LCCA of HMA overlay and chip sealing, but not as a component of the total life cycle cost of a pavement. All these studies have something in common. They were able to identify the most cost-effective option in the long term using the probabilistic approach of

LCCA. According to Morges et al. (2017), the provinces of Ontario and Quebec are using the probabilistic approach for life cycle costing.

Table 1. Research studies on Probabilistic LCCA

Study	Description	Source of variation					Results
		Discount rate	Service life	Initial cost	Future cost	User Cost	
Akbarian et al. (2017)	Probabilistic LCCA of Asphalt versus Concrete. Minnesota, USA			✓	✓	✓	For short pavement sections, the life cycle cost of Asphalt alternative is lower than Concrete. For long sections, the results show the opposite.
Swei, Gregory, & Kirchain (2012)	Probabilistic LCCA of JPCP versus HMA. California, USA			✓	✓		Deterministic result: Similar life cycle cost. Probabilistic result: HMA more expensive than JPCP by 7%
Cheng and Hicks (2012)	Probabilistic LCCA of RHMA versus HMA. California, USA		✓	✓			The life cycle cost of RHMA is lower than HMA in most of their case scenarios
Pittenger et al. (2012)	Probabilistic LCCA of HMA overlay and chip sealing. USA	✓	✓	✓			Probabilistic LCCA results help to mitigate risk and help on the selection of preservation treatments
Whiteley, Tighe, & Zhang (2005)	Probabilistic LCCA with different overlay thicknesses. Ontario, Canada	✓	✓				The standard deviation of the total life cycle cost increases as the overlay thickness increases

JPCP= Joint Plain Concrete Pavement, HMA= Hot Mix Asphalt, RHMA: Rubberized Hot Mix Asphalt

1.1 STATEMENT OF THE PROBLEM

Although tools are available to calculate probabilistic analysis, and many studies reflect the benefits of using LCCA in pavement management, the analysis requires data that is not readily available in data management systems. Data is extracted from different data sources (historical data, expert opinion, and research studies), but some work is needed to develop the inputs required for a probabilistic life cycle cost. The validation and proper use of sources are also important factors.

Currently, some transportation agencies do not consider life cycle cost analysis when choosing between pavement alternatives, which represents a problem given that pavements are long-standing assets that have to be maintained to ensure adequate levels of service. Others consider life cycle cost in their decision-making process, but only apply the deterministic approach. This computational approach does not consider the variability associated with the inputs, and for this reason, its reliability is unknown.

Consequently, deterministic and probabilistic life cycle cost analyses will be applied in this thesis through a case study pavement section to compare both computational approaches, reflect the usefulness of this tool and to show the importance of including the variability of the inputs into the analysis.

1.2 THESIS OBJECTIVES

The main objective of this study is to improve current pavement management practices with the development of distributions to be used in the planning and management of projects as well as in the application of probabilistic Life Cycle Cost Analysis.

The specific objectives of this study are:

1. Analyze existing data to determine the variability associated with asphalt and concrete pavements service lives, timing of maintenance and rehabilitation activities, discount rate and unit costs for pavements belonging to the City of Winnipeg and the Province of Manitoba road network
2. Perform survival analyses and develop probability distributions to determine the probabilistic inputs for life cycle cost analysis
3. Determine the probabilistic life cycle cost of a case study pavement section
4. Compare the outputs of the deterministic and the probabilistic LCCA and the benefits of considering the variability of the inputs

1.3 METHODOLOGY

In this study, statistical distributions will be developed with available data from the City of Winnipeg and the Province of Manitoba to study the variability of the inputs required for LCCA. The distributions are based on historical data, and do not account for new practices; however, two approaches will be used to study pavement life, namely, survival analysis and distribution fitting. The survival analysis will be applied to all data years, but a time threshold will be used for the developments of probability distributions. In addition to pavement life, the timing of maintenance and rehabilitation activities, unit costs, and discount rate will be considered as probabilistic inputs. This will allow the comparison between deterministic and probabilistic LCCA results.

1.4 SIGNIFICANCE OF THE STUDY

This study will help transportation agencies to make better-informed decisions in the planning and management of pavement networks. This study will transform data gathered from different sources into statistical distributions that do not currently exist. These distributions can be used for pavement management practices including the analysis of the life cycle cost of pavements. In addition, this study will demonstrate the benefits of applying the probabilistic life cycle cost analysis over deterministic approach. The consideration of probabilistic LCCA in the decision-making process will allow transportation agencies to optimize infrastructure budget and avoid cost overruns.

1.5 THESIS ORGANIZATION

The study is structured as follows:

Chapter 1 emphasizes the importance of this thesis and presents the statement of the problem, the objectives, and significance of the study.

Chapter 2 presents a literature review of life cycle cost analysis and pavement life expectancy, and it introduces the software to perform LCCA. In this chapter, the benefits of considering LCCA, the steps to follow for its calculation and the computational methods are defined.

Chapter 3 contains the data and methodology used to accomplish the objectives. This chapter presents a description of the City of Winnipeg and the Province of Manitoba road network, the sample pavement sections, and describes the data analysis methods.

Chapter 4 describes the results of this investigation supported by their analysis and the limitations faced during the study. This chapter presents the variability of the inputs using survival analysis and probability distributions, and the calculation of the deterministic and probabilistic life cycle cost of a case study pavement section.

Chapter 5 presents the conclusions of this research along with the recommendations drawn based on the results obtained.

Finally, the references and appendices that support this study are included at the end.

CHAPTER 2 - LITERATURE REVIEW

2.1 APPLICATION OF LIFE CYCLE COST ANALYSIS ON TRANSPORTATION ASSETS

Transportation agencies build, maintain, own and operate infrastructure assets for the entire service life. For this reason, it makes sense to look at the life cycle cost for benefit-cost analysis rather than only initial cost. LCCA can be used as a tool to evaluate different pavement types and determine which alternative is the most cost-effective considering the costs associated with the ongoing maintenance requirements of each alternative over the period of study.

Another application of LCCA is to compare the frequency and the type of treatments to be applied over the study period. The treatments can be corrective or preventive, and the effect of these treatments can be seen on the overall cost of the alternatives. For example, in the case of concrete pavements, a preventive option could be crack sealing. A corrective option could be a partial or full-depth repair when the severity of the cracks is too high. The cost of many economical applications and the cost of few expensive applications can be compared with LCCA.

The analysis is applicable to "new construction, reconstruction, rehabilitation and even preservation projects" (FHWA, 2010). The alternatives being evaluated should provide similar benefits, for the comparison to be based only on the cost associated with each alternative (Van Dam et al., 2015). LCCA makes it possible to find a balance between costs and performance (Zoeteman, 2001). The results from the LCCA support the decision-making process, but they may not be the final decision. Other factors such as risk, budget, political and environmental issues, etc. should also be considered (FHWA, 2002). The LCCA could include all of those factors if it is possible to monetize their effect and be treated as costs (Van Dam et al., 2015).

2.1.1 Inputs for LCCA

The inputs to develop a Life Cycle Cost Analysis are analysis period, discount rate, activity timing and costs, and Salvage value.

2.1.1.1 Analysis Period

The analysis period is the "…timeframe for which initial and future costs will be evaluated for all alternatives being considered" (FHWA, 2002). This means that the analysis period will cover initial activity and future treatments. The selected analysis period should be the same for all alternatives, and long enough to show the costs differences between the alternatives being compared. The analysis period has to be sufficiently long to include at least one major rehabilitation action for each alternative (Walls & Smith, 1998). The analysis period is not the same as the design period, which is the time a pavement is designed to receive its first major rehabilitation. According to Morges et al. (2017), the analysis period used for pavement LCCA by Canadian provincial agencies ranges from 25 to 80 years. Figure 1 shows an example of analysis period for a pavement design alternative.

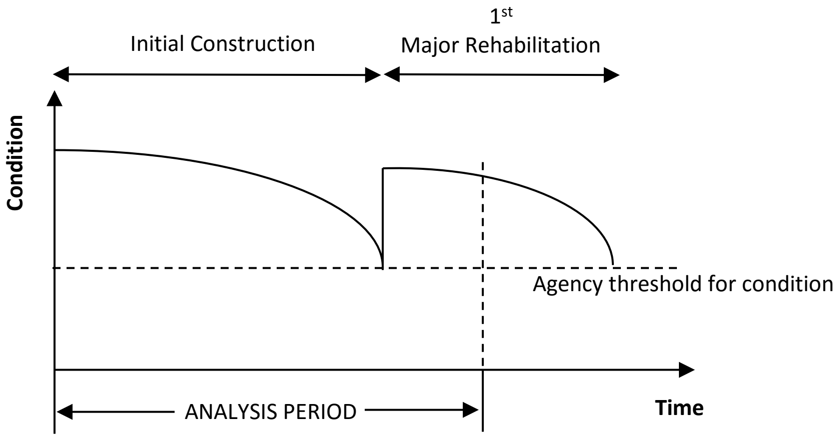


Figure 1. Analysis period for pavement life cycle cost analysis

2.1.1.2 Discount rate

A discount rate is used to convert future cost to their equivalent present value. The discount rate is approximately the difference between interest and inflation rates (Hallin et al., 2011). According to Morges et al. (2017), Canadian provincial agencies use a discount rate that ranges from 3 to 6%.

2.1.1.3 Costs

There are two types of costs, tangible and intangible. Tangible costs are those covered by the agency, such as initial construction costs, future maintenance and rehabilitation cost, etc. Intangible costs can be expressed in user costs and environmental costs. User costs are the costs incurred by the road users over the life of the pavement, and they include vehicle operating costs (VOC), user delay costs, and crash costs (Walls & Smith, 1998). Environmental costs are the cost associated with the environmental impacts of resource use and emissions to the environment (Huang & Parry, 2014). According to Morges et al. (2017), the provinces of Alberta, British Columbia, and Quebec are considering components of user costs in their LCCA. In the case of environmental costs, the provinces of British Columbia, Ontario, and Quebec consider these costs separate from LCCA, and the province of Alberta considers only emission costs on their LCCA (Morges et al., 2017).

2.1.1.4 Activity timing

The timing for maintenance and rehabilitation (M&R) activities can have a significant impact on LCCA. The service life of these activities and the time when they should be applied is important for cost estimation. These values can be obtained from historical agency data or experts opinion. According to Morges et al. (2017), the majority of Canadian provincial agencies use standards based on historical performance for activity timing. Table 2 shows the timing used by the provincial agencies.

Table 2. Activity timing used by Canadian provincial agencies (Adapted from Morges et al., 2017)

Provincial Agency	Initial Service life (years)		Rehabilitation activity & Service Life (years)	
	Flexible Pavement	Rigid Pavement	Flexible Pavement	Rigid Pavement
Alberta	20	30	Hot-In-Place Recycle: 8-11 Mill & Inlay: 10-13 Two Lift Overlay: 8-20 Reprofile & Overlay: 15-20	N/A
British Columbia	20	30	(Mill and) Resurface: 15+	N/A
Manitoba	20	Doweled JPCP: 20	Mill and Resurface: 12	Diamond Grinding: 15 CPR: 12
Nova Scotia	20	40	Mill and Resurface: 12	Diamond Grinding: 18 CPR: 10
Ontario*	DFC: 19 SMA: 21	Doweled JPCP: 28	Mill and Resurface, DFC: 12 SMA:13	Diamond Grinding: 10 CPR: 10 Resurfacing: 12
Quebec	25-30	30	Mill and Resurface: 8-12 Reconstruction: 38-49	CPR: 10 AC Overlay: 39 Reconstruction 46-49
Saskatchewan	15	N/A	Mill and Fill HMA Overlay: 15 Base Treatment and Double Seal/HMA Overlay: 15	N/A

* Service life projections based on an initial 2 million ESALs/year for flexible pavements and 3 million ESALs/year for rigid pavements, with a 3.4 percent compound ESAL growth rate. JPCP= Jointed Plain Concrete Pavement, CPR= Concrete Partial Depth Repair, DFC= Dense Friction Course, SMA= Stone Mastic Asphalt, AC= Asphalt Concrete, HMA= Hot Mix Asphalt

There are two types of maintenance: preventive maintenance and corrective maintenance. Corrective maintenance is performed as required to correct a fault. It allows the failed item to develop again its functions as required (Stenström, Norrbin, Parida, & Kumar, 2015). Preventive maintenance is performed periodically to prevent that an item fails or deteriorate at a faster rate. Preventive maintenance in pavements can delay deterioration and rehabilitation needs, improve safety and extend the pavement service life. The main difference between preventive and corrective maintenance is the cost of the activity and the improvement on pavement life.

2.1.1.5 Remaining Service Life Value and Salvage value

Remaining service life (RSL) value is the useful life that the pavement has at the end of the analysis period in dollar terms, and salvage value is the value of recycling the pavement.

2.1.2 Procedure and data to develop LCCA of pavements

The process to develop LCCA of pavements is to define pavement design alternatives, determine the timing and performance of treatment activities, determine costs, generate expenditure stream diagrams, calculate the net present value and compare the results (Walls & Smith, 1998). Table 3 shows the data needed to develop a Life Cycle Cost Analysis on Pavements and the uncertainty associated with this data.

2.1.2.1 Expenditure stream diagrams

Expenditure stream diagrams represent all the money expended on the pavement during the analysis period. These diagrams include initial construction costs and future maintenance and rehabilitation activities. Minor routine maintenance is usually not included because its effect on the net present value is insignificant. Remaining service life value or salvage value, if the asset is to be terminated (FHWA, 2002) can be added as a negative cost. Figure 2 is an example of an expenditure diagram.

Table 3. Data to develop a LCCA of pavements and its uncertainty

Life Cycle Cost Analysis Steps	Data	Uncertainty
Define design alternatives (same benefits)	Initial design life, terminal serviceability or minimum level of service	Variability of pavement service and structural life
Determine the timing and performance of treatment activities	Timing of rehabilitation activities, service life of activities	Data availability and quality, pavement design considerations, change of use or traffic, treatment application reasons
Determine agency costs	Initial construction costs, maintenance and rehabilitation activities cost, remaining service life (RSL) or salvage value, administrative costs, etc.	Unit price historical data availability and accuracy
Determine user costs	Vehicle operating costs (VOC), user delay costs, crash costs	Data availability and difficulty on costs estimation
Generate expenditure stream diagrams	Analysis period	Variability of pavement structural life
Calculate the net present value	Discount rate	Variability on the economy

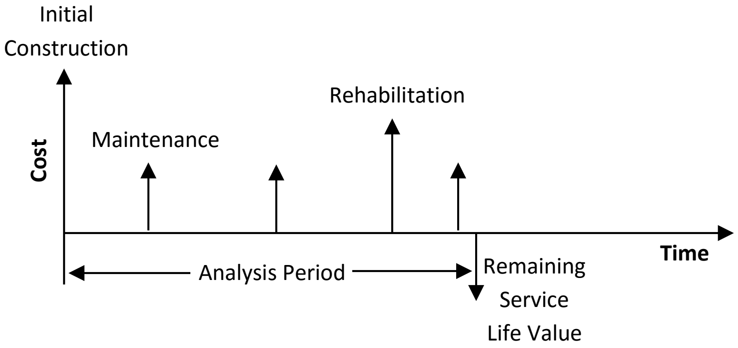


Figure 2. Expenditure diagram for pavement life cycle cost analysis

2.1.2.2 Net present value and equivalent uniform annual cost

The net present value (NPV) of the alternatives under consideration is calculated for further comparison after all costs are represented on the expenditure diagram. The net present value results from discounting all future costs to the base year and adding the initial costs. The formula used to calculate the NPV is:

$$\text{NPV} = \text{Initial Cost} + \sum_{n=1}^{N} \text{Future Cost}_n \left[\frac{1}{(1+i)^n}\right] \tag{2.1}$$

Where i = discount rate, n = year of expenditure

The equivalent uniform annual cost (EUAC) is similar to the NPV, but the costs are distributed uniformly throughout the analysis period. The formula used to calculate the EUAC is:

$$\text{EUAC} = \text{NPV}\left[\frac{i(1+i)^N}{(1+i)^N-1}\right] \tag{2.2}$$

Where i = discount rate, N = analysis period

2.1.3 Computational approaches to develop LCCA of pavements

There are two different approaches to develop LCCA calculations. The deterministic and the probabilistic. “The methods differ in the way they address the variability associated with the LCCA input values” (FHWA, 2010). The deterministic approach uses single values for each of the LCCA inputs, which are based on experience, standards, and assumptions, and the output is a single value representing the life cycle cost of the alternative.

“The probabilistic approach entails defining individual input parameters by a frequency/probability distribution (which may take many forms), rather than by discrete values”

(FHWA, 2010). This means the probabilistic approach accounts for the variability of the inputs. The probability distributions are developed using agency historical data to consider aspects that are unique to each transportation agency such as specifications, environment, traffic, etc.

The quality of the Life Cycle Cost Analysis depends on the quality of the inputs used in the process. LCCA is usually performed on long-standing assets and many different factors can affect the inputs assumed in the initial year. For example, a change in the economy can produce variations in the discount rate, and the price of oil can affect the costs of the materials, etc. The use of deterministic inputs will not capture the possible changes the inputs might experience. For this reason, a probabilistic approach should be performed to consider that variability.

Probability distributions to represent deterioration treatments can be based on the optimal or actual time to repair. A model based on optimal time to repair will assume pavements are treated when they reach the condition threshold established by the agency. On the other hand, a model based on actual time to repair will consider the external factors that could have affected the time when pavements were repaired, which could be different from the optimal time. For other inputs, such as cost and discount rate, financial data and unit price records are used. Because the inputs are distributions, the output will also be a distribution showing the variability of the Life Cycle Cost. Table 4 shows the current LCCA computational approaches and tools used by Canadian provincial agencies to develop LCCA on pavements. In this study, the software RealCost will be used given that it was developed by the Federal Highway Administration (FHWA), which represents a trustable source, and because of its current use in the province of Manitoba.

Table 4. LCCA computational approaches and tools used by Canadian provincial agencies (Adapted from Morges et al., 2017)

Agency	LCCA Computational Approach	LCCA Tools
Alberta	Deterministic (with optional Sensitivity Analysis)	MS Excel Spreadsheet
British Columbia	Deterministic (with Sensitivity Analysis)	ShortBEN Safety-BenCost
Manitoba	Deterministic	RealCost
Nova Scotia	Deterministic	DARWin
Ontario	Deterministic Probabilistic	MS Excel with Crystal Ball® OPAC 2000
Quebec	Probabilistic	RealCost
Saskatchewan	Deterministic	MS Excel LCC

2.2 LIFE EXPECTANCY

Asset life could be defined according to different perspectives. Ford et al. (2012) separate asset life into physical, service, functional and economic life. Physical life is the time the asset is on the site providing any type of service. Service life is the time the asset is providing the intended type of service at any level of service. Functional life is the time when the asset provides all the benefits intended and economic life is the time when it is worthy to keep the asset instead of replacing it.

The following are also types of asset life (Ford et al. 2012):

- Actual life: The recorded period from construction until replacement
- Estimated life: A prediction of the asset life
- Target life: The desired asset life

- Design life: The life for which the asset is designed

Additionally, the asset life extension resulting from the application of a treatment can be called treatment life (Ford et al. 2012). Life is expressed in the majority of the assets as age in years. Nevertheless, life could be also expressed in accumulated traffic, accumulated loads, etc. The life of an asset is not only dependent on age. Factors such as site conditions, asset characteristics, loads, treatment history, etc. can also have an influence.

2.2.1 Pavement Life

"Pavement life expectancy generally refers to a functional life when the intended action at the end of life is one that restores the functional adequacy of the pavement" (Ford et al. 2012). This means that pavement life is the age of the pavement when it receives a rehabilitation treatment. The life of the pavement depends on factors such as surface type, pavement structure, thicknesses, climate conditions, subgrade type, traffic loadings, maintenance treatments, etc.

According to Ford et al. (2012), there are three life estimation approaches: condition-based, age-based and hybrid. The condition-based approach is used on assets where condition is periodically recorded. The life expectancy is the time from construction or reconstruction until an agency condition threshold. This threshold considers structural adequacy, serviceability, functional obsolescence and safety for the users (Ford et al. 2012). The age-based approach is used when there is availability of records about the year of construction and the years when major rehabilitation treatments were applied. This approach quantifies the age of the asset when replaced directly from the records, which is the actual asset life. The hybrid approach is the combination of both condition and age-based. This approach studies the condition of the asset at the year of replacement. In a perfect world, an asset is repaired or replaced when a condition is met. In practice, other constraints may advance or delay the activity.

2.2.2 Optimal and actual time to repair

According to Shahin (2005), the prediction models to determine maintenance and rehabilitation requirements can be based on pavement condition. Pavement condition models are useful tools to find the optimal time to repair, which could be a function of IRI, PCI, and other pavement condition ratings. However, the optimal time to repair could be different from actual time to repair. Many factors can affect the time when treatments are applied, and make the actual time to repair different from the optimal. The actual time to repair could be shorter than the optimal if the pavement is no longer meeting the requirements of the project. This one could also be longer than the optimal due to lack of budget. Actual time to repair is found using historical treatment data available from pavements with similar characteristics. In this manner, the probability distribution of the actual time will consider the external factors that could have affected the time when pavements were repaired.

2.2.3 Methods for Life Expectancy Estimation

There are two types of methods to estimate life expectancy, mechanistic and empirical. Mechanistic methods apply principles of engineering mechanics with the use of field or laboratory test to simulate the deterioration of assets. On the other hand, empirical methods use empirical modeling techniques for estimating life. These techniques can be divided in statistical regression, Markov chains, duration models and machine learning (Ford et al. 2012). The selection of the empirical technique relies on the type of asset under study and the type of data available. Duration models can be applied to estimate life if there is lack of condition data, but there is data about replacements (Ford et al. 2012).

Duration or survival models illustrate the probability of a continuous dependent variable passing beyond or “surviving” at any given unit of time, which results on a survival/probability curve that can be used to estimate asset life (Ford et al. 2012). Duration models include Kaplan-Meier model, Cox proportional hazards models, Weibull survival distributions and others (Ford et al. 2012).

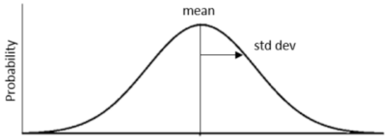
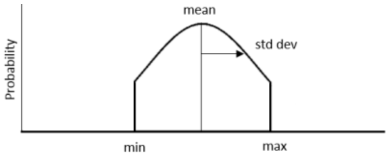
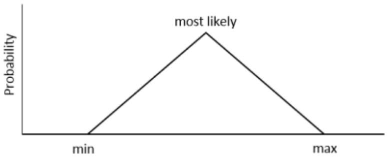
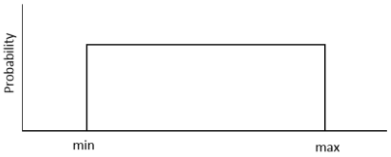
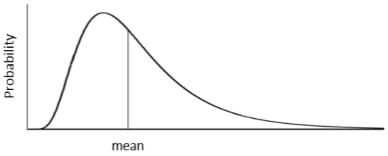
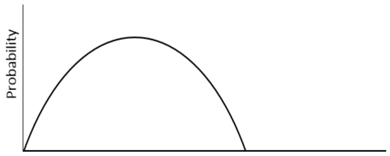
2.3 REALCOST SOFTWARE

The Federal Highway Administration developed the RealCost software. The first version was released in 2002 as RealCost 2.0 (FHWA, 2010). The software is a combination of a Microsoft Excel® 2003 spreadsheet and a Visual Basic for Applications (VBA) programming code, and it follows the methodology described in the FHWA’s LCCA Interim Technical Bulletin for the calculation of life cycle cost (FHWA, 2010). RealCost is able to calculate both the deterministic and the probabilistic LCCA, and it provides the option to include user costs on the calculation.

2.3.1 Inputs to develop LCCA on RealCost

The inputs to develop an LCCA on RealCost depend on the desired type of analysis. The software is able to develop both deterministic and probabilistic analyses. The inputs for a deterministic analysis are single values, but to develop a probabilistic analysis the inputs with a possible variability should be represented by probability distributions. Table 5 shows the eight types of distributions accepted by RealCost. The inputs can be described by any of those distributions; however, the software output will always be a normal distribution. The probabilistic inputs are, as a result, the parameters of the distributions.

Table 5. Probability distributions and parameters (Adapted from RealCost 2.5)

Distribution	Parameters	Illustration
Normal	Mean, Standard Deviation	
Truncated Normal	Mean, Standard Deviation, Maximum, Minimum	
Triangular	Maximum, Minimum, Most likely	
Uniform	Maximum, Minimum	
Lognormal	Mean, Standard Deviation	
Truncated Lognormal	Mean, Standard Deviation, Maximum, Minimum	
Beta	Alpha, Beta	
Geometric	Probability	

The accuracy of the variability presented on the results depends not only on the inputs entered; it also depends on how the nature of inputs was defined, single value or distribution.

The inputs also depend on the desired output. The software can calculate both agency costs and user costs. However, to obtain user costs, data from the work zone such as lane closures, duration, capacity, traffic hourly distribution, etc., is needed. Table 6a and Table 6b show the inputs to develop an LCCA on RealCost.

Table 6a. Inputs to develop LCCA on RealCost, Part 1 (Adapted from RealCost 2.5 software spreadsheet)

Output	Category	Input	Type of analysis	
			Deterministic	Probabilistic
Agency Costs	Agency Data	Analysis period	✓	
		Discount rate	✓	✓
	Activity Data (initial construction, reconstruction and M&R treatments)	Agency construction cost	✓	✓
		Activity service life	✓	✓
		Activity structural life	✓	✓
		Maintenance frequency	✓	✓
		Agency maintenance costs	✓	✓

Table 6b. Inputs to develop LCCA on RealCost, Part 2 (Adapted from RealCost 2.5 software spreadsheet)

Output	Category	Input	Type of analysis	
			Deterministic	Probabilistic
User Costs	Agency Data	Traffic direction	✓	
	Traffic Data	AADT Construction year	✓	
		Cars as percentage of AADT	✓	
		Single unit trucks as percentage of AADT	✓	
		Combination trucks as percentage of AADT	✓	
		Annual growth rate of traffic	✓	✓
		Speed limit under normal operating conditions	✓	
		Number of lanes in each direction during normal conditions	✓	
		Free flow capacity	✓	✓
		Rural or urban hourly traffic distribution	✓	
		Queue dissipation capacity	✓	✓
		Maximum AADT	✓	
		Maximum queue length	✓	
	Value of Time	Passenger cars	✓	✓
		Single unit trucks	✓	✓
		Combination trucks	✓	✓
	Activity Data (initial construction, reconstruction	User work zone costs	✓	✓
		Work zone duration	✓	✓
		Number of lanes open in each direction during work zone	✓	
		Work zone length	✓	
		Work zone speed limit	✓	
		Work zone capacity	✓	✓
		Traffic hourly distribution	✓	
		Time of day of lane closures	✓	
		Added time and vehicle stopping costs	✓	

CHAPTER 3 - DATA AND METHODOLOGY

The probabilistic computational approach of LCCA requires historical data to develop probability distributions that illustrate the variability of each variable. This study focused on two data sources: the Manitoba Infrastructure dataset, which contains the Province of Manitoba highway network, and the City of Winnipeg dataset. Sample sections will be selected from each dataset to perform Kaplan-Meier survival analysis and to develop probability distributions. Following these analyses, the calculation of the deterministic and probabilistic life cycle cost will be developed.

3.1 MANITOBA INFRASTRUCTURE DATASET

The Manitoba dataset contains information about pavement structure, condition, maintenance and rehabilitation (M&R) treatments, traffic, location, and other characteristics of the sections of the Manitoba highway network. Table 7 shows the content of the dataset and the range of years for the data. Pavement condition data is limited to the last ten years. However, the overlay data goes back to the year 1963. The Manitoba highway network is composed of expressway, primary and secondary arterial and collector sections adding up to 19,143,104 m of total centerline length, as shown in Table 8. Figure 3 shows the Manitoba highway network map.

Table 7. Structure of the Manitoba Infrastructure dataset

Category	Group	Fields	Years of data available
Inventory	Location	• Region • Road No • Control section • Description	
	Functional Class	• Expressway • Primary arterial • Secondary arterial • Collector	
	Surface Type	• Concrete • Asphalt • AST (Asphalt Surface Treatment) • Granular (unsurfaced)	
	Geometry	• Length • Width • Number of lanes	
Construction History	Pavement Structure	• Subbase • Base • Surface	1935-2015
Maintenance & Condition	Maintenance & Rehabilitation Treatments	• Overlay	1963-2015
		• Micro surfacing • Chip sealing	2007-2016
		• Slurry seal • Rout and seal	2011-2016
	Condition	• IRI • Cracking • Rutting	2007-2016
	Traffic	• AADT • AADTT	1995-2014
Cost	Financial Data	• Interest rate	2002-2017
		• Bid results	2016-2017
		• Weighted Average Prices	1999-2015

Table 8. Manitoba highway network by functional class

Functional Class	Number of sections	Surface area (m2)	Percent of network	Centerline length (m)
Expressway	815	14,380,456.70	9.82%	1,915,865
Primary arterial	988	26,637,193.80	18.19%	3,654,265
Secondary Arterial	882	33,621,915.20	22.96%	4,321,077
Collector	1866	71,793,539.20	49.03%	9,251,897
Total Network	4551	146,433,104.90	100%	19,143,104

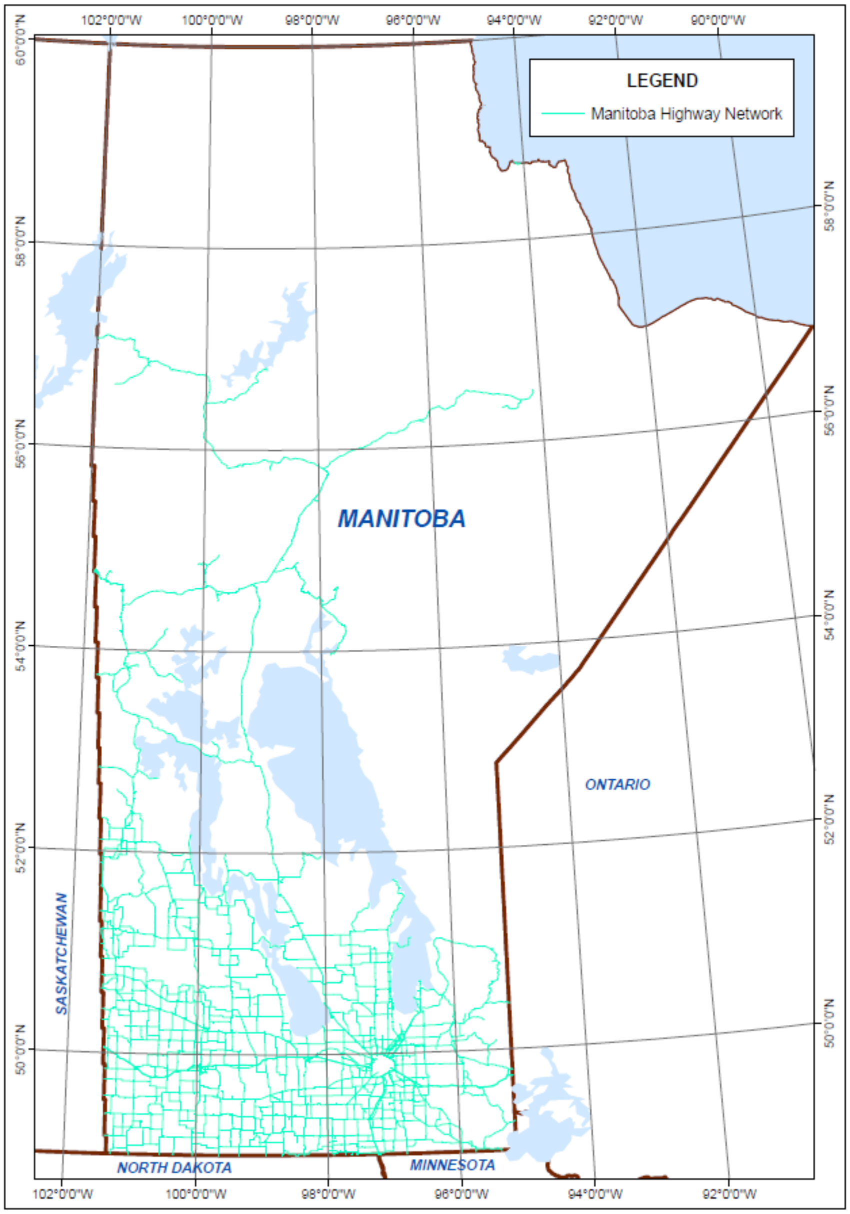


Figure 3. Manitoba highway network

The sections to develop the study were found as follows:

1. The Manitoba highway network is composed of 146 million square meters of pavement surface accounting for the width and number of lanes, as shown previously in Table 8. From which 14,380,456.70 m^2 represent expressway sections. Figure 4 shows the location of the expressway sections on the Manitoba Highway network.
2. The expressway sections on PTH 1, 16, 75, 100 and 101 were selected to be the data sample because they are the major highways in the province, and because of their significance to the transportation network. As shown in Table 9, PTH 1, 16, 75, 100 and 101 represent 10,437,126.80 m^2, which comprises 72.6% of the total expressway network. Figure 5 shows the location of the expressway sections on PTH 1, 16, 75, 100 and 101.
3. It was found the existence of first, second, third and fourth overlays on the sample, but to study pavement life, only the first overlays are studied. Table 10 shows the sample sections from the Manitoba Infrastructure dataset, where the overlays shown are the first overlays received by the pavements after their initial construction. Figure 6 shows the sample sections. The concrete sections are located in region 1 and 2 on PTH 1, 75, 100 and 101, and the asphalt sections are located in region 1, 2 and 3 on PTH 1, 16 and 101.

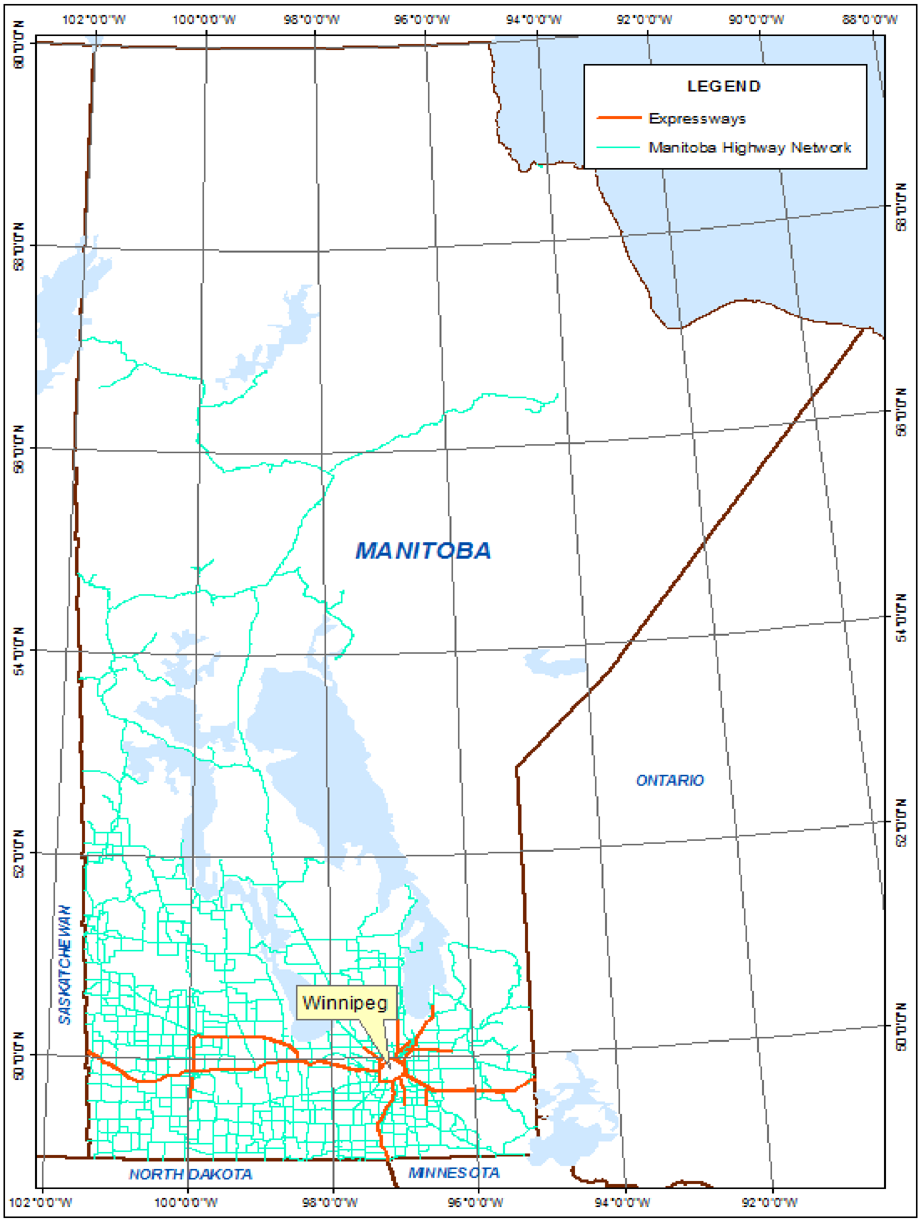


Figure 4. Expressway sections in the Manitoba highway network

Table 9. LCCA data sample (Manitoba Infrastructure)

Expressway sections	Number of sections	Surface area (m2)	Percent of network	Centerline length (m)
PTH 1, 16, 75, 100, 101	547	10,437,126.80	72.6%	1,392,692
• Asphalt pavement	486	9,104,381.20		
• Concrete pavement	61	1,332,745.60		
Other PTH	268	3,943,329.90	27.4%	523,173
Total Expressway Network	815	14,380,456.70	100 %	1,915,865

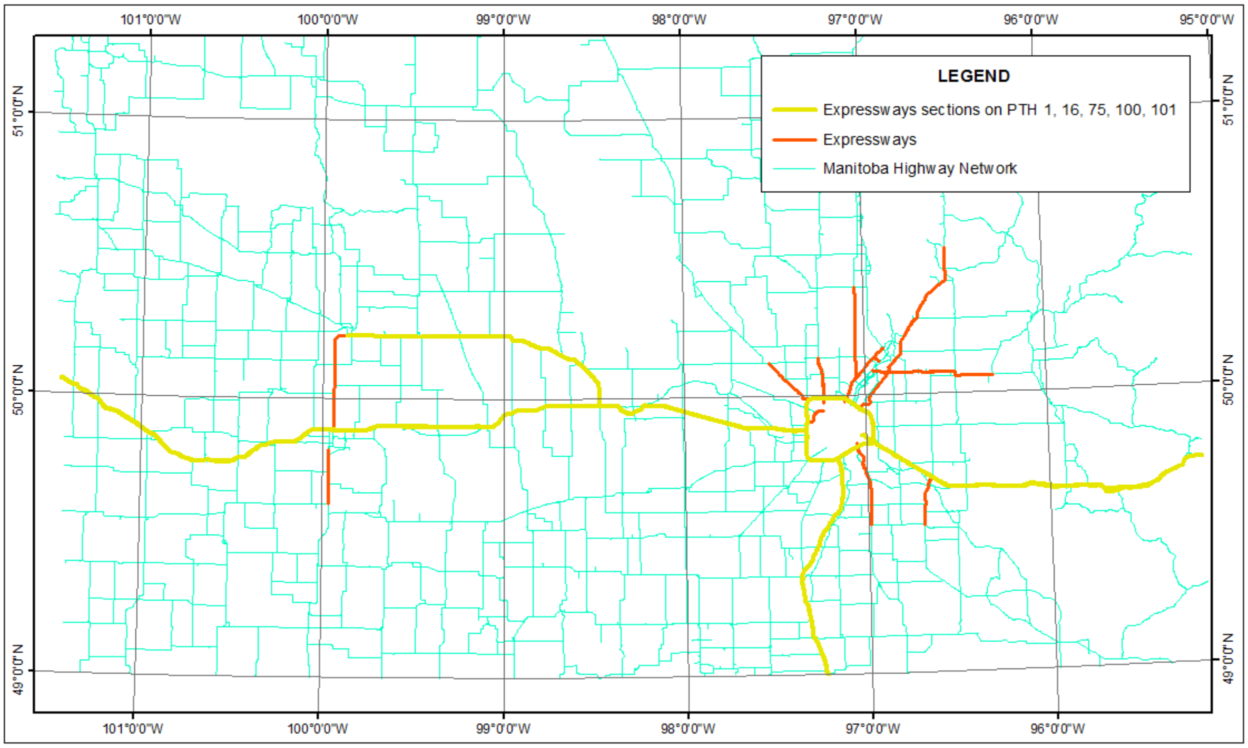


Figure 5. Expressway sections in PTH 1, 16, 75, 100 and 101

Table 10. Manitoba Infrastructure Sample Sections

Bituminous Overlays	Number of sections	Surface area (m^2)	Centerline length (m)
Over concrete pavement	138	2,515,301	339,754
Over asphalt pavement	217	4,294,551	567,885
Total	355	6,809,852	907,639

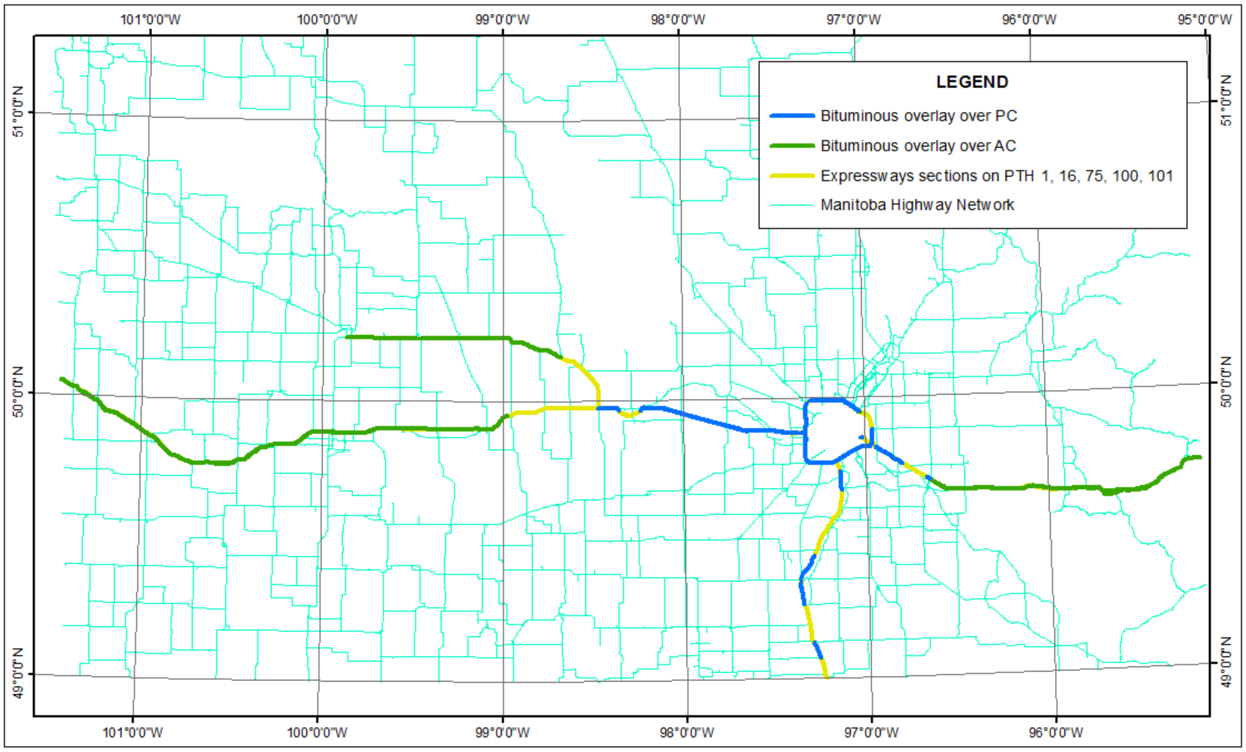


Figure 6. Manitoba Infrastructure Sample Sections

3.2 CITY OF WINNIPEG DATASET

The City of Winnipeg dataset contains information about construction year, M&R treatments, condition, traffic, location, and other characteristics of the sections of the City of Winnipeg network. Table 11 shows the content of the dataset and the range of years for the data. In this one, pavement condition data is expressed as the condition state on the last rating year. However, M&R treatment data goes back to the year 1911. The City of Winnipeg network is composed of sections that fall into four functional classes, which are arterial, collector, local and other. The total centerline length of the network is 4,200,607 m, as shown in Table 12. Figure 7 shows the City of Winnipeg road network map.

Table 11. Structure of the City of Winnipeg dataset

Category	Group	Items	Years of data available
Inventory	Location	• Street name • Intersections • Block ID • Road direction	
	Functional Class	• Arterial • Collector • Local • Others	
	Surface Type	• Concrete • Asphalt • Asphalt over Concrete • Gravel • Chip seal • Brick	
	Geometry	• Length • No of lanes	
Construction History		• Construction Year	1898-2016
Maintenance & Condition	Maintenance & Rehabilitation Treatments	• Overlay • Mill and Fill • Rehabilitation • Crack Sealing • TBO (Thin Bituminous Overlay) • Concrete repairs • Others	1911-2016
	Condition	• Condition State • Rating Year	Last recorded
	Traffic	• AADT • Speed limit	Last recorded
Cost	Financial Data	• Interest rate • Unit prices	2008-2017 2007-2016

Table 12. City of Winnipeg network by functional class

Functional Class	Number of sections	Surface area (m2)	Percent of network	Centerline length (m)
Arterial	5,792	6,754,409	21.33%	774,421
Collector	5,651	5,372,432	16.97%	743,942
Local	10,587	14,193,615	44.82%	1,972,580
Others	562	5,344,681	16.88%	709,664
Total Network	22,592	31,665,137	100%	4,200,607

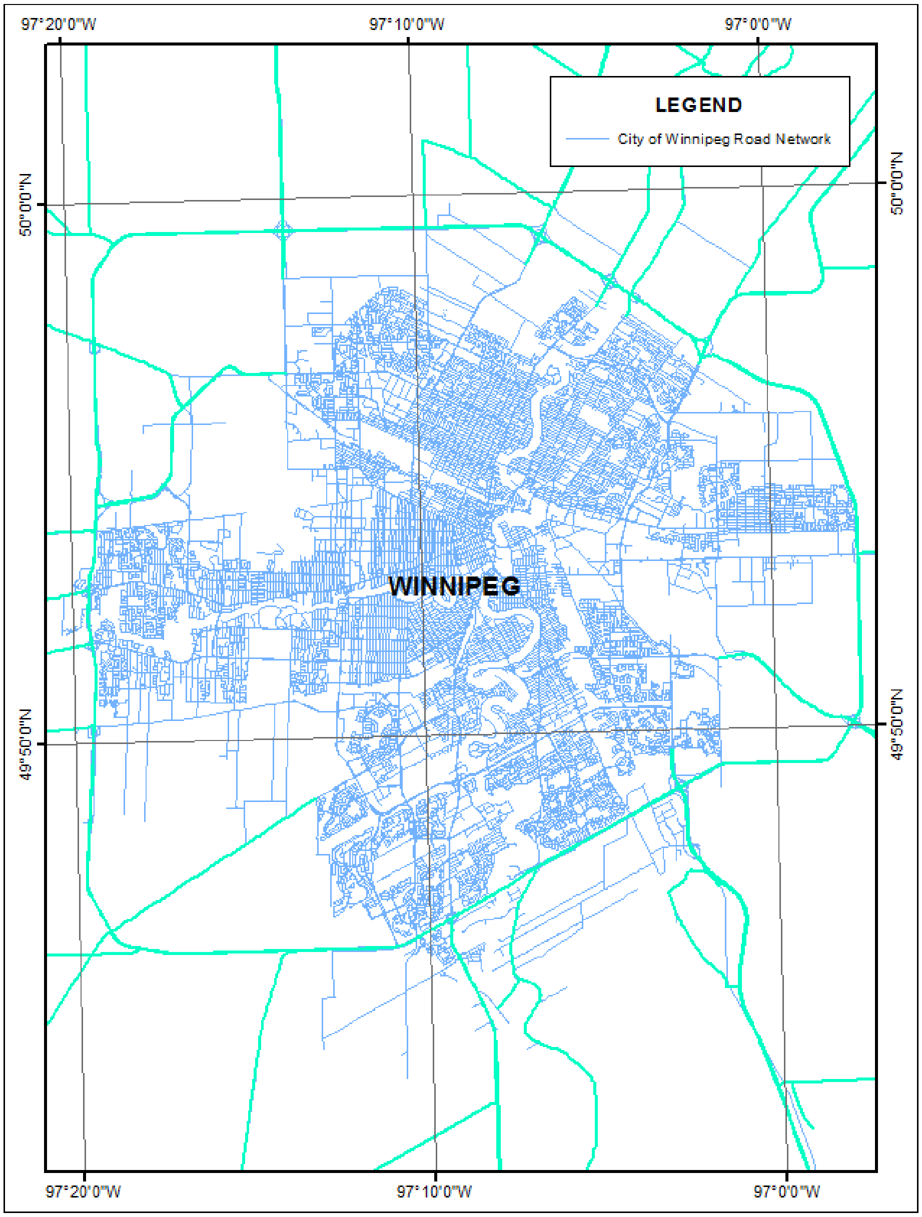


Figure 7. City of Winnipeg road network

The sections to develop the study were found as follows:

1. The City of Winnipeg road network is composed of 31 million square meters of pavement surface, accounting for the number of lanes and an assumed lane width of 3.60 m, as shown previously in Table 12. From which 6,754,409 m^2 represent arterial sections. Figure 8 shows the location of the arterial sections on the City of Winnipeg network.
2. Composite sections (bituminous overlay over concrete pavement) represent 70.7% of the total surface area of the arterial network, as shown in Table 13. Figure 9 shows the location of the composite sections on the arterial network.
3. The data sample is composed of the composite arterial sections of Bishop Grandin Boulevard, Kenaston Boulevard, King Edward Street, Lagimodiere Boulevard, Main Street, Pembina Highway and Portage Avenue. These sections were selected for being part of the inner ring of the city, and due to the significance of these roads to the transportation network. These sections are also regional sections, which have the same pavement structure disregarding their location. They were initially constructed with geotextile, geogrid, 600mm subbase, 75mm base and 230mm plain doweled concrete. As shown in Table 14, this sample represents 25% of the total composite arterial network. Figure 10 shows the location of the data sample.
4. Only the first overlays are studied. Table 15 shows the sample sections from the City of Winnipeg dataset, where the overlays shown are the first overlays received by the pavements after their initial construction. The analysis is going to be developed with these sections. Figure 11 shows the sample sections selected from the data sample.

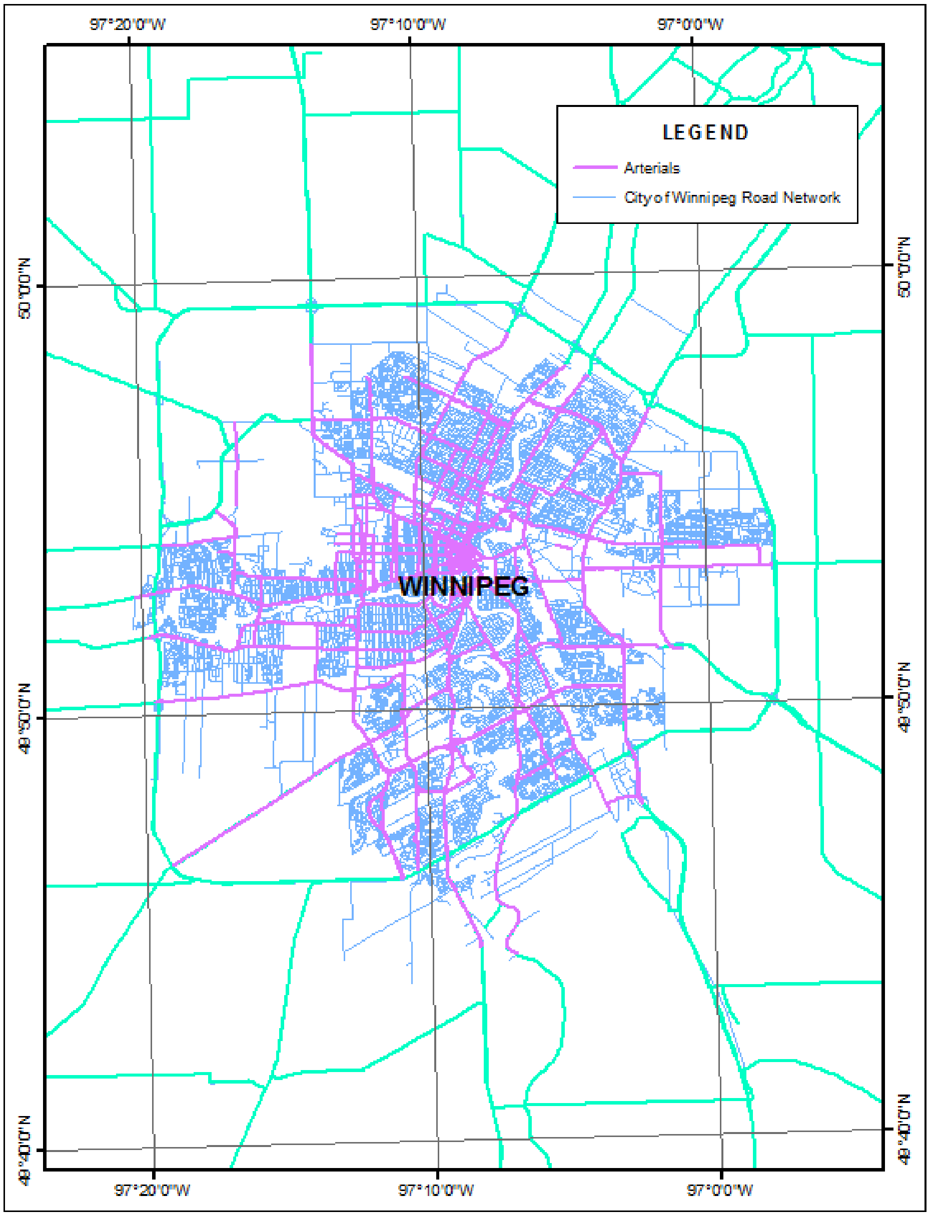


Figure 8. Arterial sections in the City of Winnipeg road network

Table 13. City of Winnipeg arterial network by pavement type

Arterial Sections	Number of sections	Surface area (m2)	Percent of network	Centerline length (m)
Asphalt over concrete (composite)	3,316	4,775,118	70.7%	510,421
Concrete	637	1,052,700	15.6%	128,717
Asphalt	84	281,888	4.2%	39,795
Others	1,755	644,703	9.5%	95,488
Total Arterial Network	5,792	6,754,409	100%	774,421

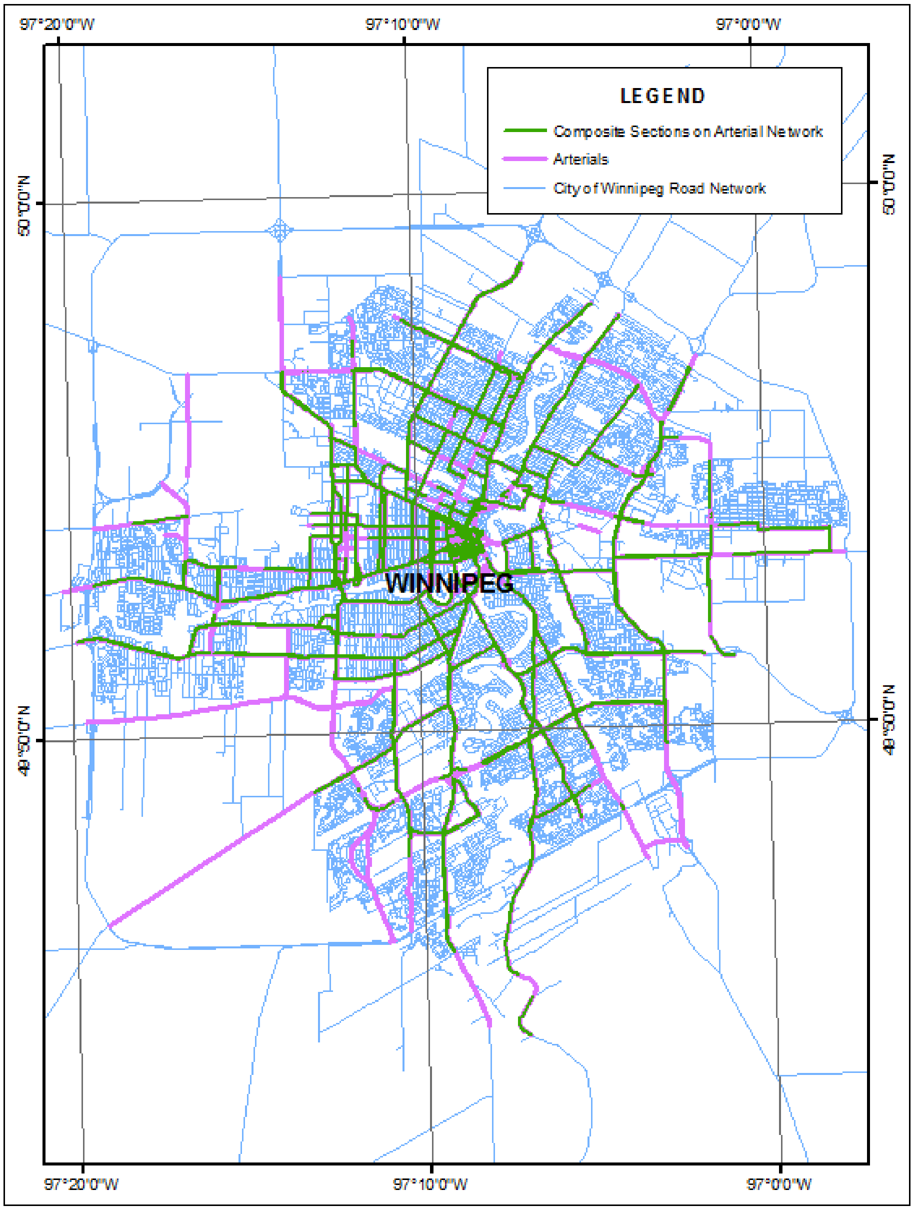


Figure 9. Composite sections in the City of Winnipeg arterial network

Table 14. LCCA data sample (City of Winnipeg)

Composite Arterial Sections	Number of sections	Surface area (m2)	Percent of network	Centerline length (m)
Bishop Grandin Blvd, Kenaston Blvd, King Edward St, Lagimodiere Blvd, Main St, Pembina Hwy, Portage Ave	781	1,195,948	25.0%	120,290
Other Regional Arterials	2525	3,538,586	74.1%	384,494
Other Arterials	10	40,584	0.9%	5,637
Total	3,316	4,775,118	100%	510,421

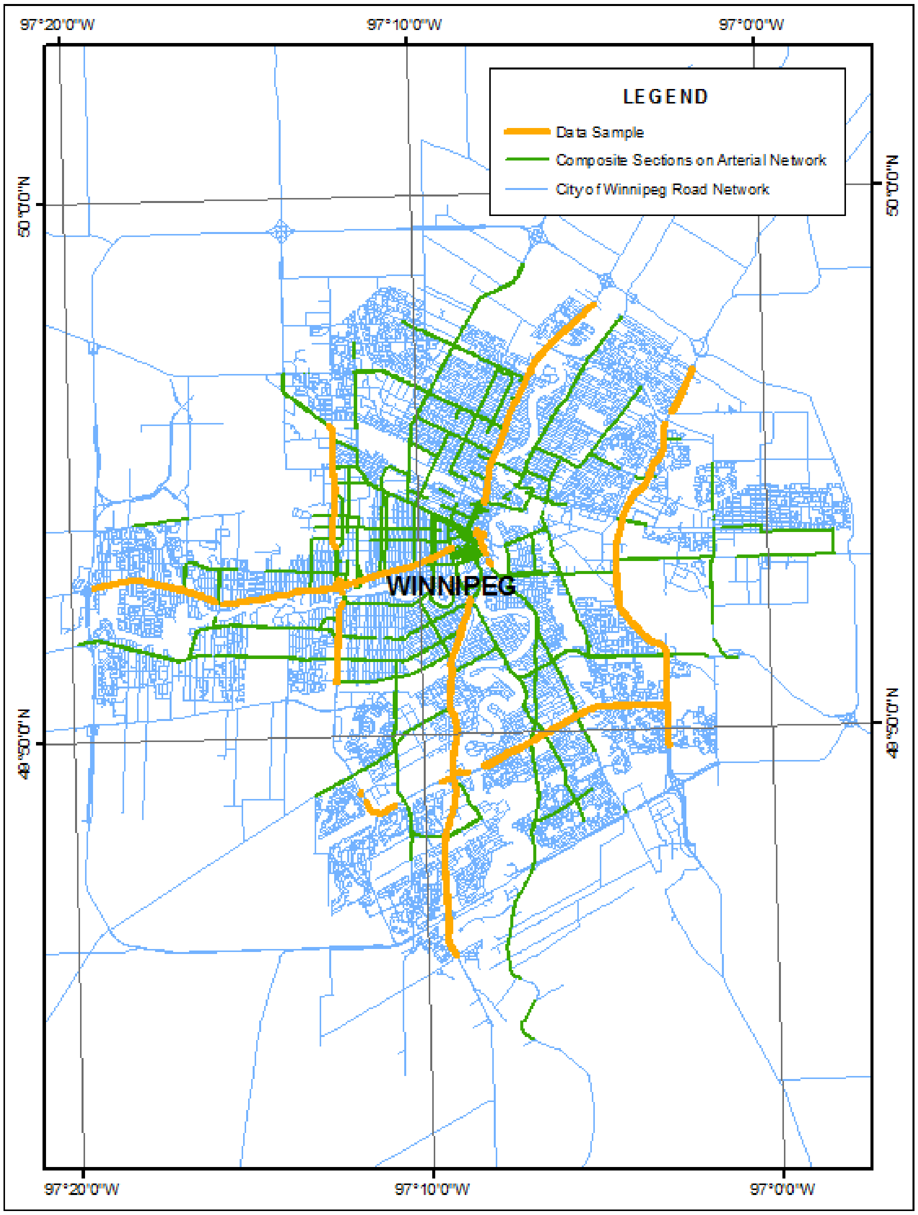


Figure 10. Composite sections of Bishop Grandin Blvd, Kenaston Blvd, King Edward St, Lagimodiere Blvd, Main St, Pembina Hwy and Portage Ave (Data Sample)

Table 15. City of Winnipeg Sample Sections

Data sample	Number of sections	Surface area (m2)	Percent of network	Centerline length (m)
Sample sections	351	489,621	40.9%	49,313
Other	430	706,327	59.1%	70,977
Total	781	1,195,948	100%	120,290

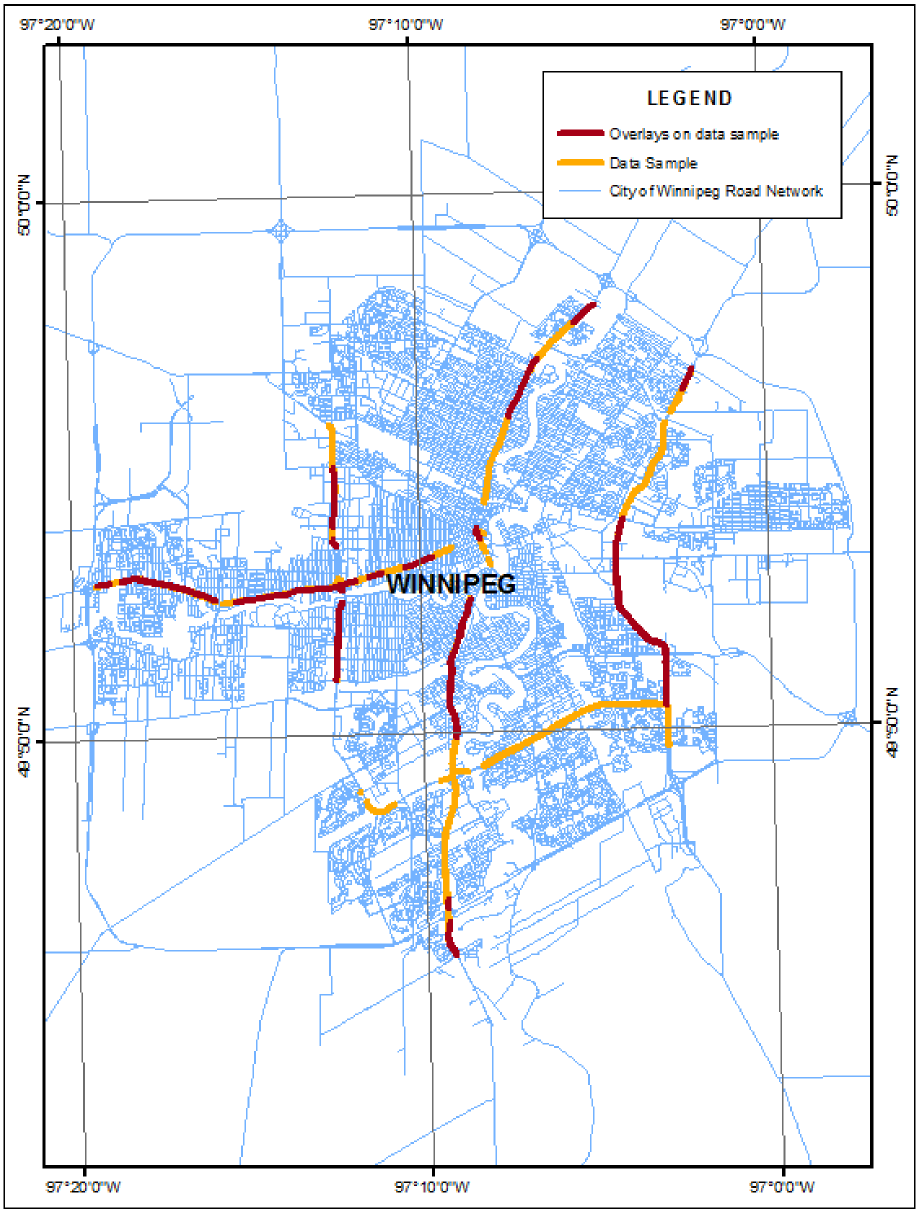


Figure 11. City of Winnipeg Sample Sections

3.3 KAPLAN-MEIER SURVIVAL ANALYSIS

Survival probability distributions provide helpful information to analyze the trend of the age of the pavement at the time of overlay. The methodology used was to separate the data into families, and to develop survival distributions using the Kaplan-Meier survival analysis method. The Kaplan-Meier method is an "empirical modeling technique for estimating life" (Ford et al., 2012). The Kaplan-Meier method defines the probability of surviving a given interval of time. According to Kaplan and Meier (1958), the individual probability "Pt" for an item to survive each year after having survived the previous years is:

$$\text{Pt} = \frac{\text{Number of items at risk in year t} - \text{Number of items dead in year t}}{\text{Number of items at risk in year t}}$$

$$= \frac{\text{Number of items surviving year t}}{\text{Number of items at risk in year t}} \qquad (3.2)$$

The total probability to survive until a year "t" (St) is calculated by multiplying the probabilities to survive each year until the year of study.

$$S(t) = P1 \;.\; P2 \;.\; \dots \;.\; Pt \qquad (3.3)$$

Therefore, the probability to survive year 2, for example, is the probability to survive year 1 multiplied by the probability to survive year 2.

The Kaplan-Meier survival analysis can generate survival distributions based on time-to-event. This method is used when the events depend only on time, and given that it cannot differentiate between items with different characteristics, it is important to separate data into families with similar characteristics. When applied to pavements, this method generates the probabilities for a pavement to survive a given time period. As a result, it helps to define the life expectancy of pavements and the optimal timing of maintenance and rehabilitation treatments.

The survival analysis of the Manitoba highway network will focus on the first bituminous overlay over concrete and asphalt pavements of the sample sections. On the other hand, the survival analysis of the City of Winnipeg network will focus on the first bituminous overlay over concrete pavement of the sample sections. As a result, time to overlay will be found.

3.3.1 Partitions for survival analysis

A family is created to represent sections with uniform characteristics. Following this idea, the pavement sections were partitioned into families to determine the service life of selected deterioration treatments. The partitioning was based on the type of pavement surface, base thickness, surface thickness, overall thickness of the pavement structure, truck traffic and drainage.

3.4 PROBABILITY DISTRIBUTIONS TO SIMULATE THE VARIABILITY OF LCCA INPUT

Probability distributions are used to develop probabilistic LCCA because they simulate the variability that each input could have. Historical agency data availability and quality play an important role in the accuracy of the distributions. These distributions could be based on condition data and optimal times for agency intervention; however, agency interventions are sometimes performed considering other factors. To develop distributions that reflect real values, only available data records are used.

Data from the period 2002-2017 was used to study the variability of the discount rate, data from the period 1999-2017 for unit prices, and data from the period 1987-2017 (last 30 years) was used to study the variability of the timing of each deterioration treatment application except the application of the first and second overlay.

3.4.1 Manitoba Infrastructure probability distributions

Manitoba infrastructure's data has records of four M&R treatments for asphalt pavements performed on the period 2007-2016; however, only records of rout and seal, chip sealing and microsurfacing were found for the data sample. Data for these treatments will be studied for the pavements sections that received a new surface in the period 1987-2017. Table 16 shows the number of sections available for each of these treatments, and the percentage they represent from the Manitoba Infrastructure asphalt pavements data sample. Table 17 shows the number of sections available that received the deterioration treatments in the period 1987-2017, and the percentage they represent from the total available sections. Only seven sections with treatment information available received more than one deterioration treatment during the period 1987-2017. Table 18 shows the number of sections for each treatment combination.

Table 16. Available sections for deterioration treatments: Manitoba Infrastructure asphalt pavement data sample

Deterioration Treatment	Number of sections available	Percent of data sample
Available sections	123	25.31%
• Rout and seal	15	3.09%
• Chip sealing	64	13.17%
• Microsurfacing	58	11.93%
Non available	363	74.69%
Total asphalt pavement data sample	486	100%

Table 17. Asphalt pavement deterioration treatments performed in the period 1987-2017

Deterioration Treatment	Number of sections	Percent of available sections
Rout and seal	14	93.33%
Chip sealing (first application)	20	31.25%
Chip sealing (second application)	5	7.81%
Microsurfacing	47	87.93%

Table 18. Pavement sections with more than one deterioration treatment performed in the last 30 years

Deterioration treatment	Number of sections
Rout and seal + Microsurfacing	1
Rout and seal + Chip sealing (first application)	2
Microsurfacing + Chip sealing (first application)	4

Additionally, data records for the first bituminous overlay were found for asphalt pavements constructed in the period 1948-2003 and concrete pavements constructed in the period 1949-1991. Because pavements designs are constantly improving, graphs were developed to study how time from initial construction to the first overlay has changed over the years. In other words, to study the changes in pavement life or time to first rehabilitation. Figure 12 shows all the concrete pavement sample sections, where the bars represent the time from initial construction to the first overlay. This figure shows no much variability in the timing of the first bituminous overlay over concrete pavement. For this reason, only outliers, such as those overlays performed 34-46 years after construction, where excluded to develop the probability distributions. Similarly, Figure 13 shows all the asphalt pavement sample sections. Due to high variability and short time bars, a time threshold was set on 1967, so the overlays used to develop the probability distributions are representatives and their timing is close to current practices.

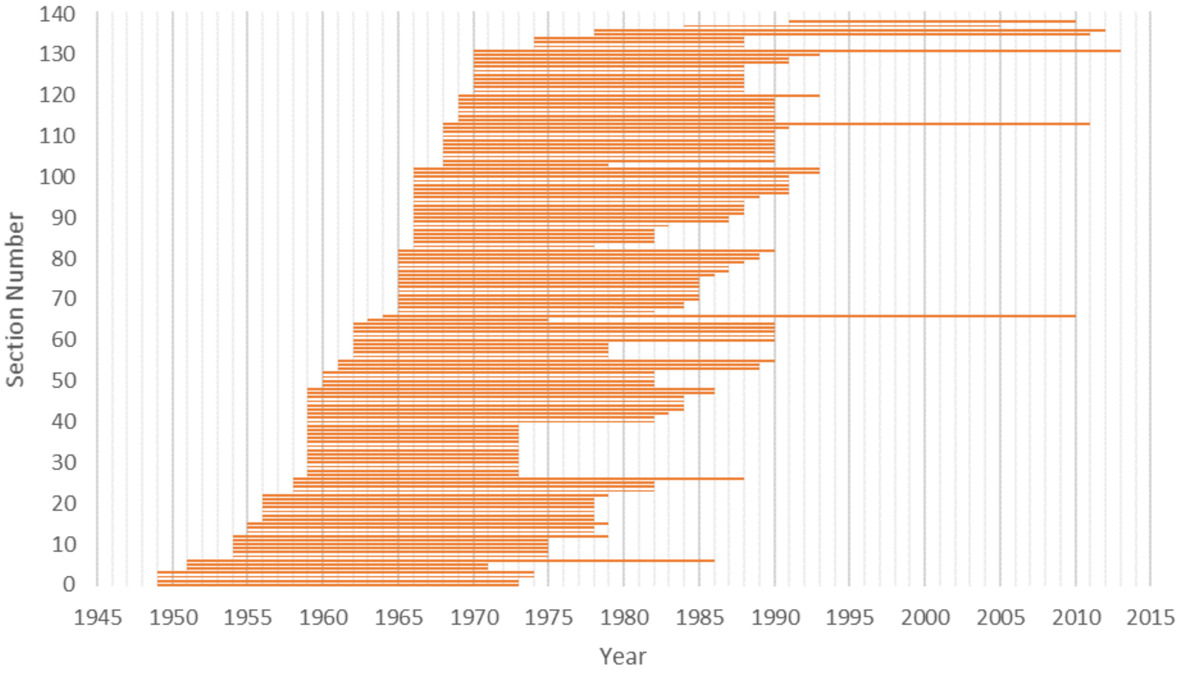


Figure 12. Time from concrete pavement initial construction to first bituminous overlay (Manitoba Infrastructure) Total sample sections: 138

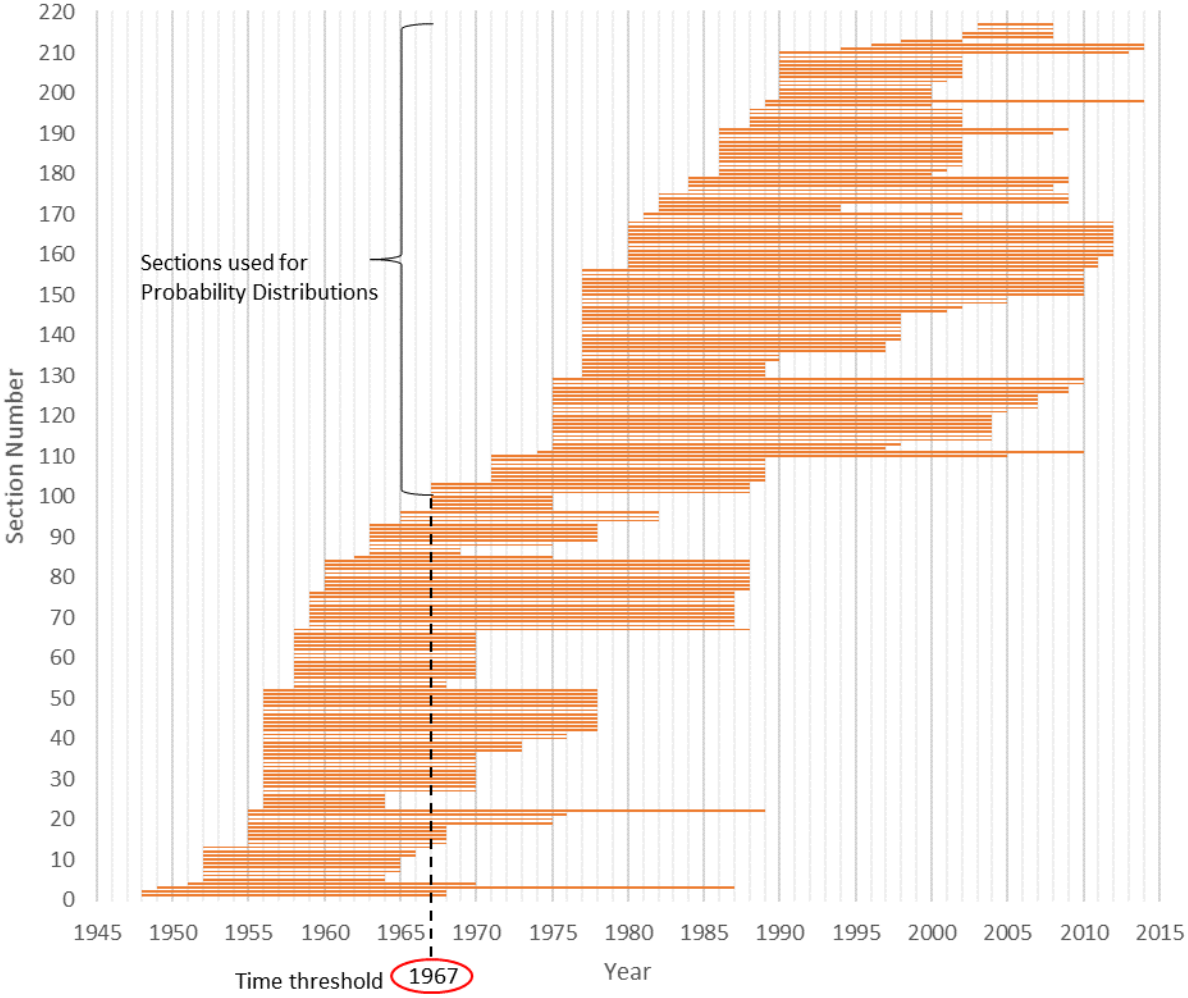


Figure 13. Time from asphalt pavement initial construction to first bituminous overlay (Manitoba Infrastructure) Total sample sections: 217

3.4.2 City of Winnipeg probability distributions

The City of Winnipeg dataset contains records for crack sealing, rehabilitation, major rehabilitation and mill and fill; however, for the data sample, the majority of the records are for crack sealing and mill and fill. Given that rehabilitation, major rehabilitation and fill and fill were performed with the same objective and at a similar stage of the pavement life, only mill and fill will be studied. Data for crack sealing, and mill and fill treatments will be studied for the pavements sections that received a new overlay in the period 1987-2017. These sections represent almost 34% of the total City of Winnipeg data sample as shown in Table 19. Table 20 shows the number of sections for each deterioration treatment, and the percentage they represent from the sections overlaid in the period 1987-2017 (last 30 years).

Only an 8% of the 265 sections received both treatments as shown in Table 21. These sections are located on Main Street and Pembina Highway.

Table 19. City of Winnipeg pavement sections overlaid in the period 1987-2017

Pavement sections	Number of sections	Percent of data sample
Overlaid in the last 30 years (≥1987)	265	33.93%
Total data sample	781	100%

Table 20. Pavement sections treated in the period 1987-2017

Deterioration treatment	Number of sections	Percentage of total
Crack sealing	45	16.98%
Mill and Fill	133	50.19%
Total sections overlaid in the last 30 years	265	100%

Table 21. Pavement sections with crack sealing and mill and fill performed in the last 30 years

Deterioration treatment	Number of sections	Percentage of total
Crack sealing + Mill and Fill	21	7.92%
Total sections overlaid in the last 30 years	265	100%

In addition to crack sealing and mill and fill, data records for the first bituminous overlay were found for concrete pavements constructed in the period 1948-1980. Following the same procedure as for Manitoba infrastructure overlays, Figure 14 shows all the concrete pavement sample sections and the time bars. Given the high variability and short time bars for the period 1948-1960, a time limit was set on 1960 to obtain probability distributions that represent a timing close to current practices.

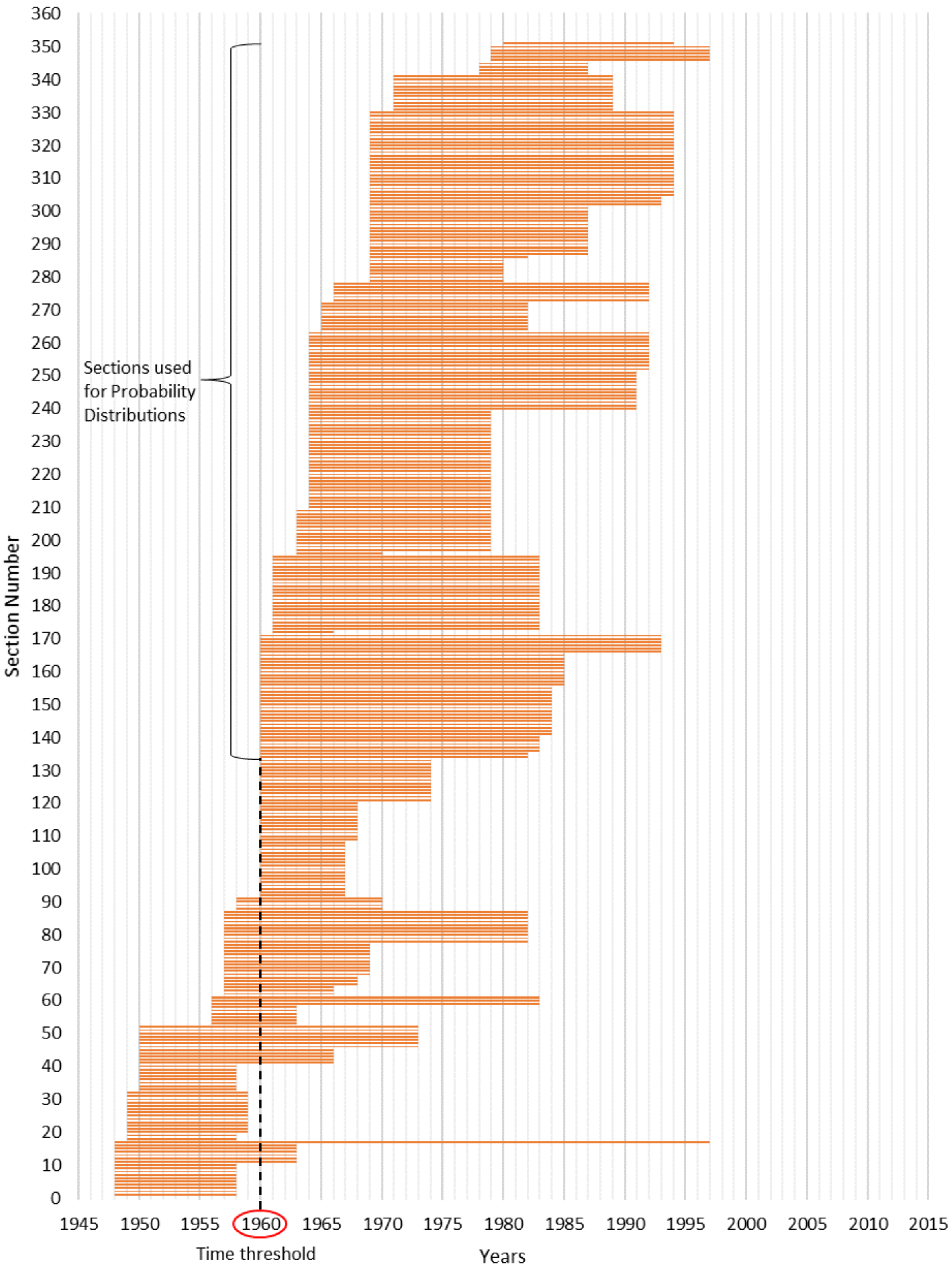
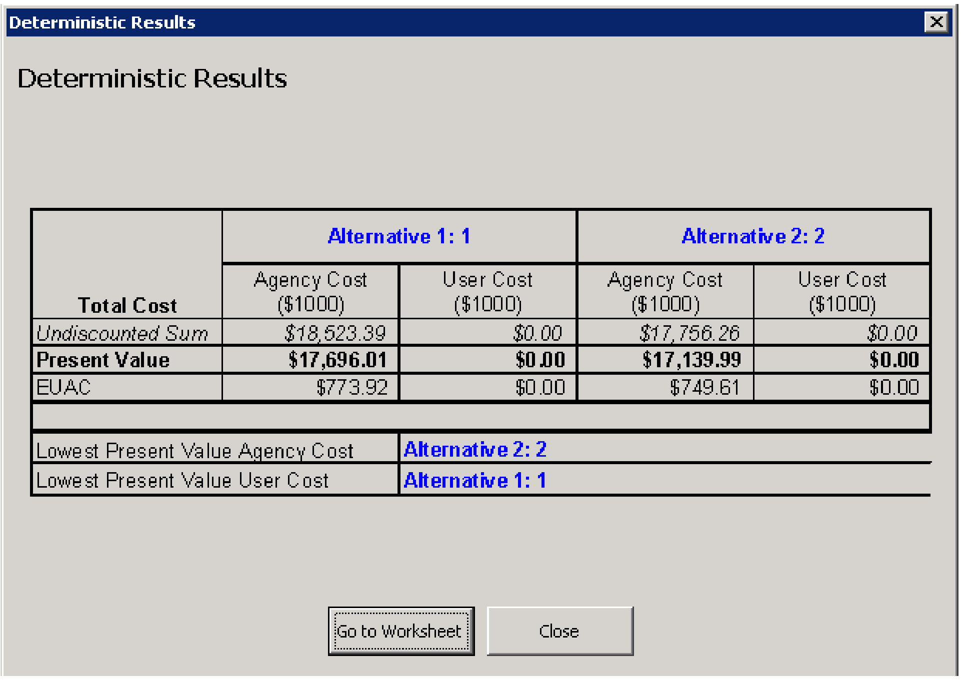


Figure 14. Time from concrete pavement initial construction to first bituminous overlay (City of Winnipeg) Total sample sections: 351

3.5 LIFE CYCLE COST ANALYSIS ON REALCOST

3.5.1 Deterministic analysis

The calculation of the deterministic life cycle cost is very simple and can be done manually with a calculator. However, RealCost can also perform this type of analysis using single values coming from the deterministic inputs and the mean or most likely values of the probability distributions (FHWA, 2010). The software uses equations 2.1 and 2.2 to calculate the net present value and equivalent uniform annual cost for each alternative. RealCost results for deterministic LCCA show the undiscounted sum of costs, the net present value and the equivalent uniform annual cost for both agency and user costs. It also displays the alternative with the lowest life cycle cost, as shown in Figure 15.



	Alternative 1: 1		Alternative 2: 2	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$18,523.39*	*$0.00*	*$17,756.26*	*$0.00*
Present Value	**$17,696.01**	**$0.00**	**$17,139.99**	**$0.00**
EUAC	$773.92	$0.00	$749.61	$0.00

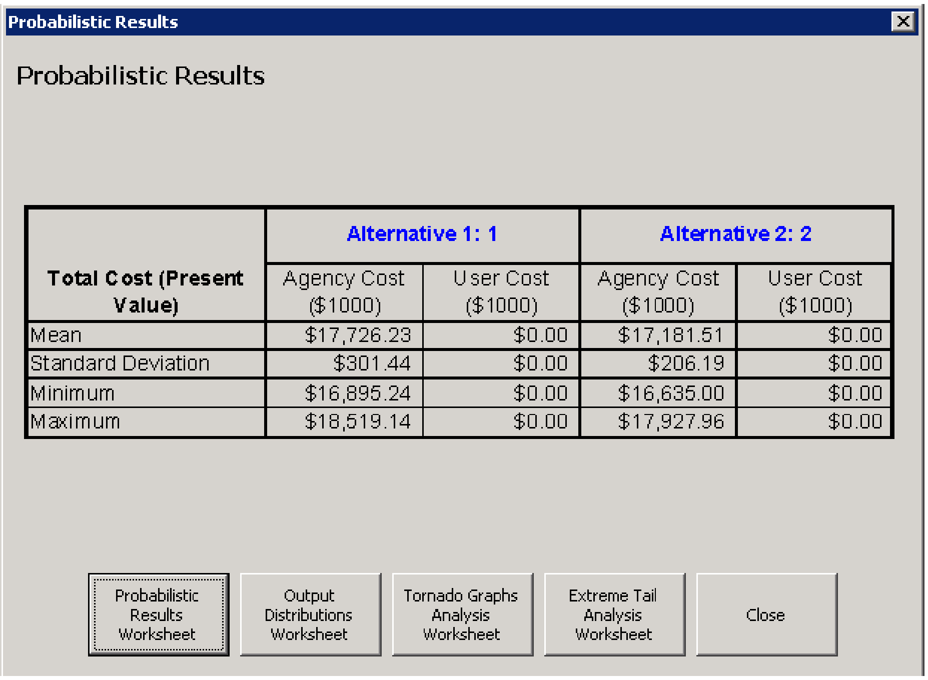
Lowest Present Value Agency Cost	Alternative 2: 2
Lowest Present Value User Cost	Alternative 1: 1

Figure 15. Example of deterministic results from RealCost

3.5.2 Probabilistic analysis

The probabilistic results are found using Monte Carlo simulations that allow accounting for the variability of the inputs. During the simulation, random values are selected from each input distribution to produce an output value. Given that each iteration produces a possible output, a distribution is developed with all possible results. The iteration process finishes when "the specified number of iterations is completed or until the simulation process converges", in other words, when additional iterations will not produce major changes on the output distribution (Walls & Smith, 1998). RealCost results for probabilistic LCCA show the mean, standard deviation, maximum and minimum of the present value for both agency and user costs, as shown in Figure 16. It also displays four options of outputs representation for further analysis and comparison of the alternatives under study. The options include probability density functions, cumulative distribution functions, tornado graphs and extreme tail analysis results.

The probability density function shows all potential results and the probability of occurrence of each of them. The area to the left of a value is the probability that the cost will not exceed that value, and the area to the right is the probability that the cost will exceed that value (FHWA, 2010). The cumulative distribution function is the area under the probability density curve for each cost. These two curves provide information to compare the life cycle cost results for each alternative. On the other hand, the tornado graphs and extreme tail analysis provide information to analyze the simulation results of the alternatives.


Probabilistic Results

Probabilistic Results

Total Cost (Present Value)	Alternative 1: 1		Alternative 2: 2	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Mean	$17,726.23	$0.00	$17,181.51	$0.00
Standard Deviation	$301.44	$0.00	$206.19	$0.00
Minimum	$16,895.24	$0.00	$16,635.00	$0.00
Maximum	$18,519.14	$0.00	$17,927.96	$0.00

Figure 16. Example of probabilistic results from RealCost

The tornado graph contains correlation coefficients that quantify the significance that input variables have on the output distribution. The graph shows how sensitive is the output to changes in these variables. The higher the correlation coefficient, the larger the bar in the graph and the higher the effect of the input variable on the output. Figure 17 shows an example of a tornado graph. In this example, the service life of Activity 1 has a correlation coefficient of -0.61. This means that service life of Activity 1 is negatively correlated to the total present value of the life cycle cost. If the mean of this variable is increased by 1 standard deviation, the mean of the present value will be decreased by 0.61 times the standard deviation of the present value.

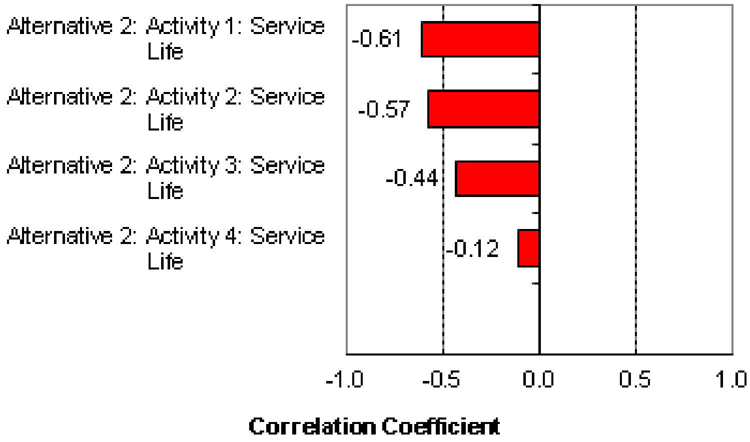


Figure 17. Example of tornado graph from RealCost

CHAPTER 4 - RESULTS AND DISCUSSION

4.1 SURVIVAL DISTRIBUTIONS

Survival distributions were developed for each dataset to study the actual time when pavements were overlaid. Manitoba infrastructure dataset allowed developing distributions for asphalt and concrete pavements. On the other hand, only concrete pavement distributions were developed with the City of Winnipeg dataset.

4.1.1 Manitoba infrastructure survival distributions

4.1.1.1 Bituminous overlay over concrete pavement

The age of the concrete pavement at the time of overlay ranges from 11 to 46 years. The majority of the overlays were constructed before the year 30 after initial construction. Figure 18 shows the amount of surface and number of sections overlaid through the years.

Figure 19 shows the Kaplan-Meier survival analysis. This figure shows that 50% of the total surface area received an overlay before the year 22 after initial construction. It also illustrates that between ages 20 to 25 exist a zone with the highest percentages of overlays, where 55% of the total surface area was overlaid. In other words, the majority of the pavements received an overlay between ages 20 to 25.

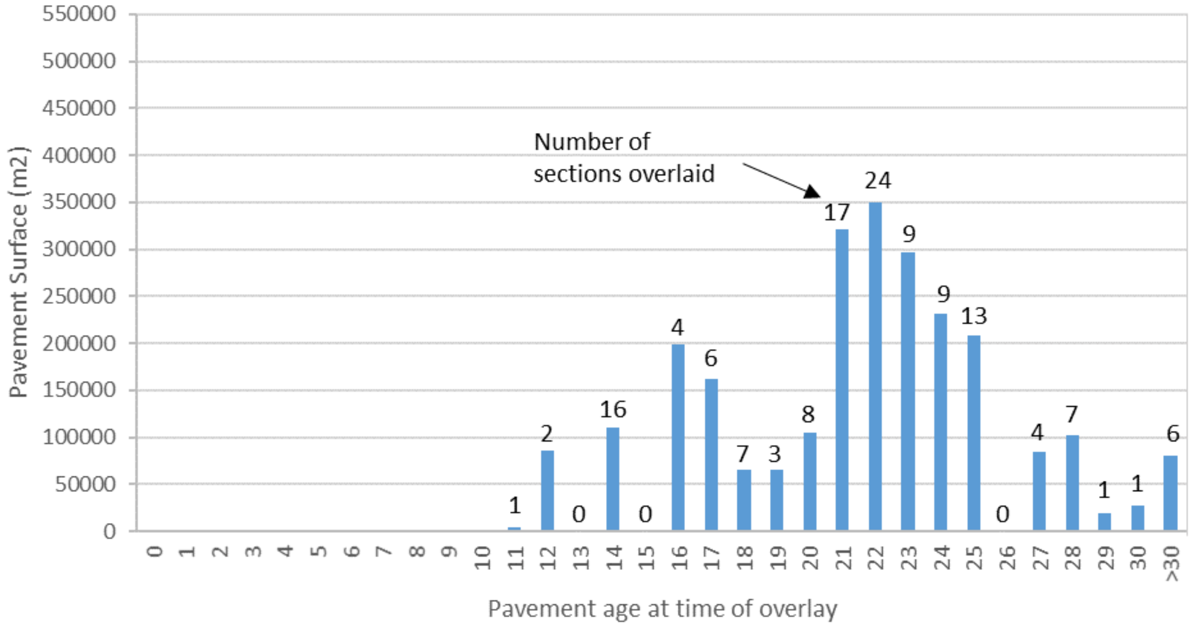


Figure 18. Age of concrete pavement at time of bituminous overlay (Manitoba Infrastructure)

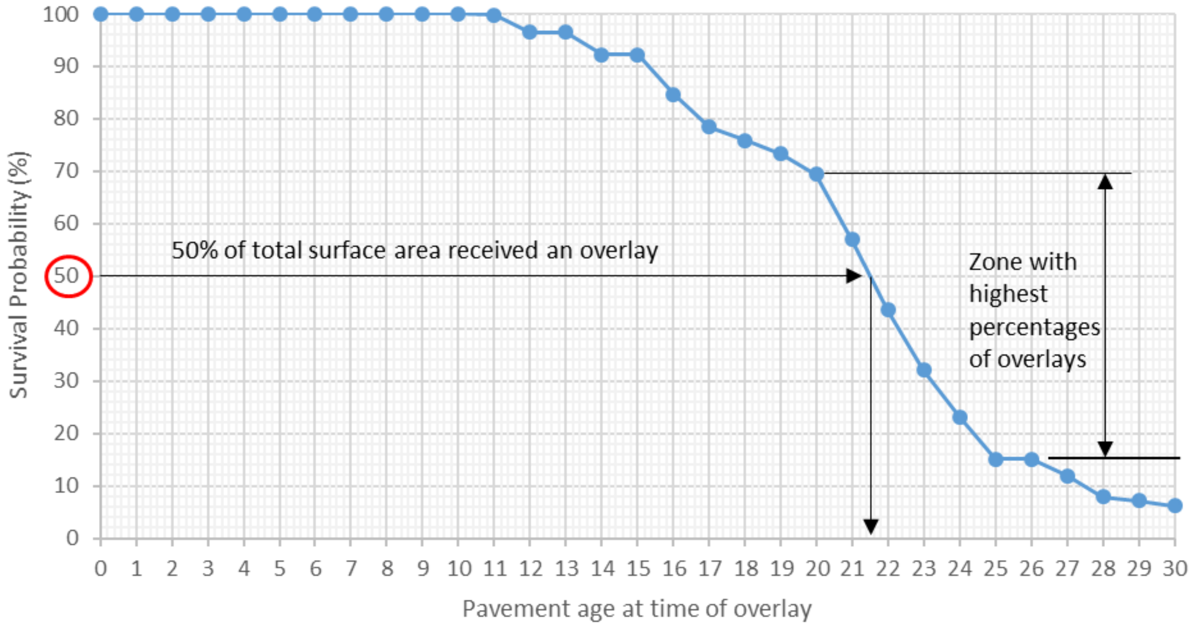


Figure 19. Survival probability vs age of concrete pavement at time of bituminous overlay (Manitoba Infrastructure)

4.1.1.1.1 Partitions based on base thickness

The base thickness of the sample ranges from 50mm to 304mm. The sample was partitioned into families as shown in Table 22. The base thickness greater than 152 mm was not considered for the survival probability analysis given its difference with the other thicknesses and the small number of sections and surface it represents.

Table 22. Surface distribution for each concrete pavement family based on base thickness (Manitoba Infrastructure)

Base thickness (mm)	Number of sections	Surface area (m^2)	Percent of surface area	Centerline length (m)
50-76	86	1,592,608	63.3%	216,025
100-152	48	868,969	34.6%	116,469
>152	4	53,724	2.1%	7,260
TOTAL	138	2,515,301	100%	339,754

Figure 20a shows the survival probability versus age of concrete pavement at the time of bituminous overlay for each family. Figure 20b shows the pavements corresponding to each base thickness family. Figure 20a shows that a thicker base could delay the time to overlay in about 20%, but after 22 years from initial construction, the effect of the base thickness is negligible. Both families show that 50% of their surface area received an overlay before the year 22 after initial construction.

The slab thickness in 98.56% of the sections was 200-203 mm; therefore, the effect of different slab thicknesses was not considered in the analysis. Additionally, the results obtained from studying the sample based on overall thickness are similar to those based on base thickness.

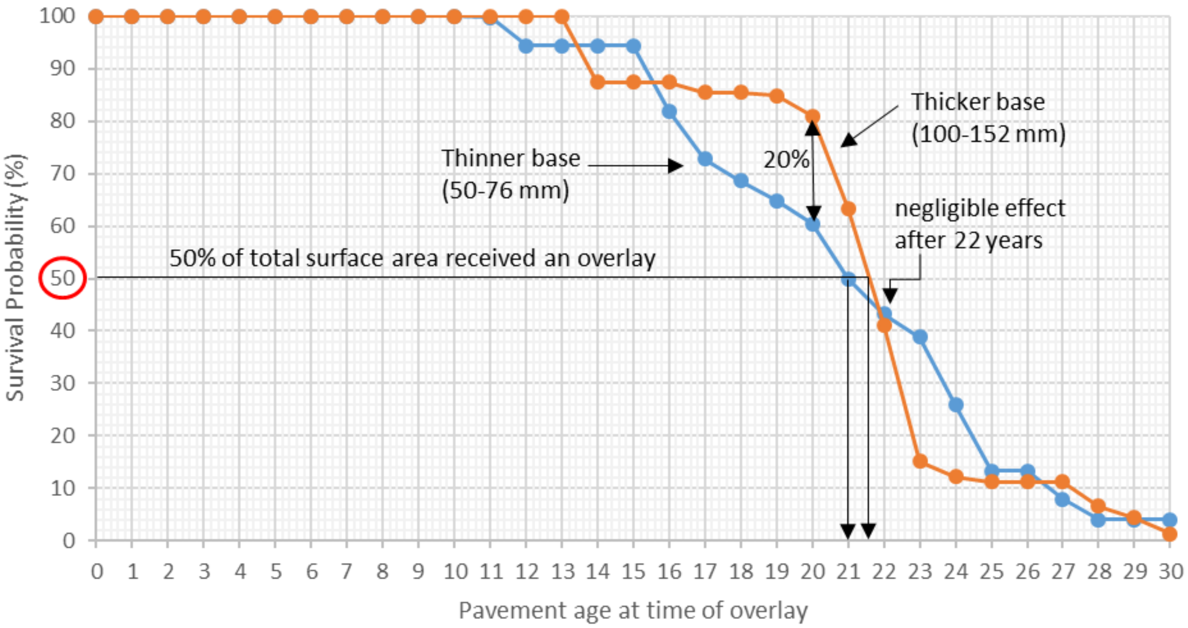


Figure 20a. Survival probability vs age of concrete pavement at the time of bituminous overlay based on base thickness

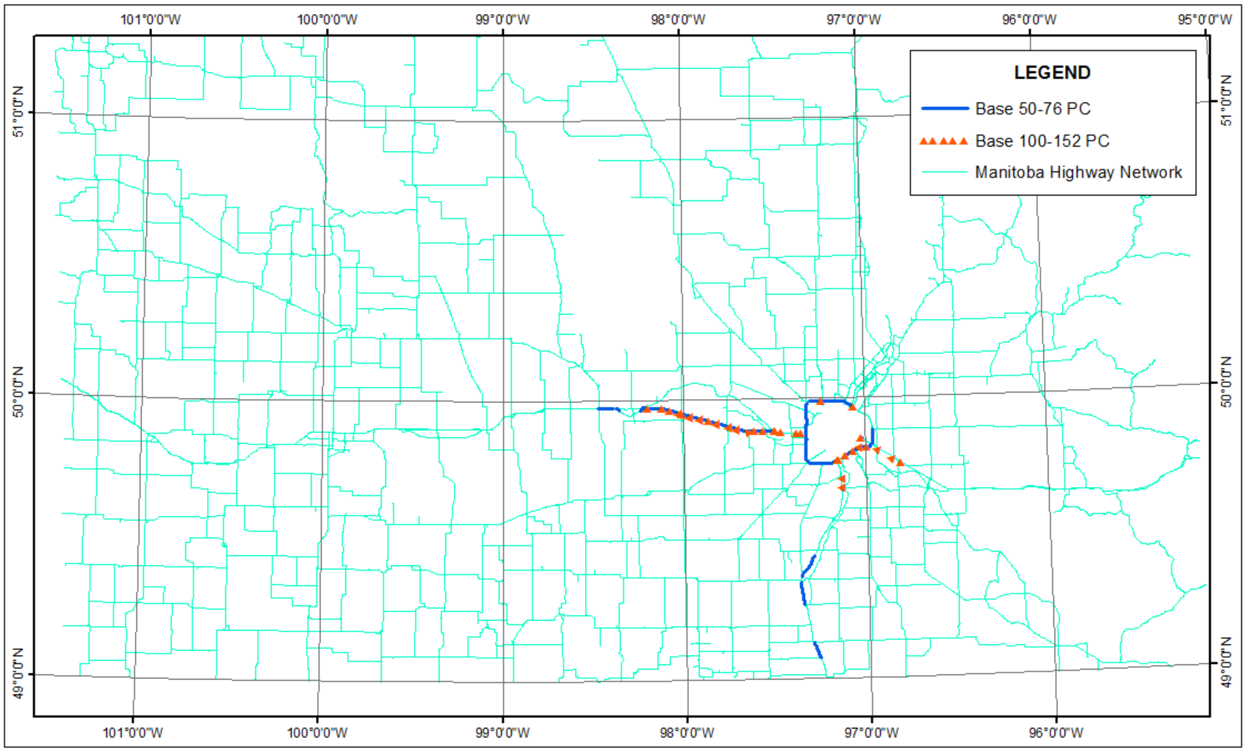


Figure 20b. Base thickness families of concrete pavements

4.1.1.1.2 Partitions based on Average Annual Daily Truck Traffic

The sample was partitioned according to the AADTT per lane to study the time from construction to overlay of each truck traffic range. Table 23 shows the number of sections, surface area and centerline length of each family. Table 23 also shows that 75% of the sections had an AADTT higher than 500. This high traffic is expected for concrete sections. However, it was found an AADTT lower than 300 with the highest concentration on PTH 75 as shown in Figure 21b.

Table 23. Surface distribution for each concrete pavement family based on AADTT

Traffic	Number of sections	Surface area (m^2)	Percent of Surface area	Centerline length (m)
AADTT <300	10	199,070	7.9%	26,842
300<AADTT<400	10	184,456	7.3%	25,153
400<AADTT<500	12	234,894	9.3%	31,846
500<AADTT<600	54	1,040,472	41.4%	139,719
AADTT >600	52	856,409	34.0%	116,194
TOTAL	138	2,515,301	100%	339,754

Figure 21a shows that 50% of the total surface area of each family received an overlay between year 20 and year 22 after initial pavement construction, with the exception of those sections with an AADTT between 300 and 400. 50% of the surface area of the sections with an AADTT between 300 and 400 received an overlay around year 27 after initial pavement construction. This could not mean those sections had a better design. The reason for being overlaid many years after the rest of the families could be that the sections were overlaid many years after required. Figure 21b shows the pavements corresponding to each AADTT family.

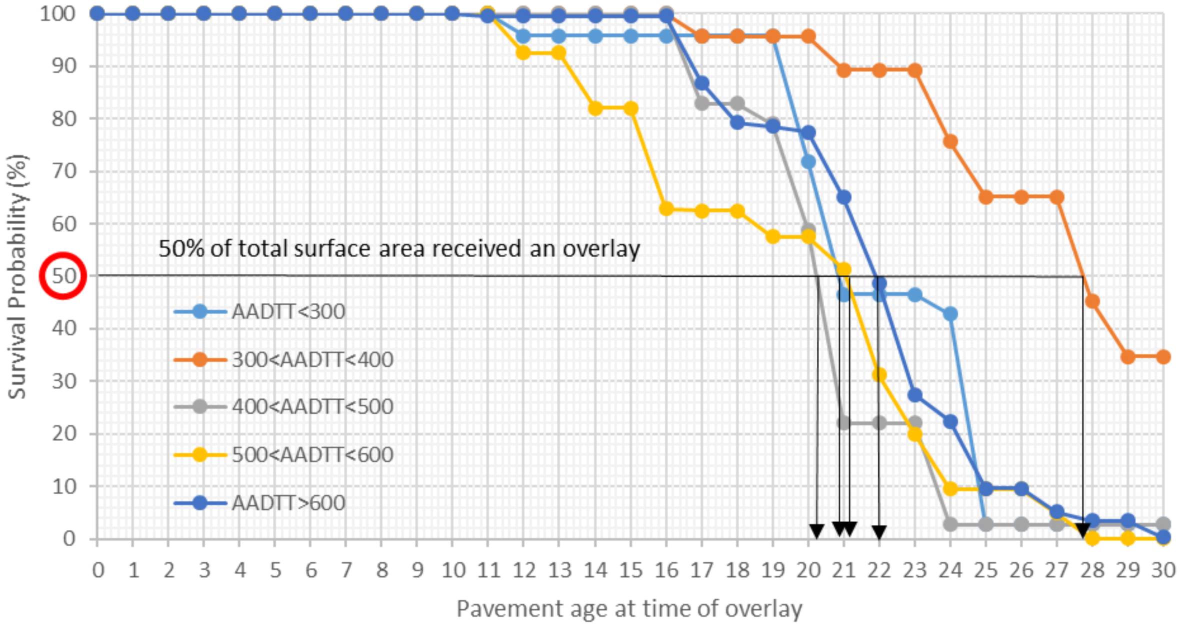


Figure 21a. Survival probability vs age of concrete pavement at the time of bituminous overlay based on AADTT

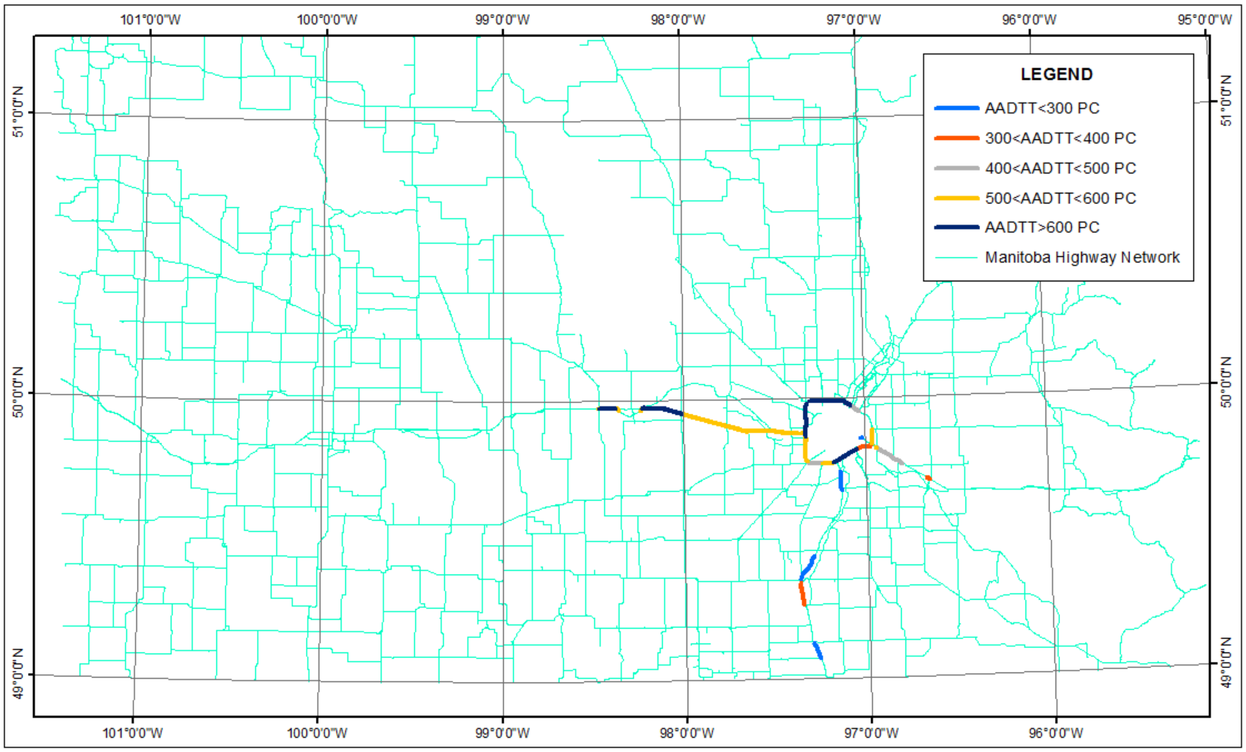


Figure 21b. AADTT families of bituminous overlays over concrete pavements sample sections

Table 24 shows the rating system for condition used by Manitoba infrastructure that considers cracking, rutting, and IRI. This system goes from 1 to 8, being condition 1 the best state. Figure 22 shows that the family with an AADTT between 300 and 400 maintained the worst condition during years 2010 to 2014. Nevertheless, this family represents only 7% of the sections. For this reason, it can be said the trend shows that sections received an overlay between year 20 and year 22 after initial pavement construction. Figure 22 allows an interpretation that efforts were made to maintain more than 75% of the section with a similar condition state in years 2010, 2012 and 2016.

Table 24. Manitoba Infrastructure condition states

Ride Bin Multiyear	**Crack Bin**	**Rut Bin**	**Condition State**
Good	Good	Good	1
Good	Good	Poor	2
Good	Poor	Good	3
Good	Poor	Poor	4
Poor	Good	Good	5
Poor	Good	Poor	6
Poor	Poor	Good	7
Poor	Poor	Poor	8

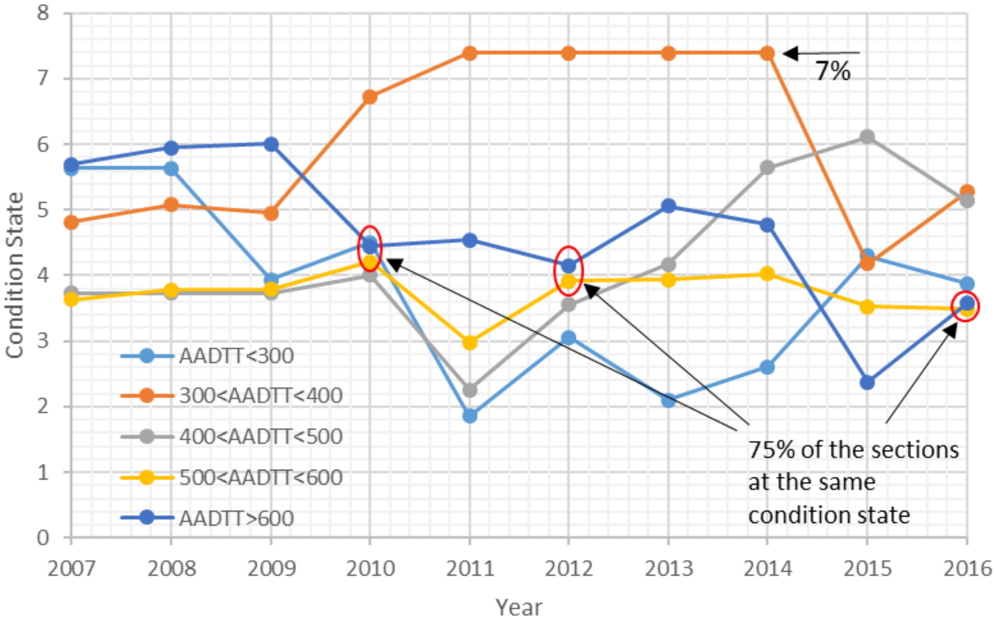


Figure 22. Condition data trend of bituminous overlays over concrete pavements sample sections based on AADTT

4.1.1.2 Bituminous overlay over asphalt pavement

The sections under study are placed over a granular base and the age at the time of overlay ranges from four to 38 years. The majority of the overlays were constructed before the year 33. Figure 23 shows the amount of surface overlaid through the years. Figure 24 illustrates that 50% of the total surface area received an overlay by year 19 after initial construction.

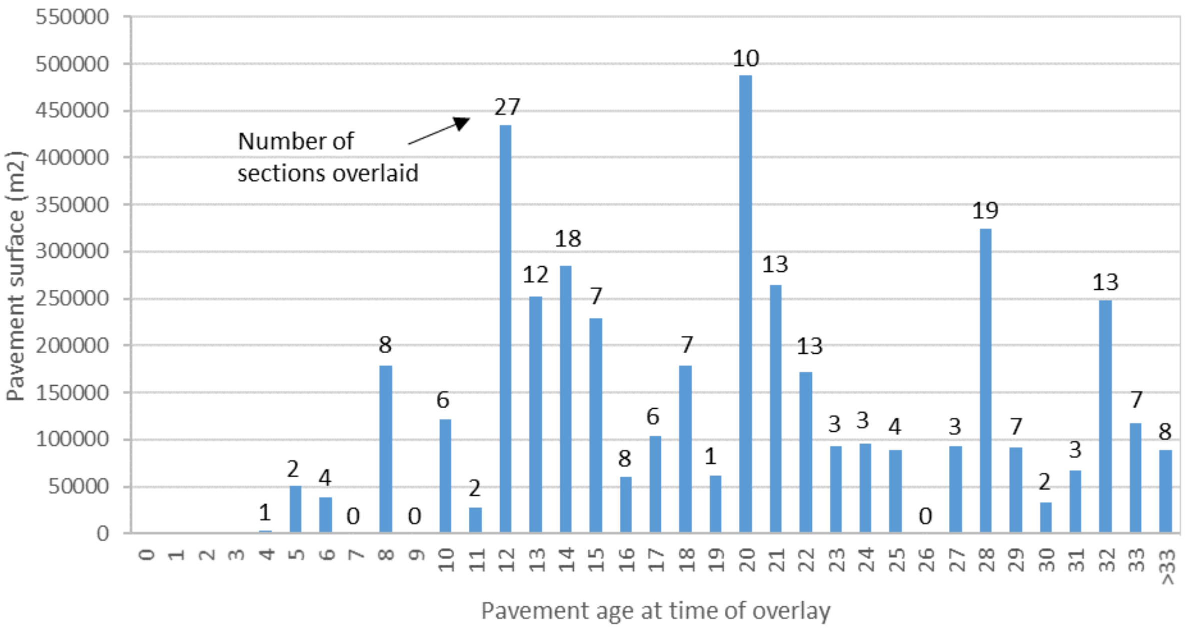


Figure 23. Age of asphalt pavement at the time of bituminous overlay

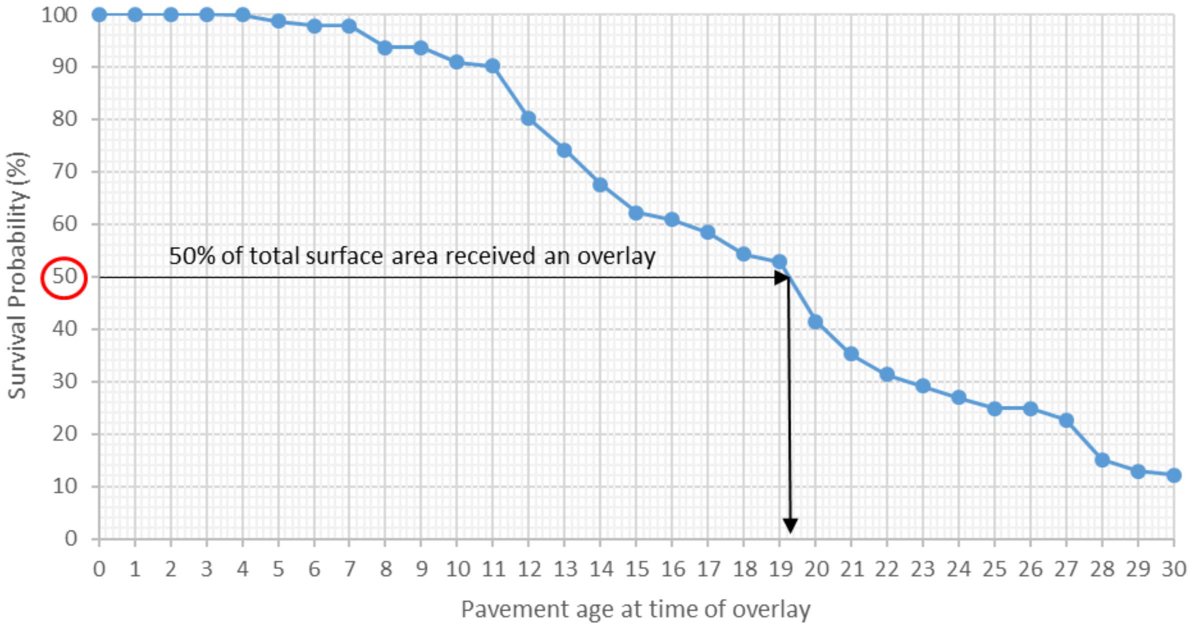


Figure 24. Survival probability vs age of asphalt pavement at the time of bituminous overlay

4.1.1.2.1 Partitions based on base, surface and overall thickness

To analyze how the time to overlay changes according to the different thicknesses of the pavement structure, the sample was partitioned into families as shown in Table 25.

The surface thicknesses below 50mm and greater than 176mm were not considered for the survival probability analysis given the small surface they represent and the uncertainty of being typos or outliers.

Table 25. Surface distribution for each asphalt pavement family based on base, surface and overall thickness of the original pavement

Base thickness (mm)	Number of sections	Surface area (m^2)	Percent of surface area	Centerline length (m)
75-153	84	1,655,265	38.5%	211,740
175-254	55	1,016,904	23.7%	137,203
300-355	38	1,056,128	24.6%	142,361
406-609	40	566,254	13.2%	76,581
TOTAL	217	4,294,551	100	567,885
Surface thickness (mm)	Number of sections	Surface area (m^2)	Surface area	Centerline length (m)
<50	7	86,847	2.0%	11,736
50-79	105	2,275,383	53.0%	301,474
100-176	104	1,920,481	44.7%	253,075
>176	1	11,840	0.3%	1,600
TOTAL	217	4,294,551	100	567,885
Overall thickness (mm)	Number of sections	Surface area (m^2)	Surface area	Centerline length (m)
105-253	80	1,617,842	37.7%	208,238
270-355	46	890,454	20.7%	119,855
380-430	29	959,506	22.3%	129,951
450-989	62	826,749	19.3%	109,841
TOTAL	217	4,294,551	100	567,885

Figure 25a, 26a, and 27a represent the survival probability versus age of asphalt pavement at the time of bituminous overlay for each family based on base, surface and overall thickness of the original pavement. Figure 25b, 26b and 27b show the pavements corresponding to each family on the Manitoba highway network.

Figure 25a shows that a thick base of 406mm or higher could delay significantly the time to overlay. 50% of the surface area of sections with a base thickness between 75mm to 355mm received an overlay around years 16 to 19 after initial pavement construction. However, 50% of the surface area of sections with higher thickness reached an age of 24 years without an overlay. The majority of the sections were overlaid around year 19 after initial pavement construction.

The probability to overlay based on the surface thickness and the overall thickness illustrated in Figure 26a and 27a shows similar trends for all their families. This shows that the structures are designed to meet the requirements of the projects, and the different thicknesses do not have a significant effect on the age of asphalt pavement at the time of bituminous overlay. However, the overall thickness 450-989mm family includes pavements with thick base, and pavements with thin base plus subbase, which shows that having a similar overall thickness does not mean the pavements are going to have an equal life. The quality of the material used on the pavement structure does have an effect on the age of asphalt pavement at the time of bituminous overlay. Other factors such as good drainage, truck loading, type of embankment soil and quality of construction may also affect the time when a pavement is overlaid.

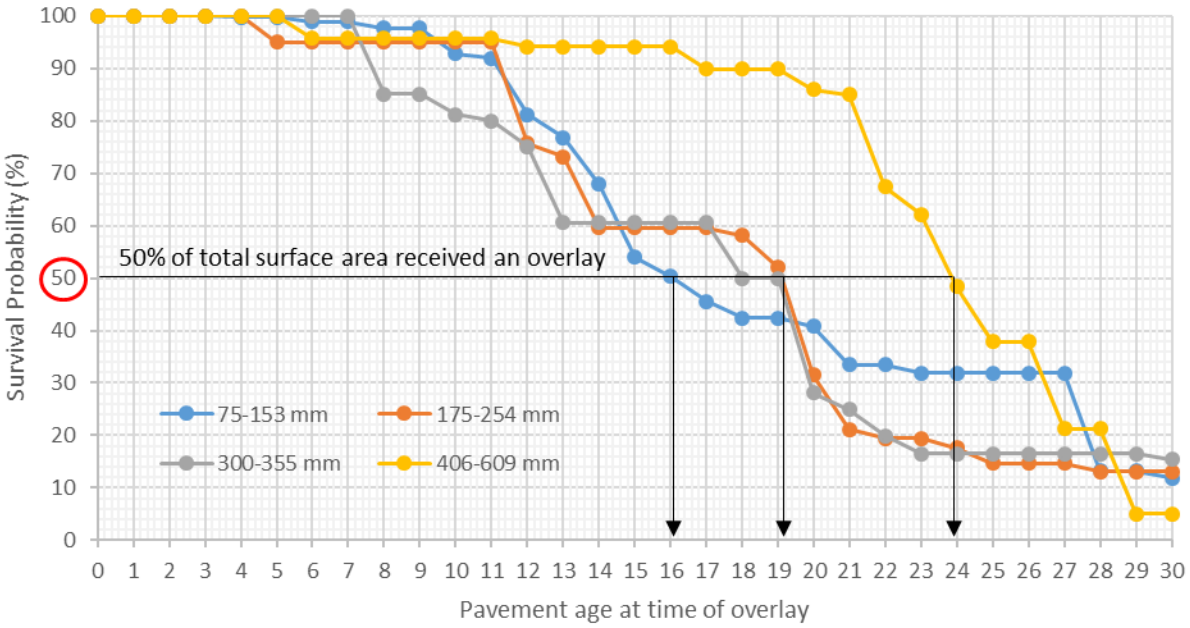


Figure 25a. Survival probability vs age of asphalt pavement at the time of bituminous overlay based on the base thickness

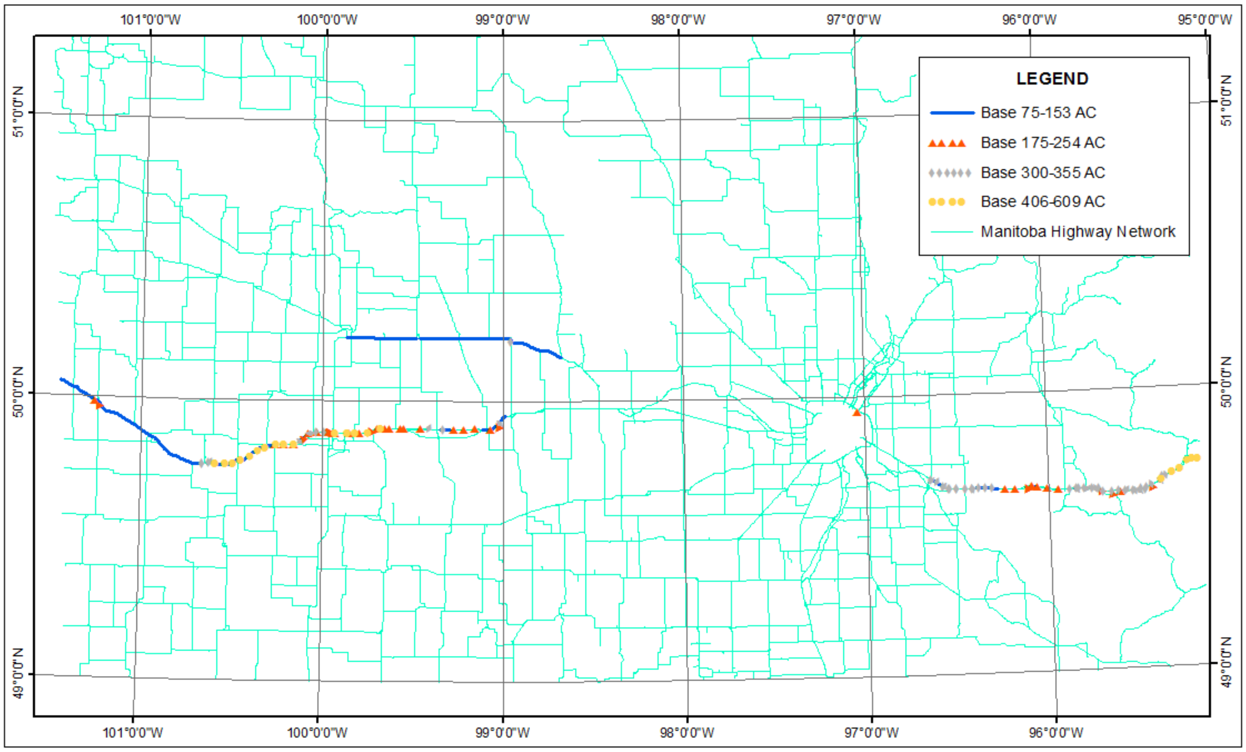


Figure 25b. Base thickness families of asphalt pavements

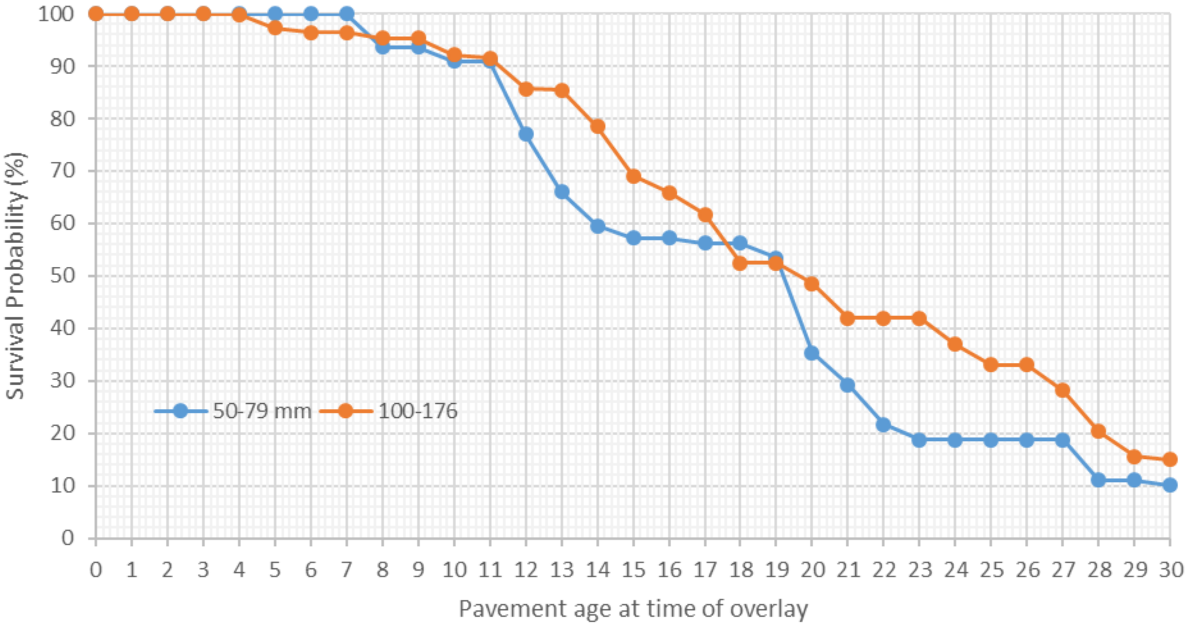


Figure 26a. Survival probability vs age of asphalt pavement at the time of bituminous overlay based on the surface thickness

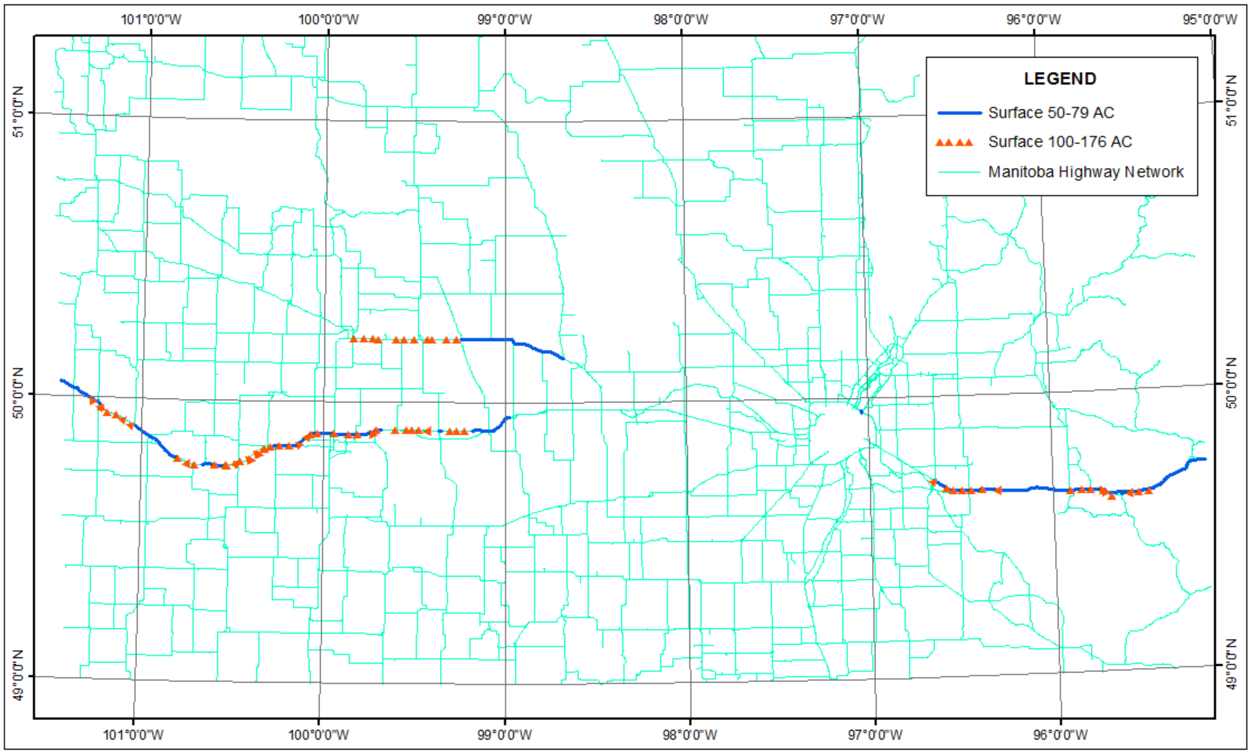


Figure 26b. Surface thickness families of asphalt pavements

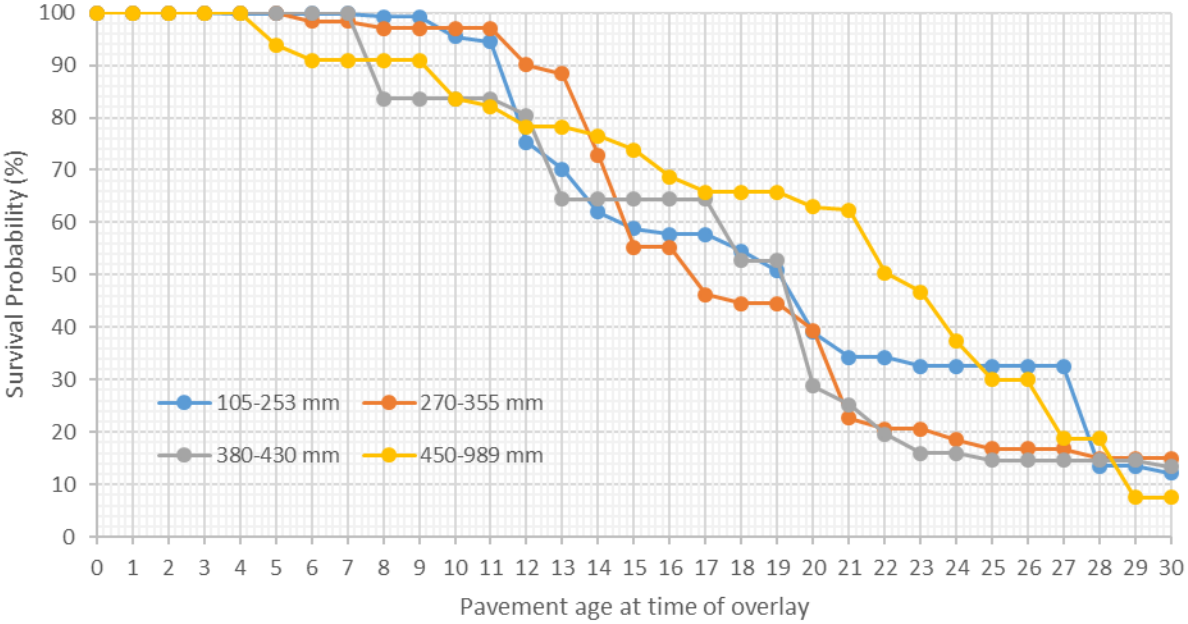


Figure 27a. Survival probability vs age of asphalt pavement at the time of bituminous overlay based on the overall thickness

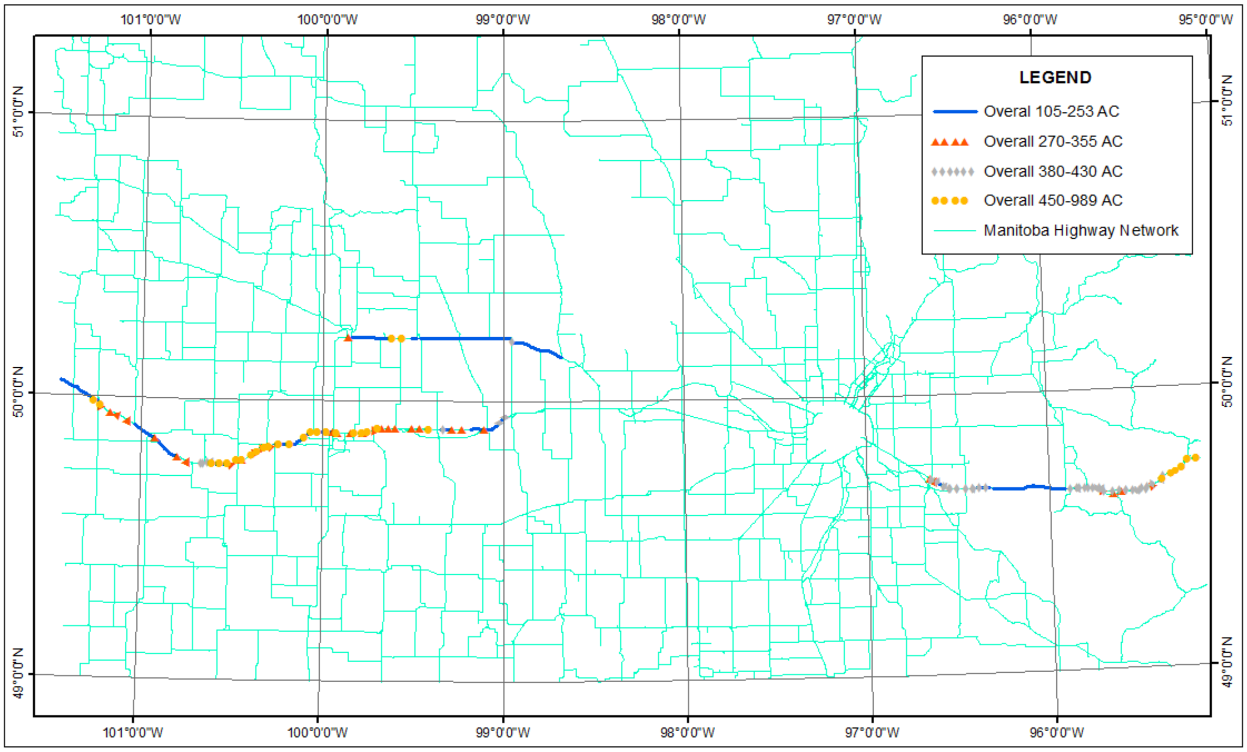


Figure 27b. Overall thickness families of asphalt pavements

4.1.1.2.2 Partitions based on Average Annual Daily Truck Traffic

The sample was partitioned according to the AADTT per lane to study the age of pavements of each range of truck traffic at the time of overlay. Table 26 shows the ranges of AADTT of each family. The majority of the sections had an AADTT under 600.

Table 26. Surface distribution for each asphalt pavement family based on Average Annual Daily Truck Traffic

Traffic	Number of sections	Surface area (m^2)	Percent of surface area	Centerline length (m)
AADTT <300	60	1,067,590	24.9%	132,353
300<AADTT<400	46	1,200,142	27.9%	162,811
400<AADTT<500	55	1,175,501	27.4%	158,730
500<AADTT<600	54	832,838	19.4%	111,591
AADTT >600	2	18,480	0.4%	2,400
TOTAL	217	4,294,551	100%	567,885

Figure 28a shows that 50% of the surface area of each family received an overlay between year 19 and year 21 after initial pavement construction, with the exception of those sections with an AADTT between 400 and 500. 50% of the surface area of the sections with an AADTT between 400 and 500 received an overlay on year 14 after initial pavement construction. Figure 28b shows the pavements corresponding to each AADTT family. Figure 29 shows all families maintained similar condition states from year 2007 to 2016.

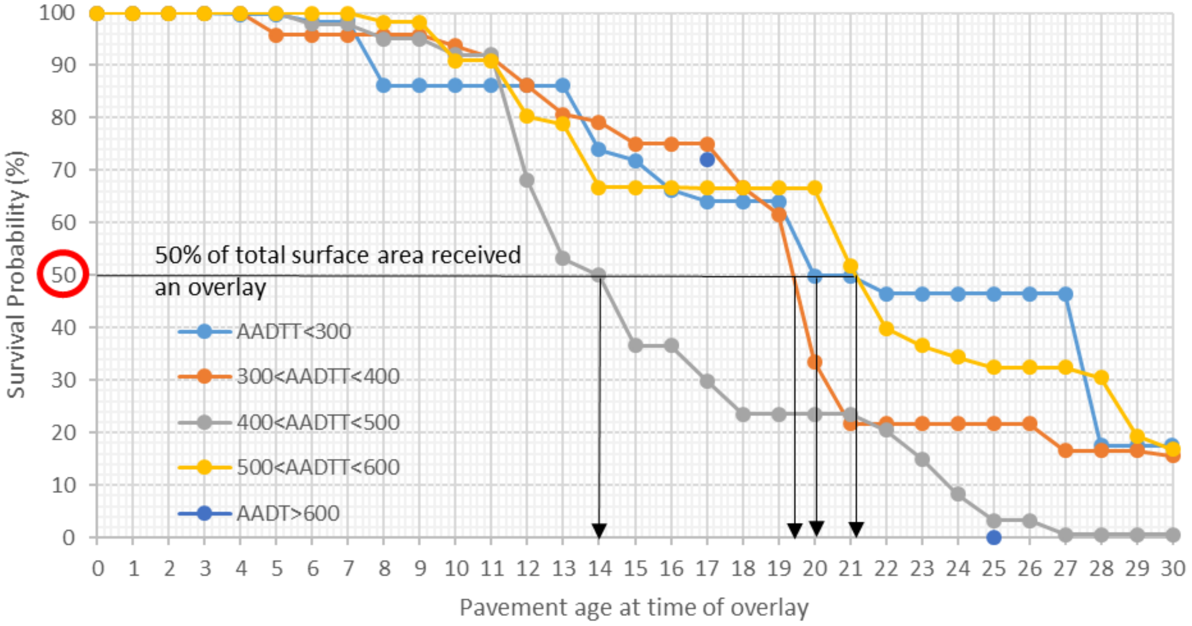


Figure 28a. Survival probability vs age of asphalt pavement at the time of bituminous overlay based on AADTT

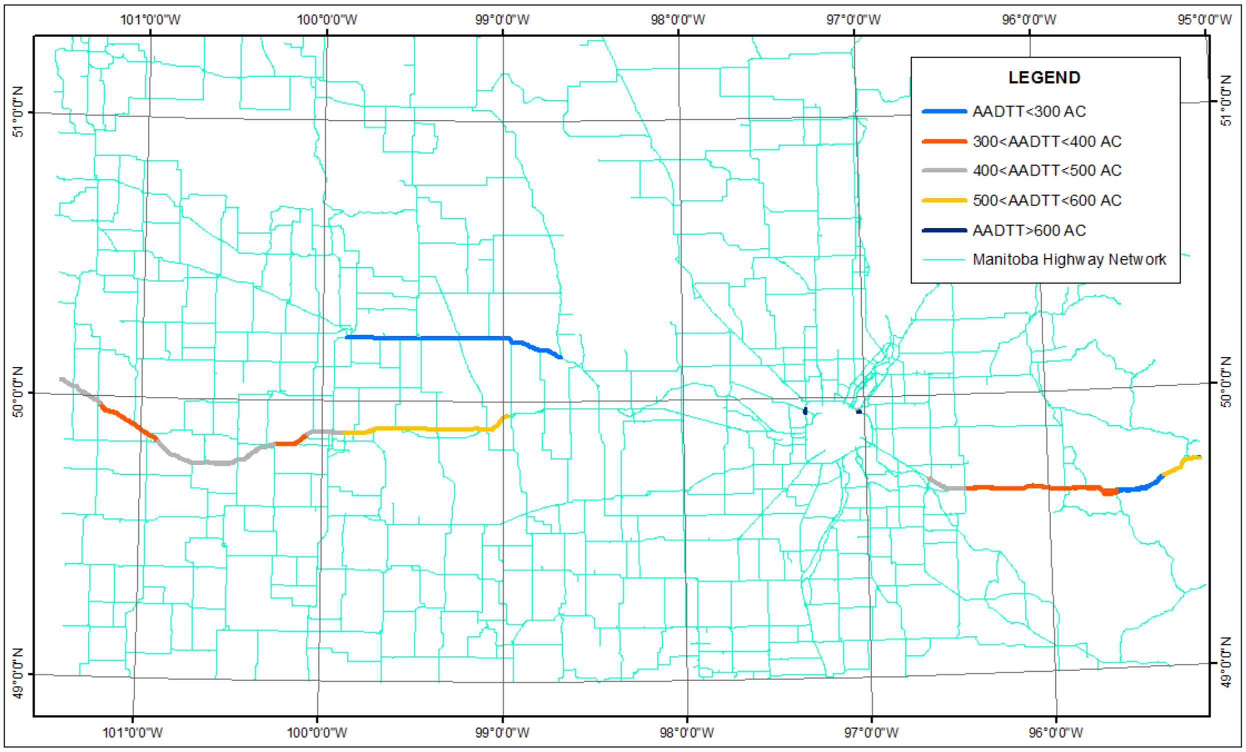


Figure 28b. AADTT families of bituminous overlays over asphalt pavements sample sections

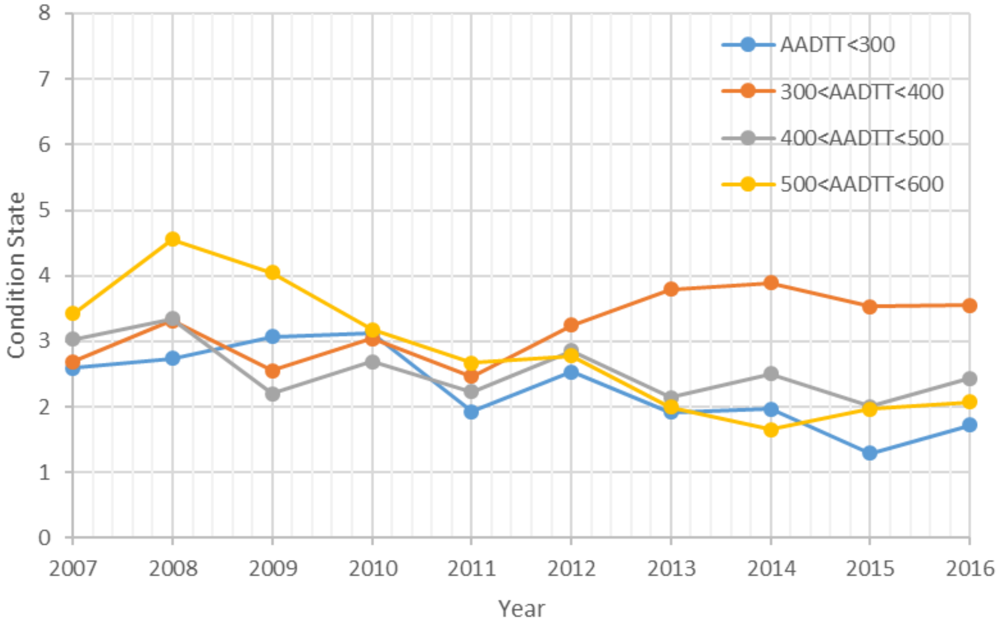


Figure 29. Condition data trend of bituminous overlays over asphalt pavements sample sections based on AADTT

4.1.2 City of Winnipeg survival distributions

4.1.2.1 Bituminous overlay over concrete pavement

Figure 30 shows the amount of surface and number of sections overlaid in the last 70 years. The age of the pavement at the time of overlay ranges from 5 to 49 years. The majority of the overlays were constructed before the year 28. Figure 31 shows the Kaplan-Meier survival analysis. This figure illustrates that 50% of the total surface area received an overlay before the year 18 after initial construction. To analyze the reasons behind this behavior, the overlays were partitioned. Given that all sections were built with the same pavement structure, the partition was made based on the type of drainage found through Street View from Google Maps.

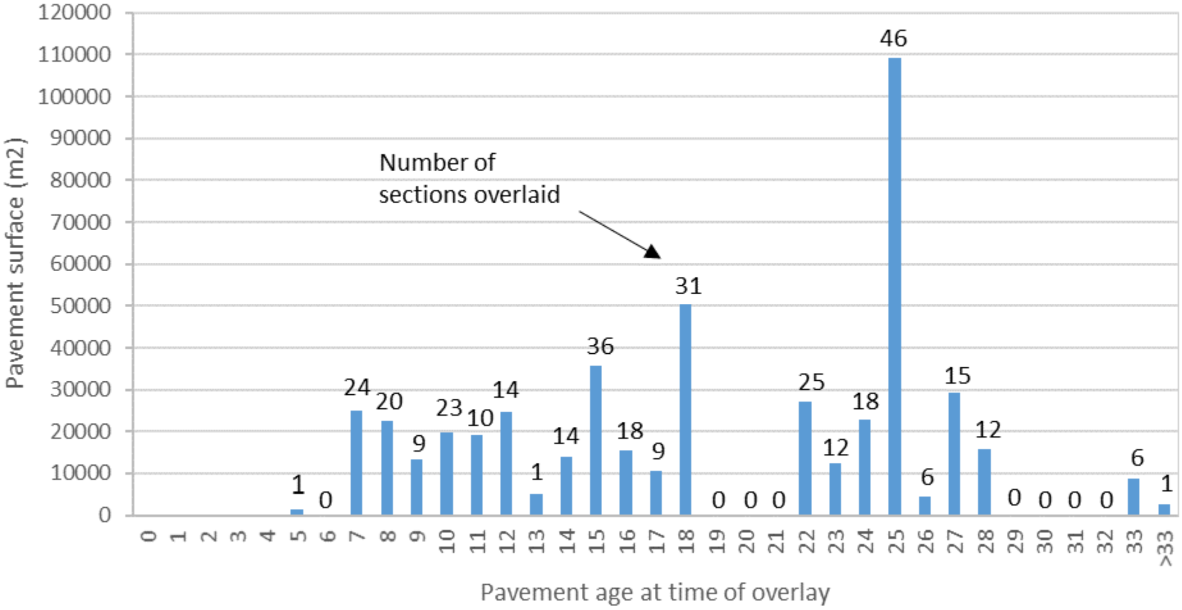


Figure 30. Age of concrete pavement at time of bituminous overlay (City of Winnipeg)

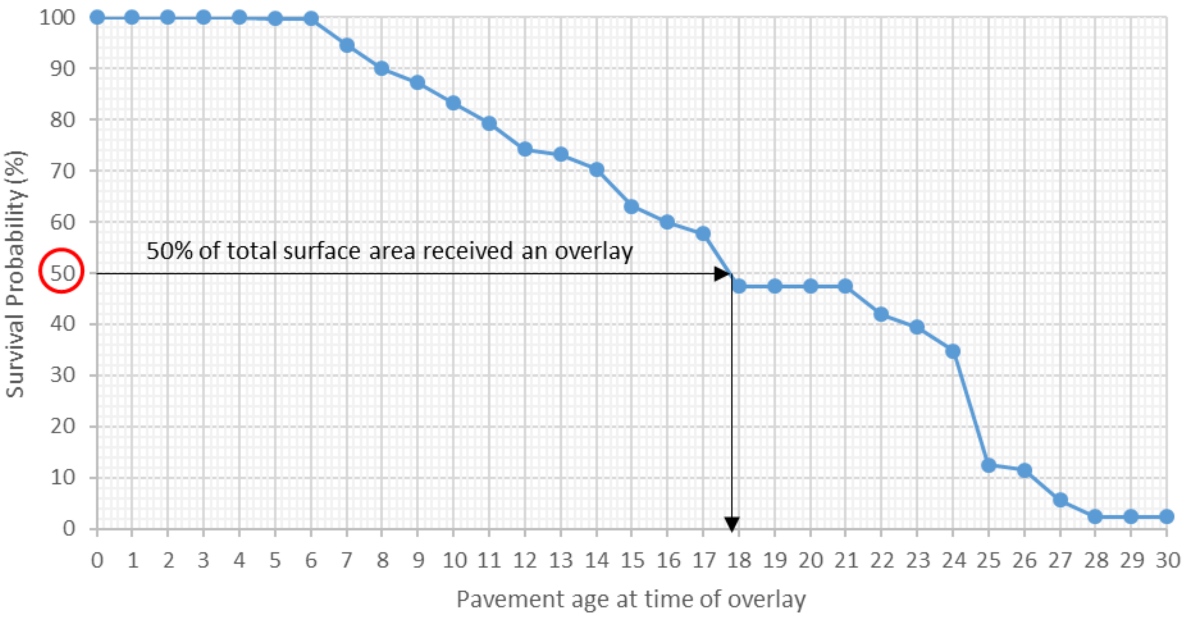


Figure 31. Survival probability vs age of concrete pavement at time of bituminous overlay (City of Winnipeg)

4.1.2.1.1 Partitions based on drainage type

The partition was made based on the type of drainage. Table 27 shows that the majority of the sample sections have curb and gutter as their type of drainage. For this reason, this partitioning is not significant for this data. A similar result was obtained when the data was partitioned based on speed limit.

Table 27. Surface distribution for each concrete pavement family based on type of drainage (City of Winnipeg)

Type of drainage	Number of sections	Surface area (m^2)	Percent of surface area	Centerline length (m)
Curb and Gutter	318	384,333	78%	35,619
Ditch	33	105,288	22%	13,694
TOTAL	351	489,621	100%	49,313

4.2 PROBABILITY DISTRIBUTIONS PARAMETERS

This study considers the variability of the discount rate, unit costs and the timing of M&R activities (service life). The parameters of the probability distributions that account for these variabilities are needed to develop a probabilistic LCCA. Table 28 shows a comparison of the sources of variation considered in this study and other research studies on probabilistic LCCA.

Table 28. Comparison of sources of variations considered on Probabilistic LCCA research studies

Study	Source of variation				
	Discount rate	Service life	Initial cost	Future cost	User Cost
This Study	✓	✓		✓	
Akbarian et al. (2017)			✓	✓	✓
Swei, Gregory, & Kirchain (2012)			✓	✓	
Cheng and Hicks (2012)		✓	✓		
Pittenger et al. (2012)	✓	✓	✓		
Whiteley, Tighe, & Zhang (2005)	✓	✓			

4.2.1 Parameters of treatment timing and discount rate distributions

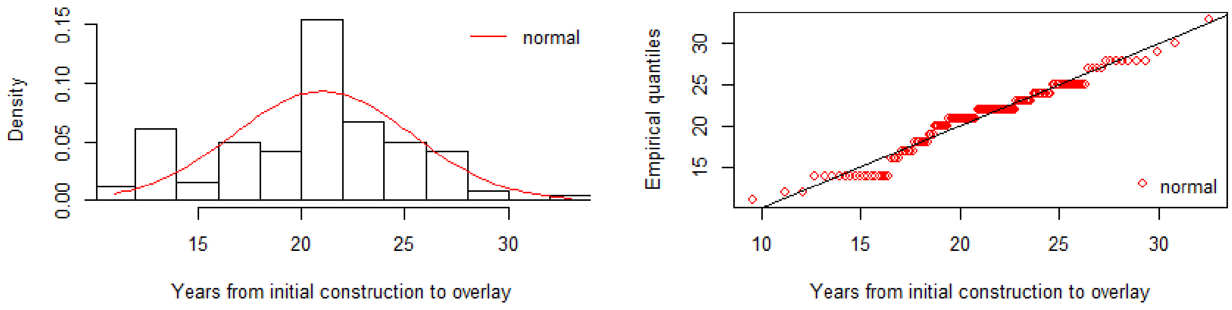
By using the software R and the package "fitdistsplus", it was possible to find the distribution that best fitted the different groups of data. Only the distributions accepted by RealCost were considered. Table 29 shows the results, where most of the treatment timings followed a normal distribution. For this reason, it was assumed that the timing for all treatments followed a normal distribution. The timing for rout and seal and the second application of chip sealing for the Manitoba Infrastructure data sample did not have sufficient data points, and consequently, it was not possible to evaluate the goodness of fit. Figure 32 shows the goodness-of-fit plots (density function, Q-Q plot, cumulative distribution function and P-P plot) for the timing of the first bituminous overlay over concrete pavement of the Manitoba Infrastructure data sample. The plots for the rest of the distributions can be found in Appendix A.

Table 29. Distribution fitting results

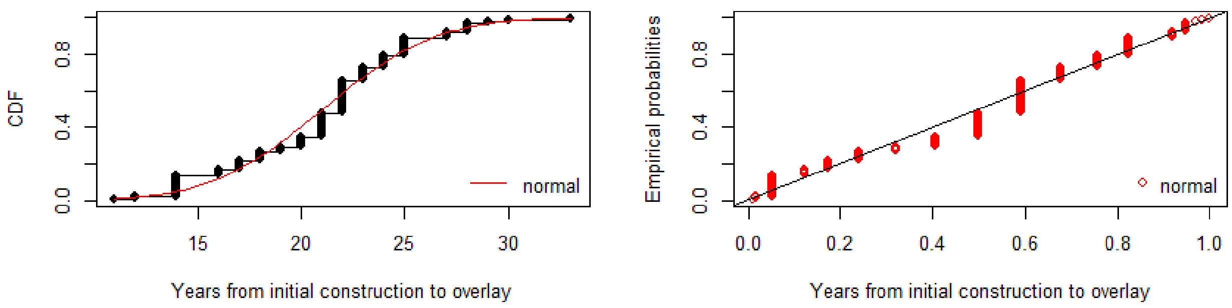
Agency	Data	n	Distribution
Manitoba Infrastructure	Discount rate	16	Normal
	Timing of Treatment activities		
	• Rout and Seal	14	Not defined
	• Chip sealing (1st application)	20	Uniform
	• Microsurfacing	47	Normal
	• Chip sealing (2nd application)	5	Not defined
	• Bituminous overlay over AC	117	Normal
	• Bituminous overlay over PCC	133	Normal
	• 2nd Bituminous overlay over AC [x]	22	Lognormal
City of Winnipeg	Discount rate	10	Normal
	Timing of Treatment activities		
	• Crack sealing	45	Lognormal
	• Mill and Fill	133	Normal
	• Bituminous overlay over PCC	218	Normal

AC= Asphalt Concrete pavement, PCC= Portland Cement Concrete pavement

[x] From the time of the first overlay



a. *Histogram* b. *q-q plot*



c. *cumulative density function* d. *p-p plot*

Figure 32. Goodness-of-fit plots for timing of the first bituminous overlay over concrete pavement for the Manitoba Infrastructure data sample

Table 30 shows the parameters of the normal distributions of the Manitoba Infrastructure data sample, and Table 31 the parameters of the City of Winnipeg data sample.

Table 30. Probability distribution parameters (Manitoba Infrastructure)

Manitoba Infrastructure Data	Parameters*	
	Mean	Std. Dev.
Discount rate (%)	3.07	0.97
Timing of Treatment activities (years)		
• Rout and Seal	3.64	1.80
• Chip sealing (1st application)	8.35	4.22
• Microsurfacing	15.45	5.29
• Chip sealing (2nd application)	19.6	1.50
• Bituminous overlay over asphalt pavement	21.76	8.48
• Bituminous overlay over concrete pavement	21.03	4.29
• 2nd Bituminous overlay over asphalt pavement [x]	13.14	6.68

* Assumed as normal distributions, [x] From the time of the first overlay

Table 31. Probability distribution parameters (City of Winnipeg)

City of Winnipeg Data	Parameters (*)	
	Mean	Std. Dev.
Discount rate (%)	3.88	0.88
Timing of Treatment activities (years)		
• Crack sealing	5.04	1.13
• Mill and Fill	18.62	3.63
• Bituminous overlay over concrete pavement	20.79	5.45

* Assumed as normal distributions

The results for the time to first rehabilitation, in this case first bituminous overlay, were compared to two recent studies as shown in Table 32. The Province of Manitoba reported that is currently using a time to first rehabilitation of 20 years for both pavements (Morges et al. 2017), and the results obtained in this study for both asphalt and concrete provincial pavements are similar to those reported. These timings also fall on the range used by Canadian Provincial

Agencies and State Highway Agencies (SHAs). The results for the time to overlay applying the survival analysis and after fitting the data to a probability distribution were found similar, and the reason for the difference is the data years studied. The timing found with the probability distributions is the most appropriate because the data was filtered to be close to current practices. For the City of Winnipeg, the results obtained for the timing of first rehabilitation of concrete pavement using probability distributions are similar to those found for the Province of Manitoba.

Table 32. Comparison of time to first rehabilitation

Timing of first rehabilitation	**This Study**		**Robbins et al. (2017)**		**Morges et al. (2017)**	
	Survival Analysis*	Probability distribution ^{x}	State Highway Agencies survey	LTPP sections ^{x}	Canadian Provincial Agencies	Province of Manitoba
Manitoba Infrastructure						
Asphalt	19 years	22 years	10-26 years (Majority 10-15)	18 years	15-30 years	20 years
Concrete	22 years (Majority 20-25)	21 years	10-35 years (Majority 20-25)	24 years	20-40 years	20 years
City of Winnipeg						
Concrete	18 years	21 years	No information about Municipal Roads			

* Median of survival distribution, ^{x} Mean of probability distribution

4.2.2 Parameters of cost distributions

Treatment costs were also assumed to follow a normal distribution when data for two or more years was available. The items with data for only one year were treated as deterministic. Table 33 shows the parameters of the distributions for 17 cost items of Manitoba Infrastructure, and Table 34 the parameters for 13 cost items of the City of Winnipeg.

Table 33. Costs distributions parameters (Manitoba Infrastructure)

Manitoba Infrastructure Items	Unit	Parameters*	
		Mean ($)	Std. Dev. ($)
Common excavation	m^3	5.45	2.72
Granular Fill, Modified	tonne	13.30	4.67
Crushed Rock, 50 mm Minus, Limestone	tonne	31.00	0
Granular Base Course Class "A", Modified	m^2	16.95	3.91
Concrete Pavement, 255mm Plain Dowelled	m^2	89.11	17.03
Concrete Pavement, 255mm Fiber Reinforced – Dowelled	m^2	75.00	0
Construction of Concrete Sidewalk-100mm, Modified	m^2	92.00	0
Bituminous Pavement, Class "B", Modified	tonne	35.40	9.73
Stone Rip-Rap, Class 350 mm	m^3	99.75	0
Concrete Repair - Full Depth	m^2	242.93	80.41
Concrete Repair - Partial Depth	m^2	874.22	403.33
Micro-Surfacing	m^2	7.50	0
Milling Bituminous Pavement	m^2	2.50	0.28
Chip Seal	m^2	3.25	0
Crack Routing and Sealing	m	5.50	0
Rec Bit Pvmt Cl "B", Modified (Oils Supp by Cont)	ton	75.62	3.23
Recycled Bituminous Pavement, Class "B"	ton	30.82	9.43

* Normal distributions assumed

Table 34. Costs distributions parameters (City of Winnipeg)

City of Winnipeg Items	Unit	Parameters*	
		Mean ($)	Std. Dev. ($)
Excavation	m^3	18.53	6.31
Sub-Grade Compaction	m^2	0.80	0.35
Crushed Sub-base Material, 50 mm	tonne	28.12	3.60
Supplying and Placing Base Course Material	m^3	76.86	14.88
Slab Replacement, 200 mm Concrete Pavement, Reinforced	m^2	121.08	8.06
Partial Slab Patches, 200 mm Concrete Pavement, Type A	m^2	184.42	19.63
Construction of Asphaltic Concrete Overlay, Main line, Type IA	m^2	96.23	9.18
Planning of Asphalt Pavement			
• 0 - 50 mm Depth	m^2	4.82	1.16
• 50 - 100 mm Depth	m^2	5.00	0.97
Construction of 230 mm Concrete Pavement, Plain-Dowelled	m^2	99.49	11.75
Construction of 200 mm Concrete Pavement, Reinforced	m^2	107.84	12.42
100 mm Concrete Sidewalk	m^2	72.54	9.67
Reflective Crack Maintenance	m	3.83	0.42

* Normal distributions assumed

A comparison of the probability distributions obtained was compared to other studies of probabilistic LCCA as shown in Table 35, where costs are mainly represented by normal distributions, discount rate by triangular and normal distributions, and the service life by various shapes.

Table 35. Comparison of probability distributions used on studies of probabilistic LCCA

Probability Distribution	**This study**	**Wu et al. (2017)**	**Pittenger et al. (2013)**	**Pittenger et al. (2012)**	**Whiteley et al. (2005)**
Discount rate	Normal	Normal	Triangular	Triangular	Triangular
Initial Cost	Deterministic	Not considered	Not considered	Normal	Deterministic
Future Cost	Normal	Triangular	Normal	Deterministic	Deterministic
Service life	Various	Deterministic	Triangular	Triangular	Normal, Lognormal

4.3 CASE STUDY PAVEMENT SECTION

A case study section was selected to compare the deterministic and the probabilistic LCCA results. This section is part of the Manitoba Infrastructure network and was initially constructed in 2010. Table 36 shows the description of the section data and Figure 33 shows its location.

Table 36. Case study section data

Category	Description
Transportation Agency	Manitoba Infrastructure
Road Number	Provincial Trunk Highway 1 (PTH1)
Functional Class	Expressway
Location	Region 1, from PR 207 to PTH 12
Control Section	0100125HB
Length	24.8 km
Surface	7.3 m
Direction	Westbound
Surface Type	Asphalt Pavement
Initial Cost	$15,037,584.00
Year of Construction	2010

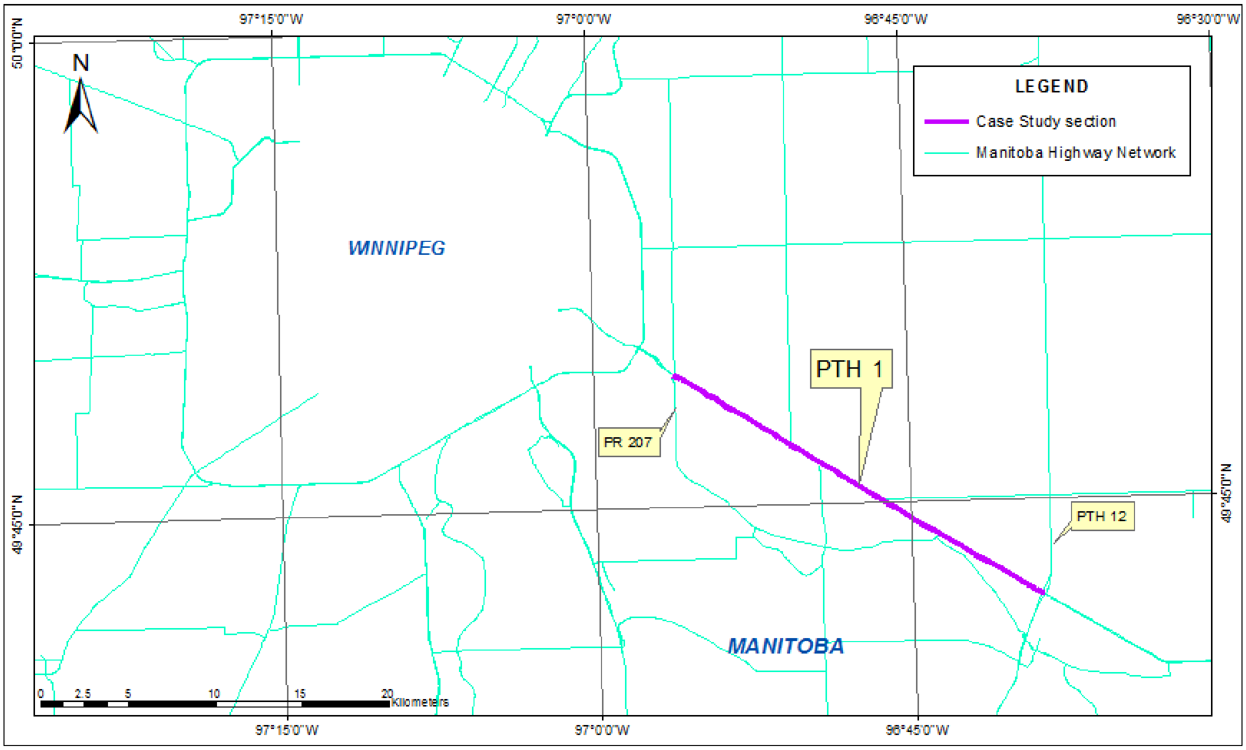


Figure 33. Case study section

The combination of the data from the case study section and the results obtained for the discount rate, timings and cost of treatments allowed creating the inputs for the analysis of the life cycle cost on RealCost. The activity sequence and quantities for each activity were based on Manitoba Infrastructure's standard No. MEB- P005 found in Appendix B. Table 37a and 37b show the inputs for the calculation. According to the standard No. MEB- P005, 35mm of the pavement will be milled before an overlay of 50mm is placed, and the quantities for all the treatments are 100%. The density used for the bituminous pavement is 2350 kg/m^3 based on TAC (2016). Only agency costs will be evaluated.

Two alternatives will be studied. On Alternative 1, all activity timings are considered probabilistic. On Alternative 2, the timing of minor rehabilitation treatments such as rout and seal, chip sealing and microsurfacing are considered deterministic.

Table 37a. Probabilistic inputs for LCCA on RealCost

Category	Inputs	Distribution	Mean	Std. Dev.
Analysis	Analysis Period (years)	Deterministic	30	0
	Discount Rate (%)	Normal	3.07	0.97
Structural Life	Initial Construction (years)	Normal	21.76	8.48
	Mill and Overlay (years)	Normal	13.14	6.68
Cost	Initial Construction	Deterministic	$15,037,584	0
	Rout and Seal*	Deterministic	$136,400	0
	Chip Sealing*	Deterministic	$588,380	0
	Microsurfacing*	Deterministic	$1,357,800	0
	Mill and Overlay*	Normal	$2,061,097	$119,946

* Inflation is not accounted for

Table 37b. Parameters of normal distributions representing the year of activity occurrence

Input Category	**Mean (years)**	**Std. Dev. (years)**	
		Alternative 1	**Alternative 2**
Initial Construction	0	0	0
Rout and Seal	3.64	1.80	0
Chip Sealing	8.35	4.22	0
Microsurfacing	15.45	5.29	0
Chip Sealing (2nd Application)	19.6	1.50	0
Mill and Overlay	21.76	8.48	8.48

Figure 34 is the expenditure stream diagram that shows all expenses during the analysis period. The x-axis represents the year when each expense is expected to occur. The values are based on the deterministic inputs and the mean pf the probabilistic inputs. The negative cost represents the remaining service life value of the pavement at the end of the analysis period. The y-axis is the cost of each activity on the expected year, without being discounted to the present and without the effect of inflation.

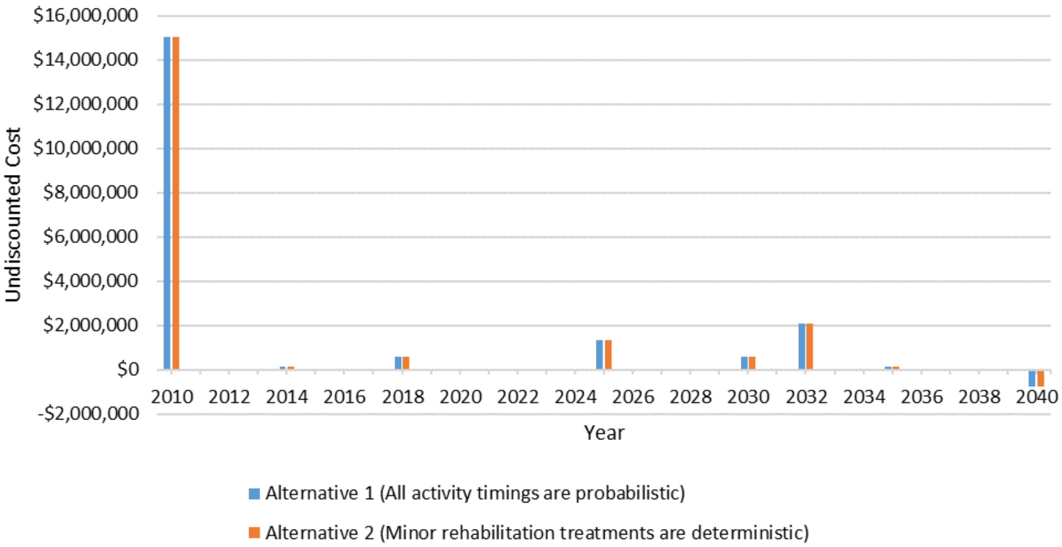


Figure 34. Expenditure Stream Diagram of the costs considered for LCCA

4.3.1 Deterministic results

Table 38 shows the present value of the life cycle cost of the case study after running a deterministic LCCA. The result for both alternatives is the same because, as mentioned before, the deterministic approach uses only deterministic inputs and the median of distributions to calculate the life cycle cost, and these values are the same for both alternatives. Given that this approach uses single value inputs, the output is also a single value.

Table 38. Deterministic results of the Total Life Cycle Cost

Total Cost	**Agency Cost**			
	Alternative 1 (All activity timings are probabilistic)		Alternative 2 (Minor rehabilitation treatments are deterministic)	
	Total Project	Per Kilometer	Total Project	Per Kilometer
Undiscounted Sum	$19,134,259	$771,543	$19,134,259	$771,543
Present Value	$17,616,671	$710,350	$17,616,671	$710,350
EUAC	$906,941	$36,570	$906,941	$36,570

4.3.2 Probabilistic results

RealCost uses the probabilistic inputs to run the Monte Carlo simulation. During the simulation, a limitation of RealCost was discovered, and the reason is the high standard deviation of the timing distributions that causes overlapping. This overlapping introduces the assumption that some treatments may happen before or at the same time as the previous one. In real life, for example, an overlay may be needed instead of microsurfacing due to loss of structural support, but this will cause a reconfiguration of the activity sequence, and RealCost is programmed to follow a defined sequence. Walls & Smith (1998) states that a way to deal with this limitation is to establish bounds for the distributions. For this reason, the timing distributions will be trimmed to a percentage of their standard deviation and will be defined as truncated normal distributions with maximum and minimum limits, as shown in Table 39. Figure 35a is an example of overlapping between distributions and Figure 35b shows the truncated normal distributions to avoid the overlapping.

Table 39. Parameters of truncated normal distributions representing the year of activity occurrence

Alternative	**Input Category**	**Mean (years)**	**Std. Dev. (years)**	**Min (years)**	**Max (years)**	**% Std. Dev.**
1	Initial Construction	0	0	-	-	-
(All activity	Rout and Seal	3.64	1.80	2.29	4.99	75%
timings are	Chip Sealing	8.35	4.22	5.19	11.52	75%
probabilistic)	Microsurfacing	15.45	5.29	11.75	19.15	70%
	Chip Sealing (2nd Application)	19.6	1.50	19.15	20.05	30%
	Mill and Overlay	21.76	8.48	20.06	23.46	20%
2	Initial Construction	0	0	-	-	-
(Minor	Rout and Seal	3.64	0	-	-	-
rehabilitation	Chip Sealing	8.35	0	-	-	-
treatments	Microsurfacing	15.45	0	-	-	-
are	Chip Sealing (2nd Application)	19.6	0	-	-	-
deterministic)	Mill and Overlay	21.76	8.48	20.06	23.46	20%

Figure 35a. Overlapping between distributions

Figure 35b. Truncated normal distributions to avoid overlapping

After the modification of the inputs, the simulation was run again, and this one converged after 600 iterations. Given that this approach uses distribution inputs, the output is also a distribution of all possible costs. Table 40 shows the present value of the life cycle cost of the case study after running the simulation. The minimum and maximum are the extreme values found in the simulation result, in other words, the highest and lowest possible values. These values are more than three standards deviation apart from the mean. The standard deviation of Alternative 1 is higher because this alternative considers more inputs as probabilistic. At the 95% reliability level, Alternative 1 is more expensive than Alternative 2 by $141,970. Knowing that costs occurring closer to the present increase the present value more than those happening in a later future, there might be a higher probability that treatments will happen before the expected mean value.

Table 40. Probabilistic results of the Present Value of the Total Life Cycle Cost

Total Cost (Present Value)	**Agency Cost**			
	Alternative 1 (All activity timings are probabilistic)		Alternative 2 (Minor rehabilitation treatments are deterministic)	
	Total Project	Per Kilometer	Total Project	Per Kilometer
Mean	$17,570,043	$708,470	$17,569,432	$708,445
Standard Deviation	$692,005	$27,903	$621,318	$25,053
Minimum	$15,246,370	$614,773	$13,954,300	$562,673
Maximum	$20,018,220	$807,186	$19,708,220	$794,686
95% Reliability	$18,954,053	$764,276	$18,812,068	$758,551

Figure 36 shows the probability density functions and the cumulative distribution functions for both alternatives. The probability density function shows the similarity between the means. If the true present value is between $17.1 - $18.1 million Alternative 1 has a greater opportunity for low cost, also called upside risk. However, if the true present value is lower than \$17.1 or higher than \$18.1 million Alternative 1 has a greater opportunity of money loss, also called downside risk.

The cumulative distribution function shows that Alternative 1 has greater variability due to a flatter slope, as expected due to the inclusion of the variability of all M&R treatment timings. This distribution allows studying the cost at various reliability levels. Analyzing the sections at 10% and 90% reliability, this distribution shows that there is a 10 percent probability that the present value of Alternative 2 will be greater than Alternative 1 by \$148,810. On the other hand, there is a 10 percent probability that the present value of Alternative 1 will be greater than Alternative 2 by \$74,510.

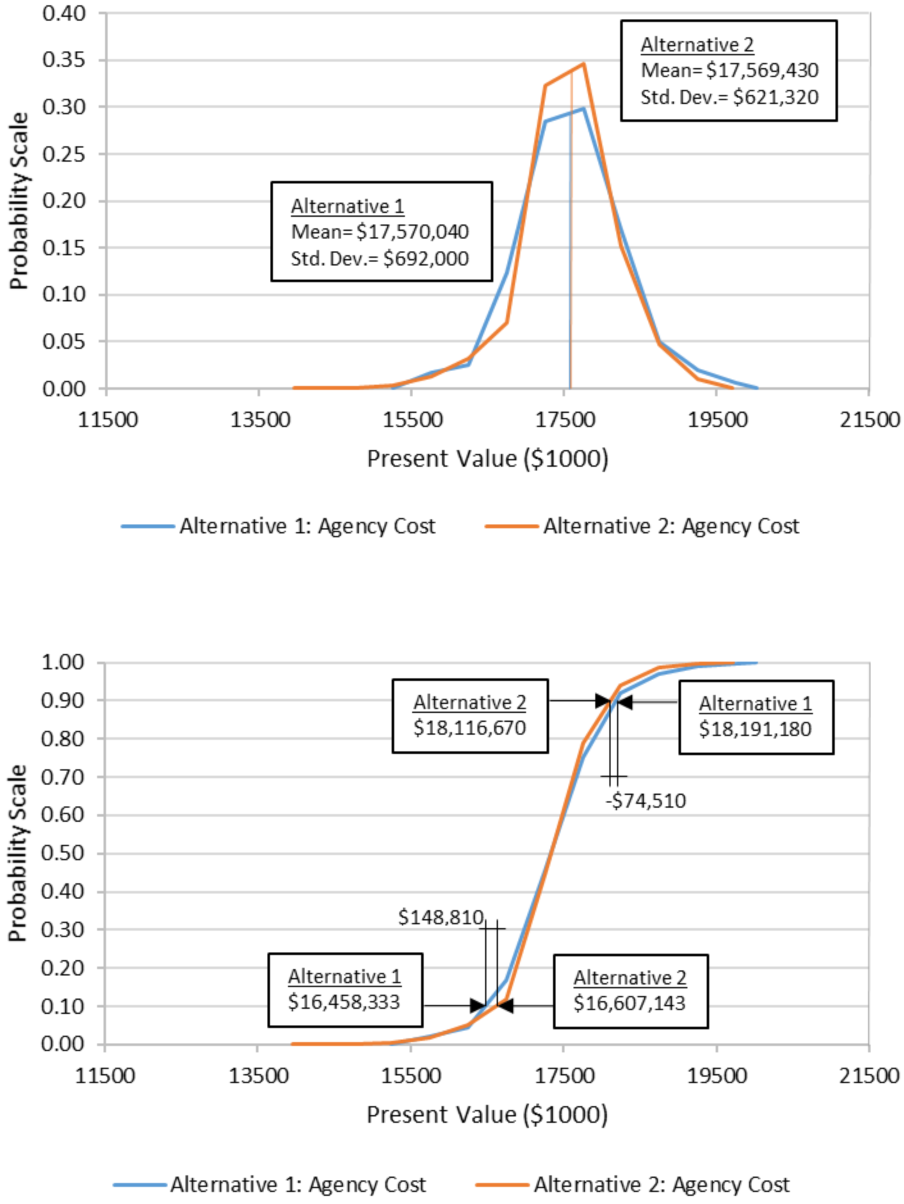


Figure 36. Probability Density Functions and Cumulative Distribution Functions of the Present Value of the Total Life Cycle Cost

Figure 37 shows the tornado graphs for the alternatives. The graph shows the different factors that have an effect on the total present value and their correlation coefficients. The present value is negatively correlated with all the factors shown, except the cost of mill and overlay on Alternative 2. Increasing the value of the negatively correlated factors will decrease the present value. For example, discount rate has a correlation coefficient of -0.46 for Alternative 1. This means that if the discount rate moves one standard deviation in a direction, then the present value will move 0.46 of its standard deviation in the opposite direction. The service life of the first chip sealing application, the discount rate and the service life of rout and seal appear to have a greater effect on the present value of Alternative 1 than other factors. For Alternative 2, the discount rate has the greatest effect on the present value.

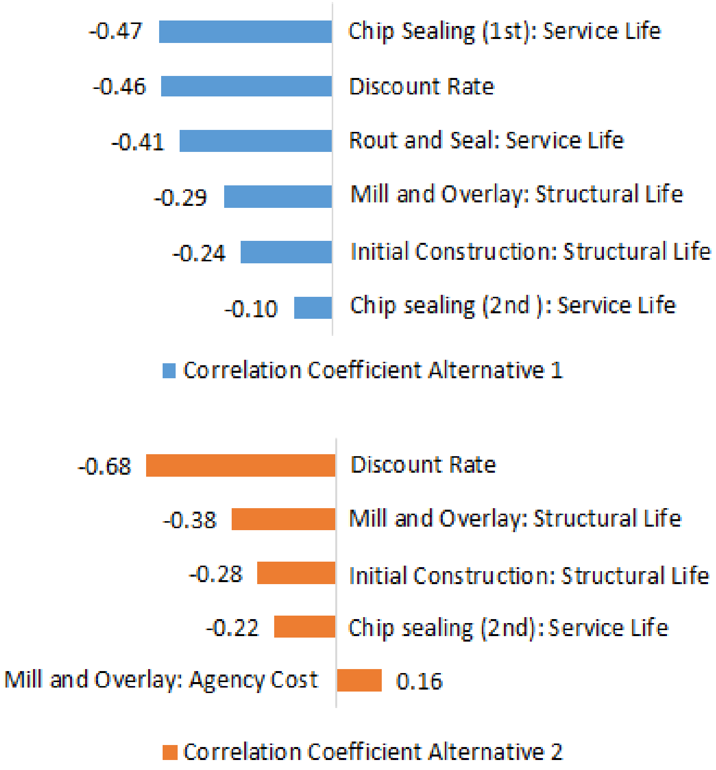


Figure 37. Correlation coefficients affecting the Present Value of the Total Life Cycle Cost

4.4 DISCUSSION

The main advantage of the probabilistic approach over the deterministic approach is that the output does not only provide the expected value of the total cost, it also provides information about the reliability and variability. The additional information is an important feature to evaluate the anticipated financial risk in selecting an alternative. For the case study, selecting to work with the probabilistic results at a 95% reliability, a cost overrun of about $1,3M could be avoided given the high-reliability levels that cannot be obtained from the deterministic analysis.

The probabilistic approach allows for studying the cost at various reliability levels, so agencies can estimate the risk of exceeding a certain budget, and compare alternatives based on their cost and potential for cost overruns. The inclusion of the variability of minor treatments does not have a significant effect on the mean of the present value, but it changes the main factors affecting total cost and the risk associated with the alternative.

4.5 LIMITATIONS

In this study, efforts were made to develop accurate distributions; however, the lack of condition data was a limiting factor. Condition data can help to screen the timing of overlays and M&R treatments and to exclude the ones that were performed prematurely or too late. For this reason, the statistical distributions were developed using actual treatment timings. In the case of the Province of Manitoba, the lack of data for rout and seal and chip sealing was also a limitation and a normal distribution was assumed to describe their timing. On the other hand, due to the uniformity of the concrete pavement structure across the City of Winnipeg, the data was not enough to create useful and distinctly different survival distributions.

For both datasets, the extraction of useful information was laborious because of the data structures. Another limitation found was the sensitivity of RealCost to distributions with high standard deviations. The software works with a defined sequence and the possibility of overlapping between activities is not permitted. To avoid the overlapping of activity timing, minimum and maximum bounds were assigned to the distributions.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Transportation agencies are seeking high certainty when making investment decisions. For this reason, a probabilistic life cycle cost analysis that considers the variability of the inputs should be performed and be followed by a risk analysis. The use of statistical distributions allows describing those variabilities. Survival analysis and distribution fitting are useful tools to develop distributions, but their accuracy depends on the data used. Distributions used in LCCA may be developed using historical data. However, it is important to exclude data that is derived from old practices that are not currently acceptable.

This study considered pavement life, timing of maintenance and rehabilitation activities, unit costs and discount rate as probabilistic inputs, and its variability was based on available historical agency data. It was found that the majority of the distributions for activity timing and structural life followed a normal distribution with large standard deviations.

The probabilistic life-cycle cost results showed that this computational approach provides levels of reliability necessary for the evaluation of the present value of the total project cost. The deterministic approach provides a single value, but the probabilistic approach provides a distribution of all possible values with their respective probabilities of occurrence, which permits analyzing the risk associated with each alternative and avoiding cost overruns. The probabilistic results identified the main factors affecting the total cost. The variation of these factors will result in varying the total cost. It was demonstrated that the inclusion of the variability of more inputs changes the distribution of the total cost allowing a better risk estimation.

LCCA is a tool that provides an estimate of the total life cycle cost of a pavement, and its results should be used to help in the decision-making process besides other factors.

5.2 RECOMMENDATIONS

- Transportation agencies should consider probabilistic life cycle cost analysis as part of their decision-making process due to the economic benefits and reliability levels that this computational approach provides

- A data management system that is structured to provide the information needed to develop LCCA would make the application of this tool to be easier

- The distributions developed should be used as a guide for asset management planning of future projects, budgeting purposes as well as in the selection of pavement materials.

- The distributions should be updated when more data becomes available to represent current practices

- This study focuses on expressway sections of the Province of Manitoba network and regional arterial sections of the City of Winnipeg because of their significance to the transportation network. It will be useful for transportation agencies to extend the probabilistic LCCA study to other functional classes

- The availability of user data will improve the comparison between alternatives.

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APPENDIX A. Goodness-of-fit plots

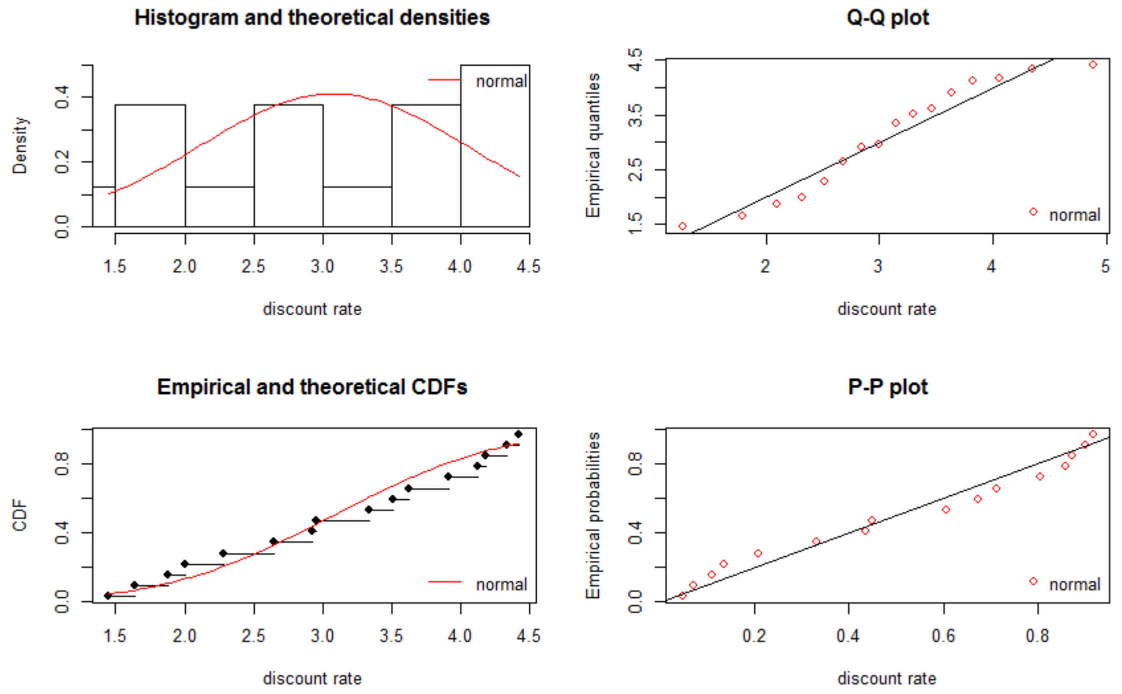


Figure A1. Goodness-of-fit plots for discount rate (Manitoba Infrastructure)

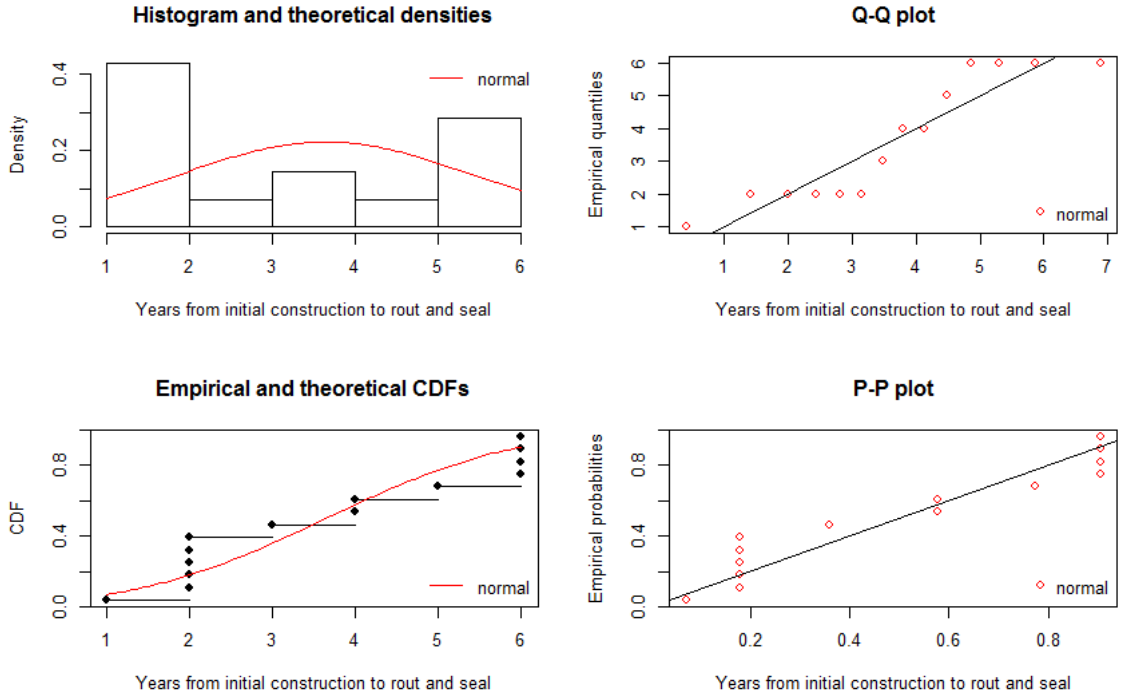


Figure A2. Goodness-of-fit plots for rout and seal timing (Manitoba Infrastructure)

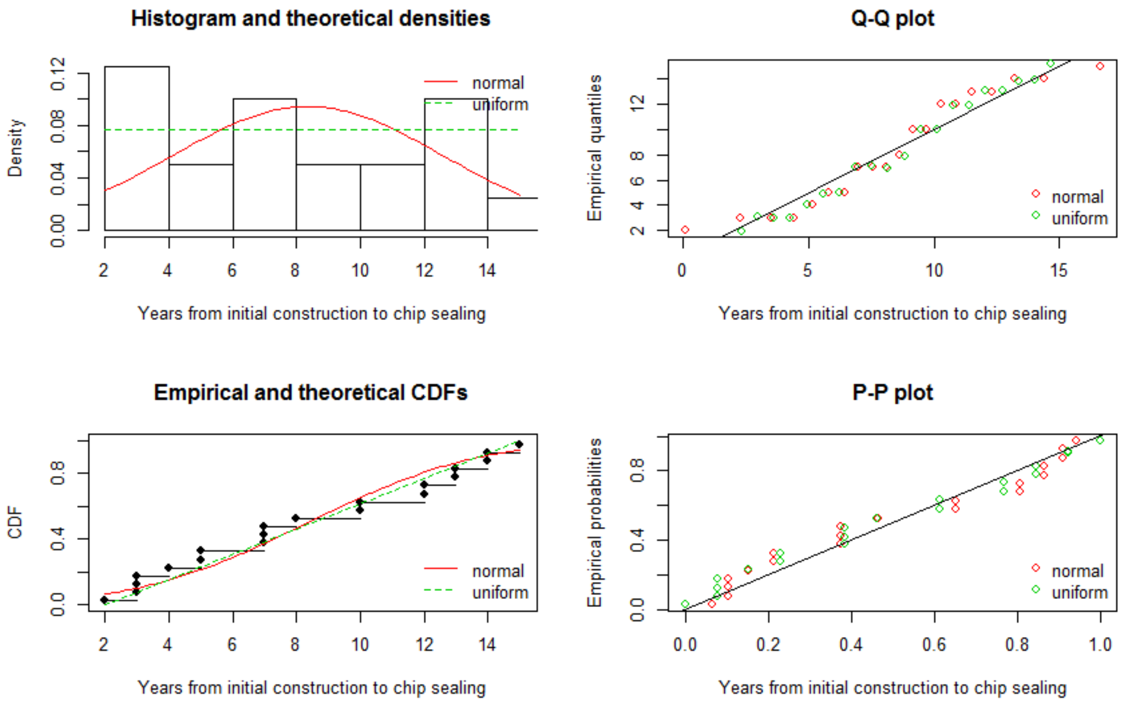


Figure A3. Goodness-of-fit plots for chip sealing timing (Manitoba Infrastructure)

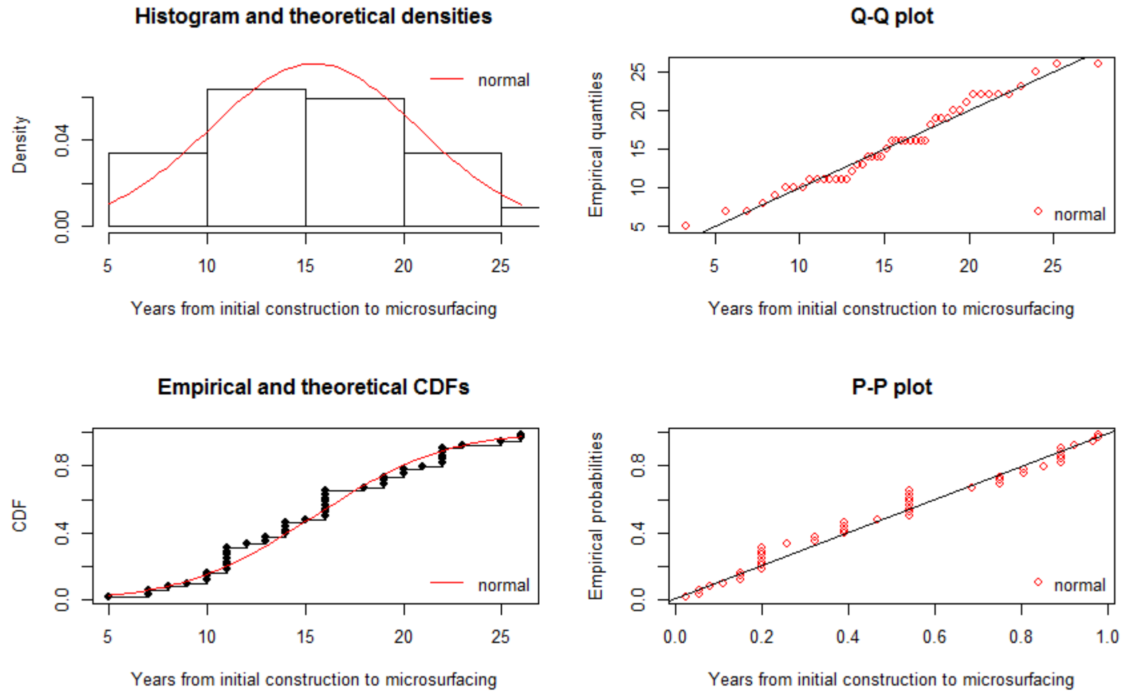


Figure A4. Goodness-of-fit plots for microsurfacing timing (Manitoba Infrastructure)

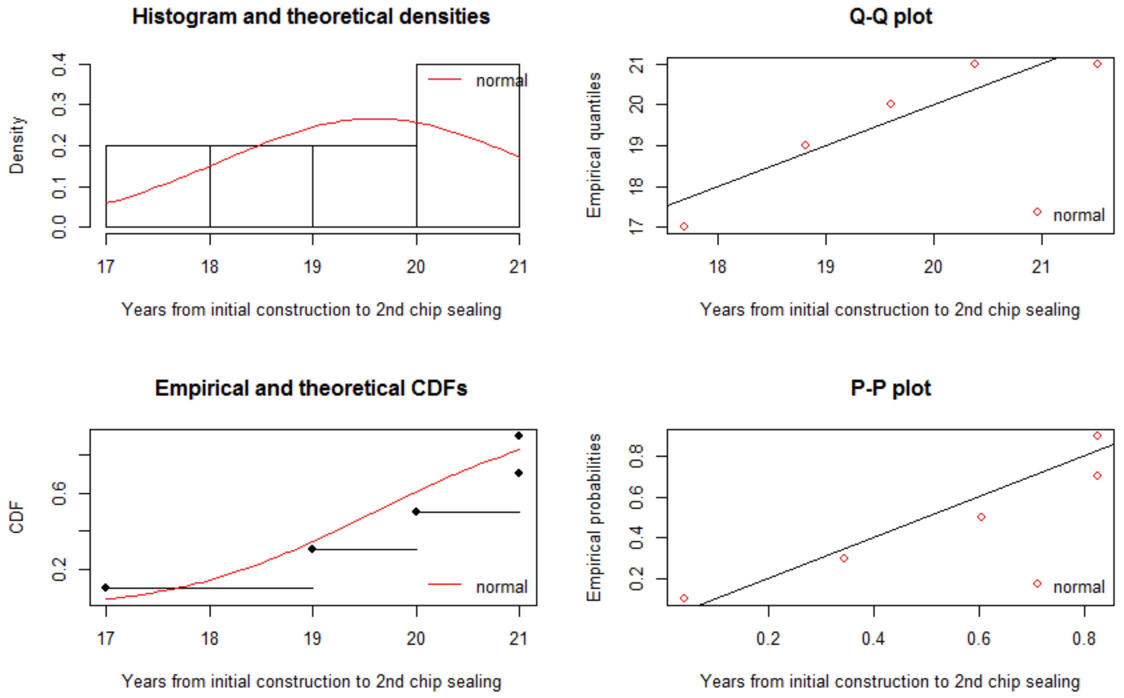


Figure A5. Goodness-of-fit plots for the timing of the second application of chip seal (Manitoba Infrastructure)

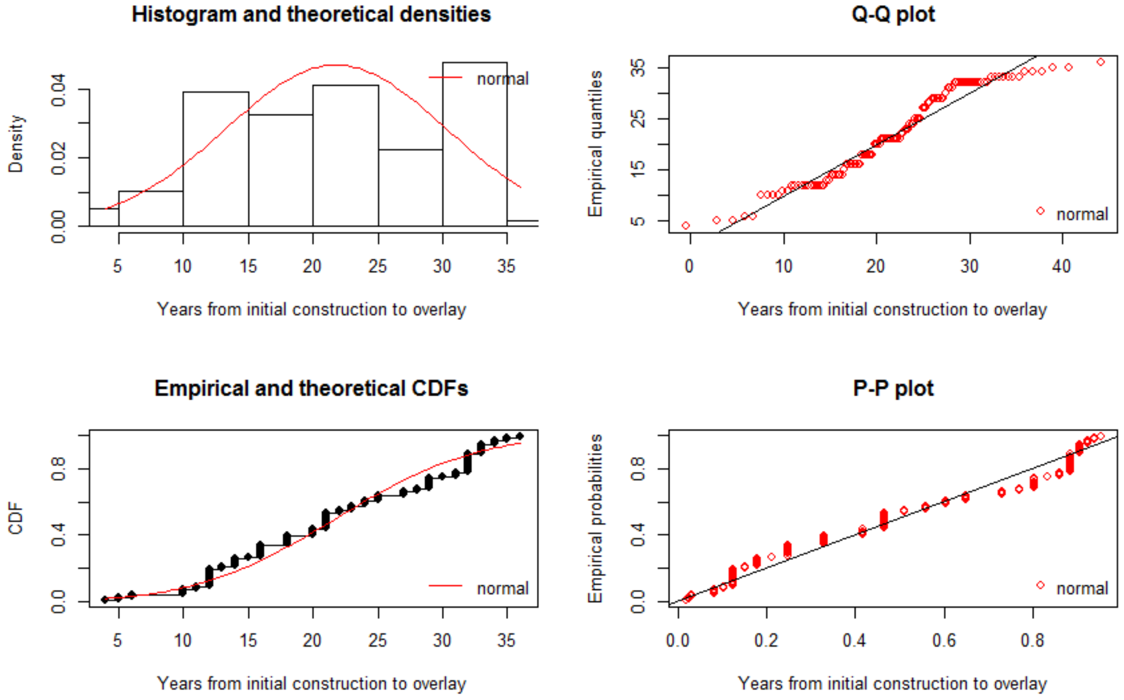


Figure A6. Goodness-of-fit plots for timing of the first bituminous overlay over asphalt pavement (Manitoba Infrastructure)

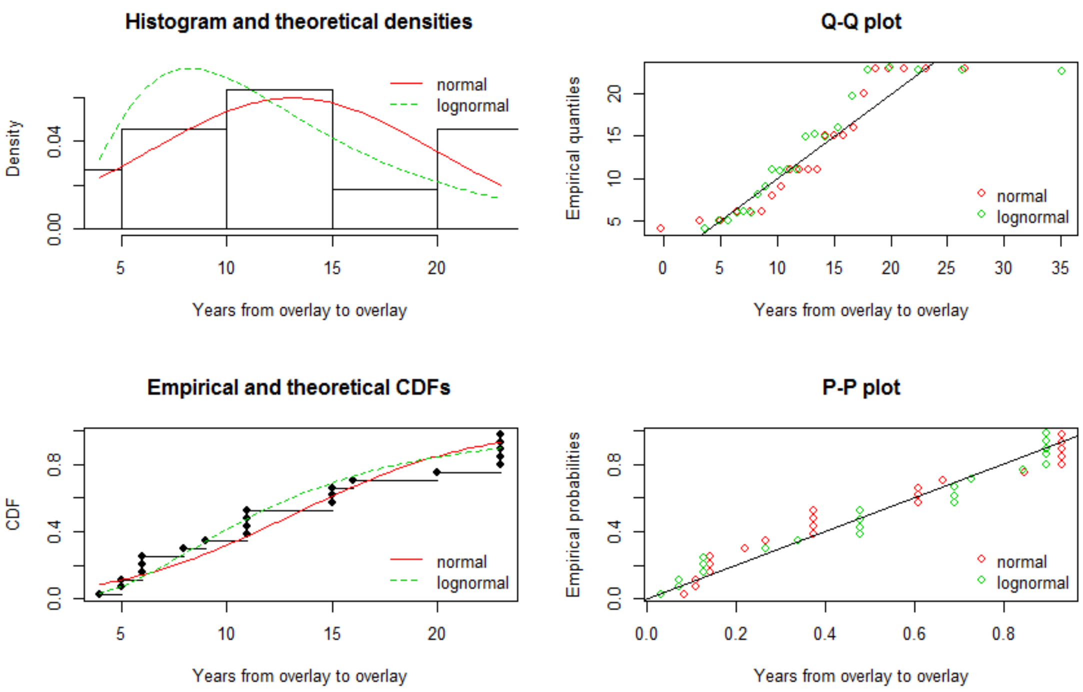


Figure A7. Goodness-of-fit plots for structural life of bituminous overlay over asphalt pavement (Manitoba Infrastructure)

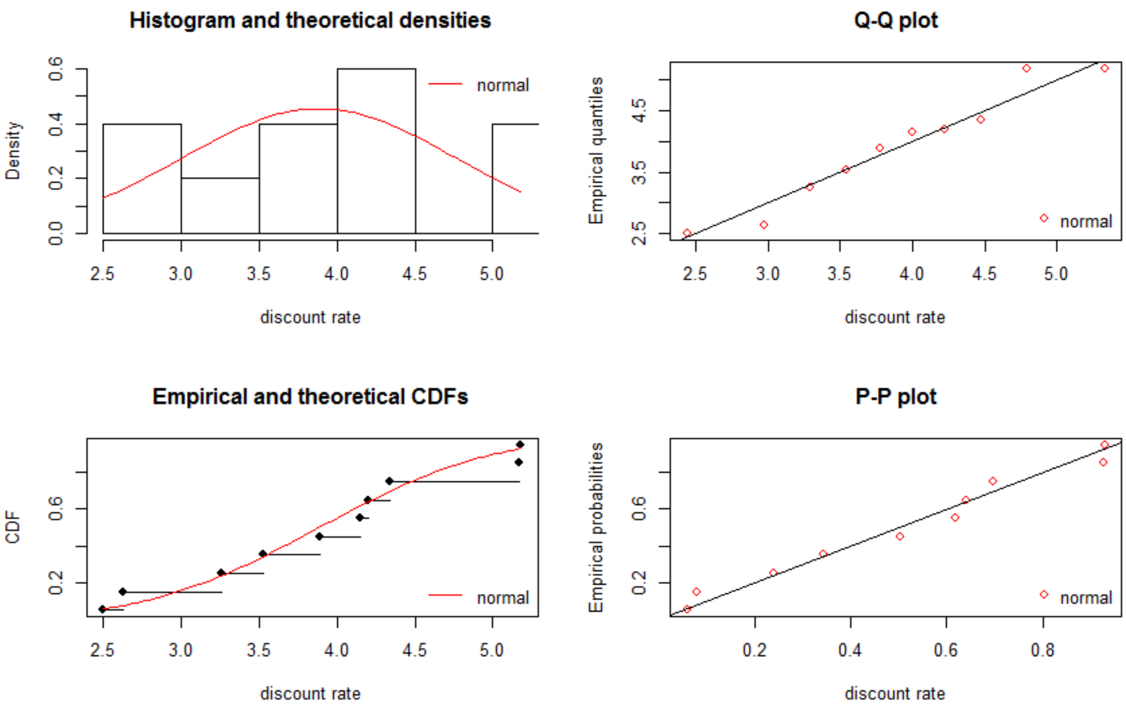


Figure A8. Goodness-of-fit plots for discount rate (City of Winnipeg)

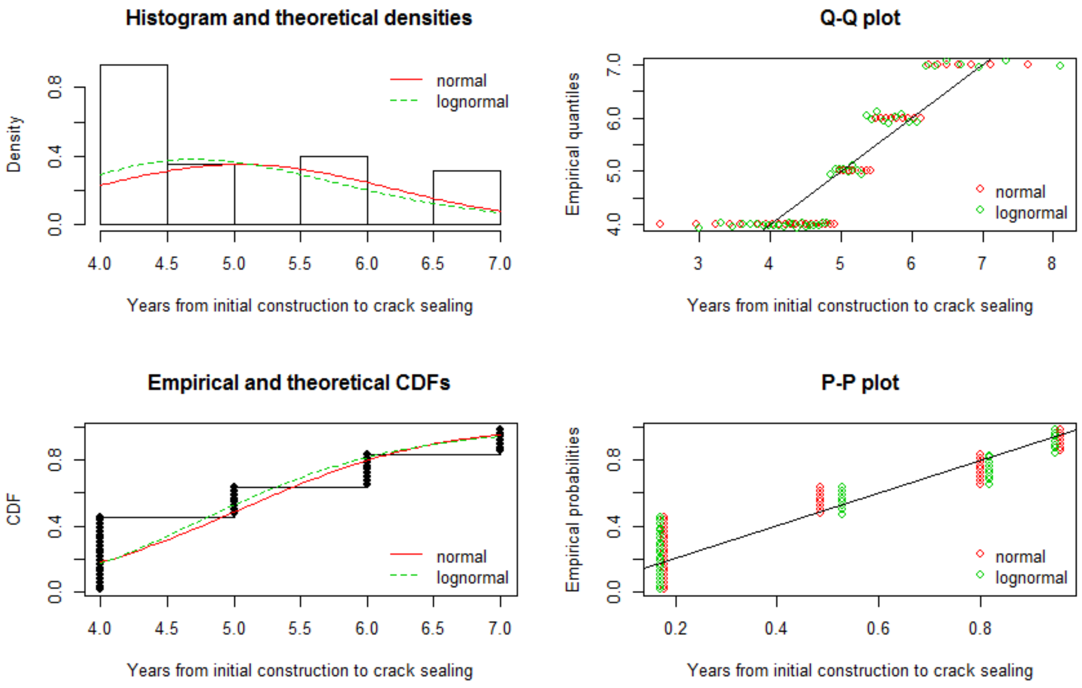


Figure A9. Goodness-of-fit plots for crack sealing timing (City of Winnipeg)

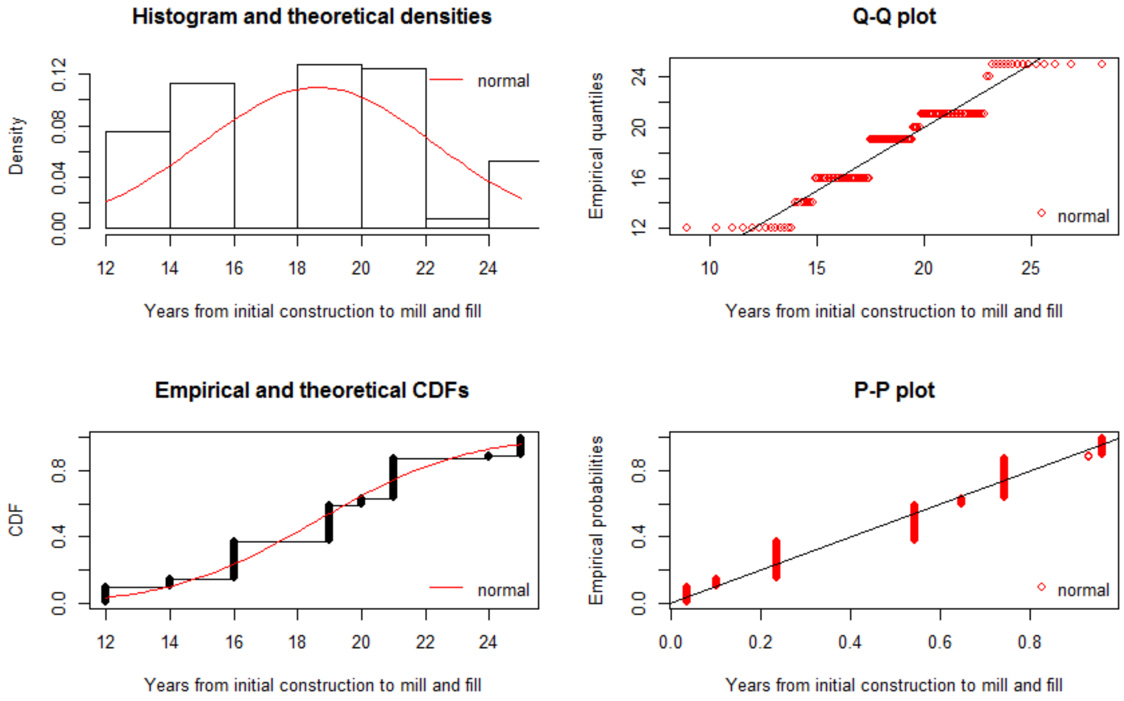


Figure A10. Goodness-of-fit plots for mill and fill timing (City of Winnipeg)

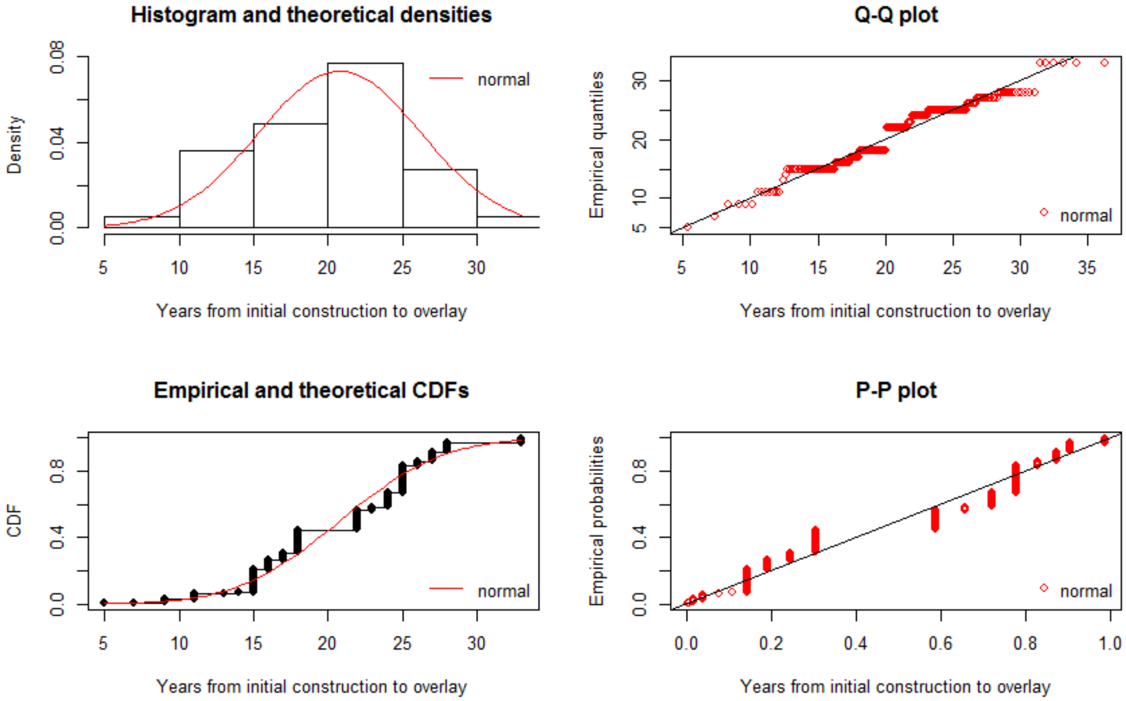
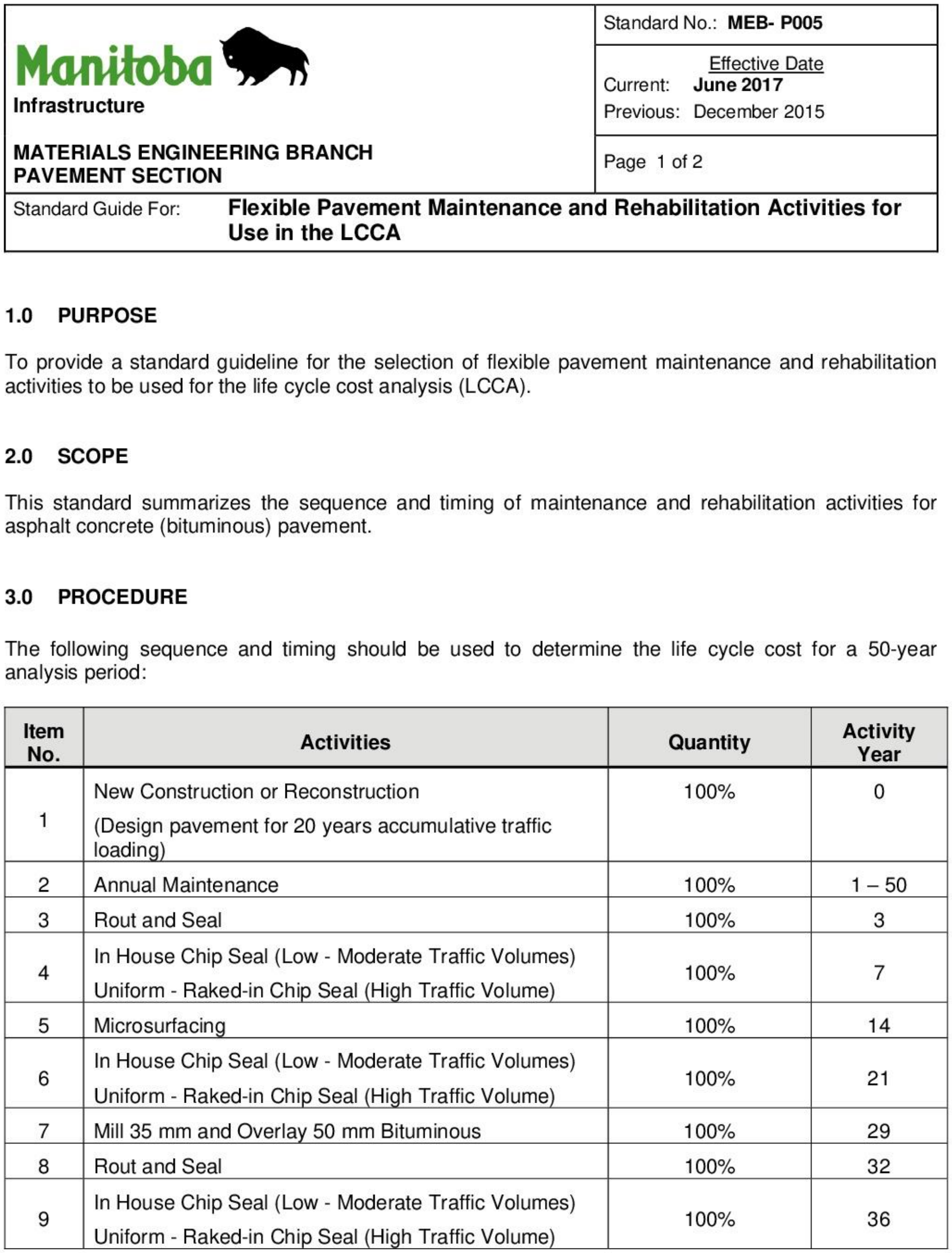


Figure A11. Goodness-of-fit plots for timing of the first bituminous overlay over concrete pavement (City of Winnipeg)

APPENDIX B. Manitoba Infrastructure LCCA Standards



Manitoba Infrastructure **MATERIALS ENGINEERING BRANCH** **PAVEMENT SECTION**	Standard No.: **MEB- P005** Effective Date Current: **June 2017** Previous: December 2015 Page 1 of 2
Standard Guide For:	**Flexible Pavement Maintenance and Rehabilitation Activities for Use in the LCCA**

1.0 PURPOSE

To provide a standard guideline for the selection of flexible pavement maintenance and rehabilitation activities to be used for the life cycle cost analysis (LCCA).

2.0 SCOPE

This standard summarizes the sequence and timing of maintenance and rehabilitation activities for asphalt concrete (bituminous) pavement.

3.0 PROCEDURE

The following sequence and timing should be used to determine the life cycle cost for a 50-year analysis period:

Item No.	Activities	Quantity	Activity Year
1	New Construction or Reconstruction (Design pavement for 20 years accumulative traffic loading)	100%	0
2	Annual Maintenance	100%	1 – 50
3	Rout and Seal	100%	3
4	In House Chip Seal (Low - Moderate Traffic Volumes) Uniform - Raked-in Chip Seal (High Traffic Volume)	100%	7
5	Microsurfacing	100%	14
6	In House Chip Seal (Low - Moderate Traffic Volumes) Uniform - Raked-in Chip Seal (High Traffic Volume)	100%	21
7	Mill 35 mm and Overlay 50 mm Bituminous	100%	29
8	Rout and Seal	100%	32
9	In House Chip Seal (Low - Moderate Traffic Volumes) Uniform - Raked-in Chip Seal (High Traffic Volume)	100%	36

10	Micro-surfacing (Non-expressways) Thin Lift Overlay (Expressways)	100%	43
11	Salvage Value: Micro-surfacing (Non-expressways) Salvage Value: Thin Lift Overlay (Expressways)	Nil (0) 3 Years of Service Life (43% of Items 10 Value)	50

Manitoba
Infrastructure and Transportation

MATERIALS ENGINEERING BRANCH
PAVEMENT SECTION

Standard No.: **MEB-P004**

Effective Date
Current: **December 2015**
Previous: September 2007 (MRB7-04)

Page 1 of 2

Standard Guide For: **Rigid Pavement Maintenance and Rehabilitation Activities for Use in the LCCA**

1.0 PURPOSE

To provide a standard guideline for the selection of rigid pavement maintenance and rehabilitation activities to be used for the life cycle cost analysis (LCCA).

2.0 SCOPE

This standard summarizes the sequence and timing of maintenance and rehabilitation activities for the jointed (dowelled) plain concrete pavement (JPCP).

3.0 PROCEDURE

The following sequence and timing should be used to determine the life cycle cost for a 50-year analysis period:

Item No.	Activities	Quantity	Activity Year
1	New Construction or Reconstruction (Design pavement for 20 years accumulative traffic loading)	100%	0
2	Concrete Partial Depth Repairs	2% Surface Area	15
3	Concrete Partial Depth Repairs	5% Surface Area	25
4	Concrete Full Depth Repairs	10% Surface Area	25
5	Diamond Grinding	100% Surface Area	25
6	Concrete Partial Depth Repairs	5% Surface Area	40
7	Concrete Full Depth Repairs	15% Surface Area	40
8	Diamond Grinding	100% Surface Area	40
9	Salvage Value	5 Years of Service Life (1/3 of Items 7 plus 8)	50

Manitoba Infrastructure and Transportation **MATERIALS ENGINEERING BRANCH** **PAVEMENT SECTION**	Standard No.: **MEB-P004** Effective Date Current: **December 2015** Previous: September 2007 (MRB7-04) Page 2 of 2
Standard Guide For:	**Rigid Pavement Maintenance and Rehabilitation Activities for Use in the LCCA**

Approved: _________Original signed by__________
S. Kass, P. Eng.
Director, Materials Engineering Branch

Manitoba
Infrastructure and Transportation

MATERIALS ENGINEERING BRANCH
PAVEMENT SECTION

Standard No.: **MEB-P006**

Effective Date
Current: **February 2016**
Previous: April 2007 (MRB7-06)

Page 1 of 2

Standard Guide For: **Selection of Pavement Type Based on Life Cycle Cost**

1.0 PURPOSE

To provide a standard approach for the selection of pavement structure type based on the life cycle costs of alternative options.

2.0 SCOPE

This standard outlines the procedures for the life cycle cost analysis (LCCA) and the strategy to select pavement structure type for new construction and reconstruction projects.

3.0 RELEVANT STANDARDS

MEB-P004: Rigid Pavement Maintenance and Rehabilitation Activities for Use in the LCCA

MEB-P005: Flexible Pavement Maintenance and Rehabilitation Activities for Use in the LCCA

4.0 PROCEDURE

4.1 The department has adopted the Real Cost software developed by the U.S. Federal Highway Administration (FHWA) and the present worth (PW) method for the calculation of life cycle costs. The PW of each activity is calculated using the following equation:

$$PW = \frac{F}{(1+i)^n} \quad (1)$$

Where,
F = activity cost per km
i = discount rate
n = year of activity application

4.2 Obtain the unit costs for different items from the respective region and estimate the per km initial construction cost for each alternative option.

4.3 Obtain the current unit costs of future maintenance and rehabilitation activities (see standards MEB-P004 and MEB-P005 for the list of activities), and estimate the per km costs for these activities.

4.4 Obtain the current discount rate from MIT's Financial Services.

4.5 Use standards MEB-P004 for the rigid pavement and MEB-P005 for the flexible pavement as guides to select the future maintenance and rehabilitation activities, and the sequence and timing (service life) of each activity. Modify the activity sequence and timing (service life) for special projects (e.g., major intersection or interchange and unconventional pavement structure), if required, in consultation with the Region, Managers and Directors.

4.6 Determine the salvage (residual) value of the final rehabilitation treatment at the end of the analysis period.

4.7 Convert the per km cost of each activity and the salvage (residual) value to present worth using Equation 1.

4.8 Determine the total life cycle cost per km for each alternative option for a 50-year analysis period using the deterministic approach in the Real Cost software.

4.9 Compare the total net present worth for all alternatives. The option with the lowest PW is the best from a life cycle cost standpoint and is usually selected for construction. See comments below for additional information and other consideration.

5.0 COMMENTS

User costs are difficult to quantify as no generally accepted model is available yet. Therefore, user costs are not included for the purposes of the life cycle cost analysis using this standard.

Although the life cycle economic analysis will provide a basis for decision making, several additional factors need to be considered together with life cycle costs for a rational decision making. These factors include, but are not limited to, geometrics, materials availability, budgets, maintenance levels, interruptions to travelers, route continuity, public perception, drainage, safety, climate, past experience with similar pavements and good engineering judgment.

Approved: Original signed by
S. Kass, P. Eng.
Director, Materials Engineering Branch