Pavement Management System Development for the P3 Concession of the South Fraser Perimeter Road

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1.0 INTRODUCTION

In recent years provincial and federal transportation agencies across Canada have turned to the Public-Private-Partnership (P3) procurement model to fund and deliver roadway corridor improvement projects. The P3 environment poses several differences to the more traditional Design-Bid-Build or Design Build project model. One of these changes is a fundamental shift towards a performance-based design approach. Another difference occurs following the completion of construction, where an asset must be operated for a fixed period to meet a prescribed set of performance requirements in each year of a pre-determined Concession Period. In many cases the Asset Preservation Performance Measures (APPMs) are more complex than typical highway agency performance thresholds. As a result, the development of Pavement Management Systems (PMS) for these projects is driven by achieving performance compliance at the lowest practicable cost. This approach varies from a traditional PMS where annual budgets are typically fixed, and the PMS program is adjusted to suit.

This paper presents an overview of a detailed pavement analysis and development of a PMS for the Concession of the 37 km South Fraser Perimeter Road (SFPR), located in the Greater Vancouver Area of British Columbia. Innovation in analysis tools and methodologies are presented, with focus on the development of performance prediction models necessary to establish the initial framework for a working PMS Database for the SFPR. This paper highlights a distribution-based roadway condition model, founded on the performance requirements presented in the project technical requirements.

In addition, this paper illustrates the development of a multi-strategy Life-Cycle Cost Analysis (LCCA) design approach, and outlines the framework used to develop the optimal Operation, Maintenance, and Rehabilitation (OM&R) program for the SFPR pavement infrastructure elements. This framework follows the general philosophy of providing the lowest present value cost OM&R program while maintaining compliance with the applicable project performance requirements.

2.0 BACKGROUND INFORMATION

2.1 Project Overview

The SFPR is predominantly a new route along the south side of the Fraser River, extending from Deltaport Way in Southwest Delta to the Fraser Heights Connector in North Surrey, in British Columbia, Canada. The SFPR project was procured by the BC Ministry of Transportation and Infrastructure (BCMoTI) as a P3 using a Design Build Finance and Operate (DBFO) model with a concession period of 20 years. The roadway in its entirety was opened to traffic in December 2013.

The SFPR alignment is approximately 40 km in length, and consists of four travel lanes (two lanes in either direction) providing connections to Highways 17, 91, and 99. The roadway itself has been constructed over a variety of unique geotechnical conditions which include highly compressible soils, old landfill sites, and areas of potentially weak/unstable soil conditions. The SFPR concession also includes a 2.0 km section of Fraser Heights Connector, which was constructed as part of the Port Mann Highway 1 Improvement Project (PMH1).

Roadway pavement elements included as part of the SFPR 20-year concession include 162 lane-km of mainline pavement, and 46 individual ramps with a total ramp length of 49 lane-km. The general roadway alignment and right-of-way is shown in Figure 1.

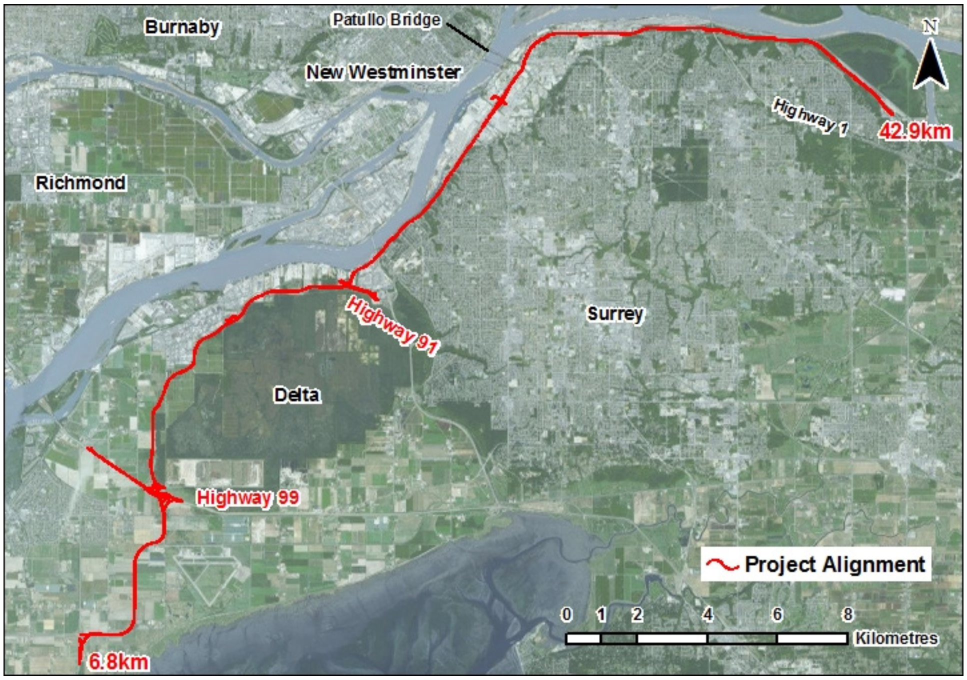

Figure 1: General Roadway Alignment

2.2 Basis for Performance-Based Design

The P3 project delivery model has introduced the concept of performance-based design. A performance-based design approach is founded on the principal where the design, construction, maintenance, and operation of an asset is completed to achieve a set of prescribed performance results. This is fundamentally different when compared to the traditional design approach which would specify a way and method to the design and construction process. In a performance-based approach, the focus of all decisions is on the level of service requirements and on the minimum required performance in use. This approach encourages the development of tools and methods that incorporate a whole life-cycle design and construction process, from the procurement and construction phases to the quantification and evaluation of results.

The four primary components to the performance-based design process are:

1. Identifying and formulating the relevant user requirements (i.e., roadway condition and smoothness);
2. Transforming the user requirements into performance requirements and measureable performance criteria;
3. The development of reliable design and evaluation tools that can measure whether potential design alternatives meet the stated criteria at a satisfactory level; and
4. Accurate and reliable evaluation of the completed infrastructure to verify compliance with the stated performance criteria.

2.3 Pavement Management for P3 Concessions

Once in operation, P3 Concession projects must be operated for a fixed period to meet a prescribed set of pavement performance requirements (maximum allowable IRI and Rut for example) at a pre-determined interval for the length of the Concession. In many cases these performance requirements are more stringent than typical highway agency performance thresholds. As a result, the development of PMS for these assets is driven by achieving performance compliance at the lowest possible cost.

As a result of this shift to a performance-based design, construction, maintenance, and operation model, a modified approach to the traditional PMS framework was required. Where the traditional PMS framework focused more on achieving an overall minimum pavement network condition for a set of budget constraints, P3 Concessions are focused more on achieving compliance with a number of pavement condition performance requirements at the minimum life-cycle cost.

An example of this modified framework is provided in Figure 2.

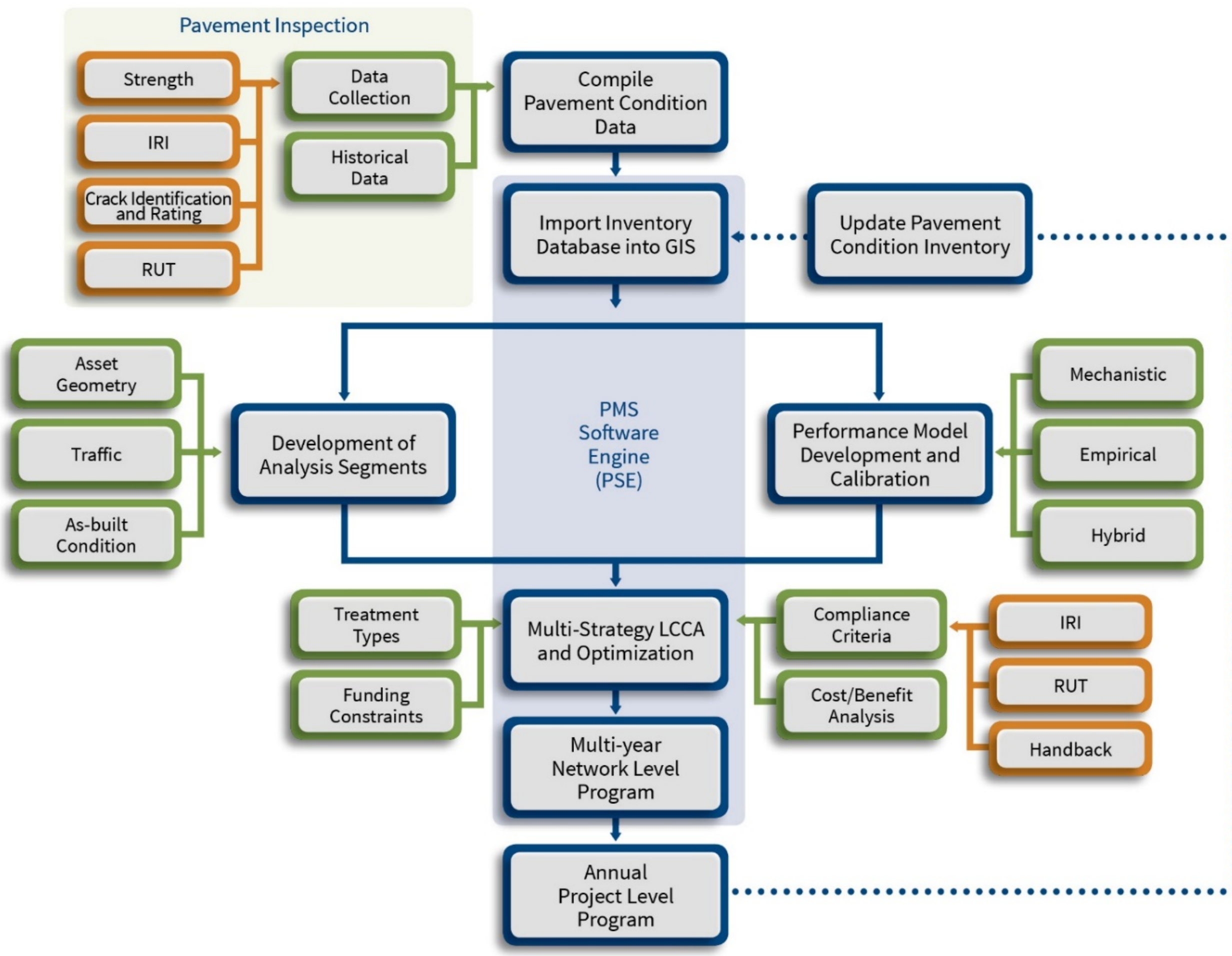

Figure 2: Framework for Pavement Management Systems Services

The framework provided in Figure 2 is founded on what are defined as Level 1 inputs, represented by the blue boxes. These Level 1 inputs are the essential components to the PMS. Level 1 inputs start with building the pavement condition and inventory database. This database is then used to develop pavement analysis segments, or sections of the roadway with similar physical (i.e., structure, subgrade, strength) and performance (traffic, design speed, etc.) characteristics. In parallel to the development of pavement analysis segments, a performance-based pavement condition model is developed. The accuracy of this model, or the ability for it to predict future pavement condition (IRI or Rut for example), is contingent on its calibration for local conditions (environment).

The pavement analysis segments and performance-based pavement condition model are programmed in the PMS Software and analyzed with Tetra Tech's Multi-Strategy Life-Cycle Cost Analysis (LCCA) and Optimization engine. This multi-strategy LCCA process is what allows the PMS to identify the optimum combination of strategies (future maintenance and rehabilitation works) achieving the lowest Present Value Cost. The output from this process is a multi-year maintenance and rehabilitation program, which can be used for network level planning and establishing a capital expenditure profile for the remainder of the Concession. In addition, this network level program can be drilled into and used to develop annual project level programs that ultimately translate into actual maintenance and rehabilitation works.

These Level 1 inputs are supported by Level 2 inputs (green boxes). These Level 2 inputs feed into the central PMS framework, and support the PMS and LCCA. For example, the development of analysis segments is supported by inputs relating to pavement structure, traffic, and as-built condition. The Performance model is supported by the performance model type. Inputs supporting the multi-strategy LCCA are the most complex and important to the PMS. They include inputs like treatment types and cost, and funding constraints, how to measure and assess the Cost/Benefit ratio of the program, and triggers based on the project-specific compliance criteria.

Level 2 inputs are further supported by Level 3 inputs (orange boxes). These inputs include the Pavement Inspection information and specifics on how to measure and quantify which compliance criteria are more influential to the model and resultant maintenance and rehabilitation program.

3.0 PROJECT PERFORMANCE REQUIREMENTS

3.1 Performance Requirements Overview

Throughout the 20-year operation term, the Fraser Transportation Group (FTG) is responsible for the OM&R of the numerous Highway Running Surfaces in such a manner as to maintain compliance with the requirements outlined in the Project Agreement (PA). Specific to this project, roadway pavement performance requirements are categorized as follows:

1. Specifications for Asset Preservation; and
2. Specifications for End of Term, or Hand-back.

These performance measures define minimum asset preservation criteria for specific Highway Running Surfaces to maintain a minimum level of service and to limit the extent of asset consumption.

Asset preservation Key Performance Measures (KPMs) for different Highway Running Surfaces have been identified and defined in the PA. KPMs provide the ability to monitor high level trends in pavement condition and performance over time, and provide a measure of overall roadway condition. KPM reporting format for the OM&R of the SFPR include the following:

1. Roughness;
2. Rutting;
3. Pavement Surface Deterioration (expressed as Pavement Distress Index, or PDI); and
4. Roadway Cross-fall.

Within each KPM there is a specified performance criteria, defined as Asset Preservation Performance Measures (APPMs). These APPMs define the specific criteria or condition that each KPM must be maintained, for example the minimum IRI condition to which the Highway Running Surfaces must be maintained.

In addition to the KPM and APPM performance requirements, the PA also specifies minimum End of Term Requirements, expressed as Remaining Service Life (RSL). For this project, RSL is defined as the minimum required service life, expressed in years, of each Highway Running Surface at End of Term. The RSL is determined from the age and type of the last pavement intervention type, as well as the surface condition of the Highway Running Surface at Hand-back.

The project is segmented by Highway Running Surface Type including, Mainline, Cross Roads, and Ramps for example. Each Highway Running Surface Type has its own unique set of KPMs and APPMs.

While there is a complex and diverse set of prescribed KPMs, APPMs, and End of Term requirements for this OM&R of the SFPR, for simplicity this paper focuses on the Mainline International Roughness Index (IRI) KPMs and APPMs performance requirement, the IRI condition forecasting model development, and its interface with the PMS.

3.2 Introduction to Cumulative Distributions

Unique to the SFPR (and potentially a small number of other P3 projects in BC), APPMs limits are expressed in the form of a Cumulative Distribution Function (CDF). The CDF $F(x)$ for a variable X is the probability that X has a value less than or equal to x. A CDF is the integral of the density function, and is bounded between 0 and 1 and is non-decreasing with x. The median is where $F(x) = 0.5$. The mean is the point where the graph of the distribution would have the same area on both sides if it were cut in half vertically.

The PA IRI requirements specify that the CDF of all 50 m average IRI segments must be better than a set 18-point distribution. Figure 3 demonstrates the CDF for the Average IRI over 50 km segments. Following the dotted line, it is noted that 71% of the 50 km segments must have an average IRI of less than 1.6 m/km.

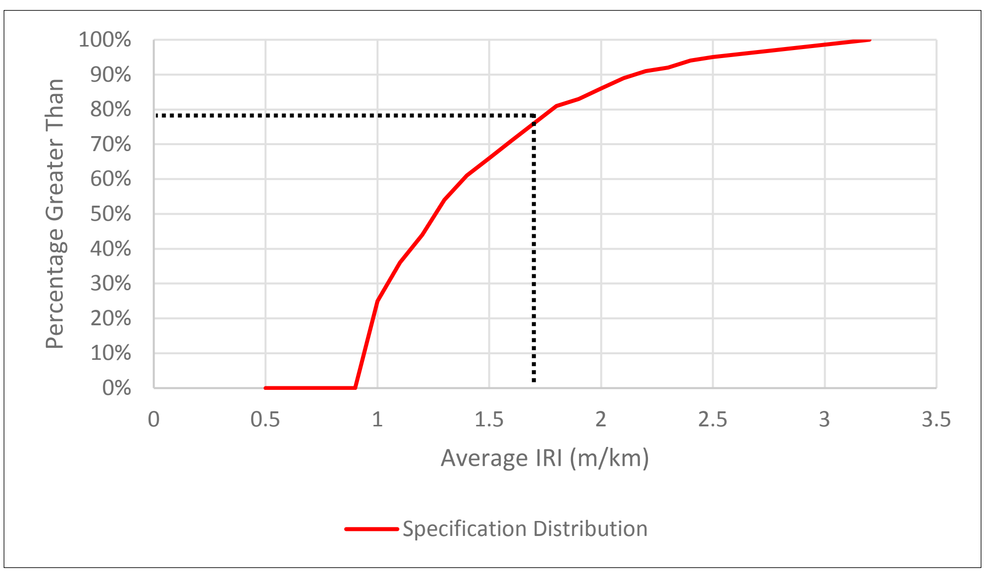

Figure 3: Mainline 50 m Average Pavement IRI 18-point Cumulative Distribution Specification

The road therefore must be maintained such that the CDF plot for the road is above the CDF plot in the specification. Figure 4 below shows an example of a compliant and a non-compliant IRI distribution.

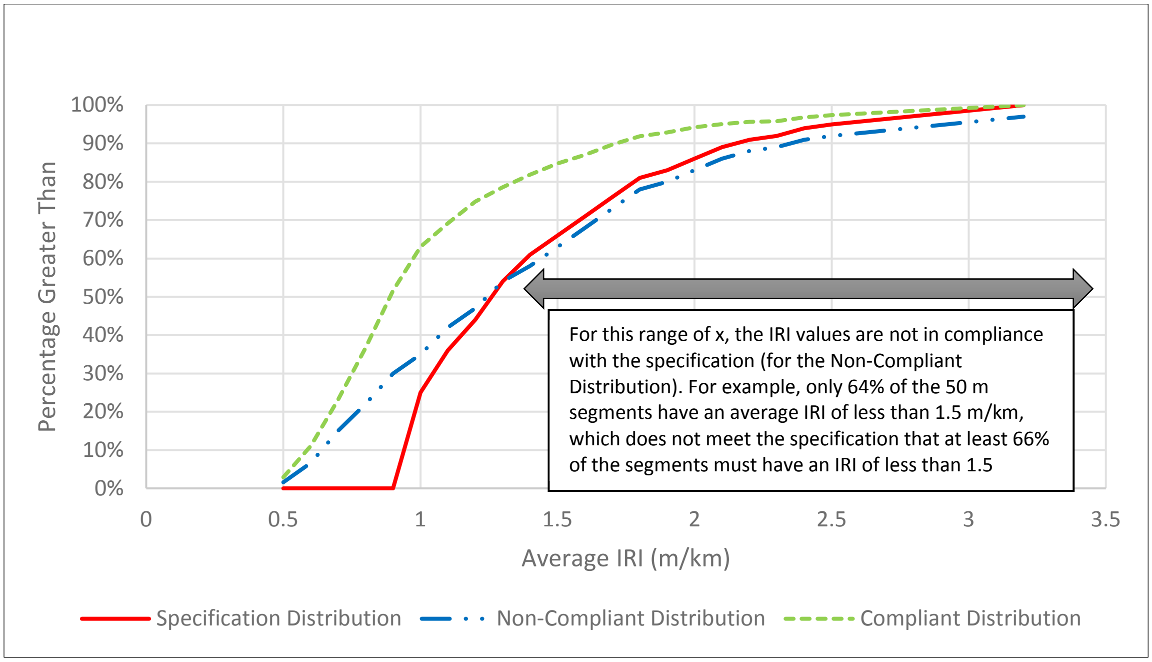

Figure 4: Example 50 m Average Pavement IRI Cumulative Distributions for Compliant and Non-Compliant Pavement Infrastructure

For the purpose of demonstrating the overall complexity of the SFPR project, imagine now that there is a similar CDF for each KPM (IRI, Rut, PDI, etc.) for each Highway Running Surface included in the OM&R of the project. In total, over 16 unique CDFs must be met for OM&R compliance for the SFPR project.

The CDF performance model introduced significant challenges in terms of its integration with the PMS. For example, APPMs for other P3 projects are much simpler, where there is only a maximum IRI value that should not be exceeded (e.g., 2.5 m/km for 1.0 km averages, or 3.2 m/km for 100 m averages). Those simplified performance models require only a single calibrated IRI progression and forecast model for each Analysis Segment (roadway section with similar physical and performance characteristics).

For the SFPR, the process is far more complex. Within each Analysis Segment a full distribution of average 50 m IRI values must be forecasted and evaluated for compliance against the 18-point compliance CDF. This additional complexity led to two key challenges for the development of the PMS of the SFPR:

1. Is it practical (or even possible) to develop a performance model that predicts the CDF for each APPM?
2. If it is proven practical, how can this model be programmed into the PMS for the purpose of developing the lowest NPV OM&R program?

The following sections of this paper provide detail on how the CDF IRI performance was modelled and integrated with the project PMS.

4.0 OBJECTIVES OF THIS ASSIGNMENT

It was determined through discussions with FTG that the objective of the PMS was to develop an OM&R program founded on achieving the lowest overall net present value (NPV) while meeting the performance and hand-back criteria. In order to meet this objective, two key challenges needed to be addressed:

1. A method for determining the annual IRI CDF in each OM&R year needed to be developed; and

2. A method for optimizing the timing and time of pavement rehabilitation/restoration interventions for the purpose of achieving low NPV needed to be developed.

In support of the performance model and PMS development, three roadway condition data sets were made available for this assignment: a base-line condition dataset collected just after substantial completion in January 2014, a second dataset collected in January 2015, and a third dataset collected in September 2015.

5.0 PERFORMANCE MODEL DEVELOPMENT

5.1 Selection of a Performance Model Framework

It is recognized that there are a number of industry recognized pavement distress models capable of predicting future roadway pavement condition. Nearly all of the most common types of distress prediction models are founded on either deterministic or probabilistic principles.

Deterministic models can be used to predict the condition of individual components of infrastructure, for example the amount of cracking on each individual segment of a pavement network. With this level of detail pertaining to the specific roadway condition, the associated treatments and costs for each Analysis Segment can be determined and their costs added up to determine total investment needs.

Probabilistic models are generally used for high level infrastructure asset management plans and can predict that a certain percentage of pavements will warrant each type of treatment. However, with a probabilistic model, the specific component of infrastructure predicted to require treatment will not generally be known. This is a limiting factor when the objective is to develop a plan to rehabilitate specific portions of infrastructure.

After much consideration and research, it was determined that the Highway Development and Management 4 (HDM-4) pavement performance model framework was the most suitable for this project. The HDM-4 framework was developed by the World Bank as a way for quantifying vehicle operating costs in order to justify investment in road improvement projects in developing countries.

The HDM models are deterministic and incremental, meaning that they predict the condition in each subsequent year based on the condition in the previous year, as shown in Equation 1:

$$[Condition]_b = [Condition]_a + \Delta[Condition] \qquad \text{Equation 1}$$

Where $\mathbf{[\mathit{Condition}]_a}$ is the condition in the current analysis year and $\mathbf{[\mathit{Condition}]_b}$ is the predicted condition for the next analysis year.

The initial condition for each portion of an asset can be measured and used to predict the condition in any subsequent year. The ability to predict the condition in any year, and select appropriate treatments for each section, allows for program optimization though multi-strategy LCCA-based asset management. For example, the application of a low-cost treatment early in the asset's life can be compared to the application of more robust and costly treatments later in the asset's life.

The HDM-4 models were developed using a structured empirical approach. The functional form and primary variables affecting deterioration were identified and then the impact of the variables was quantified with various statistical techniques. This had the advantage that the resulting models combined both the theoretical and experimental base mechanistic models with behaviour observed in empirical studies. The general framework used in developing the IRI performance model is shown in Figure 5.

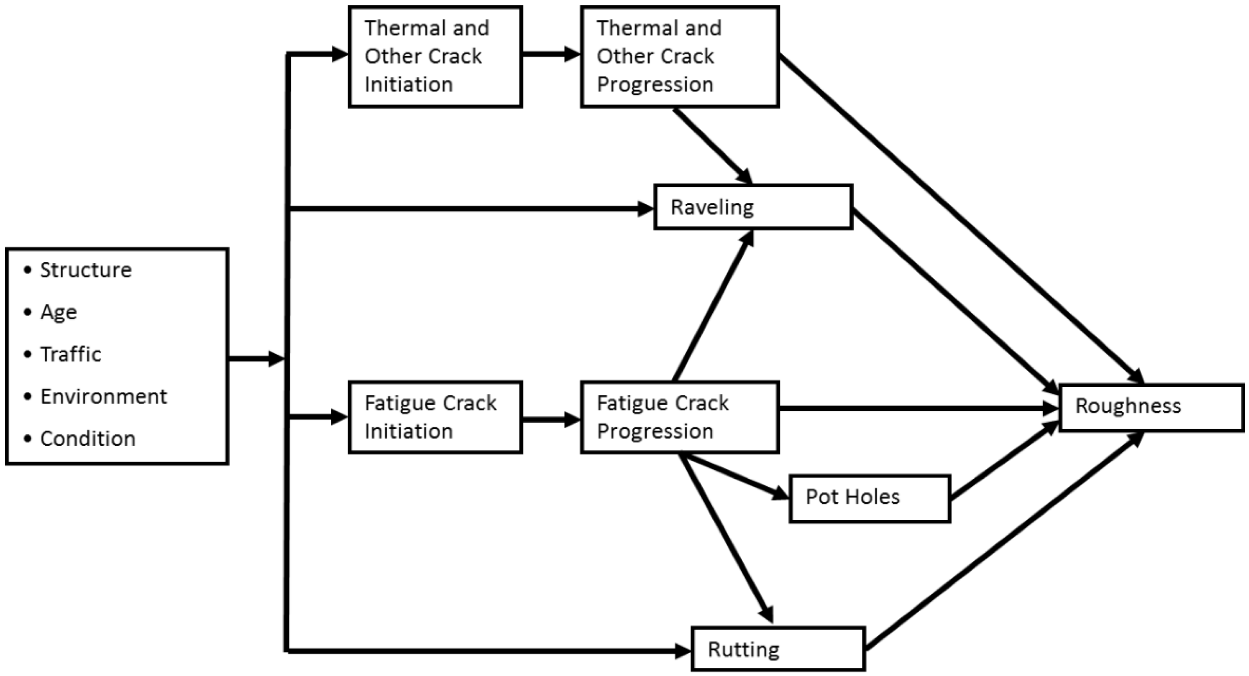

Figure 5: Modelling Pavement Performance

As shown in Figure 5, future roughness condition is a function of many inputs and parameters. First, existing roadway condition data including pavement structure/strength, pavement type, pavement age, pavement surface condition (i.e., distress), traffic loading condition, and environmental effects are compiled and used to develop a unique set of pavement Analysis Segments. Each Analysis Segment represents a length of homogenous roadway pavement expected to perform similarly from year to year. For the 148 lane-km of mainline pavement, 84 pavement Analysis Segments were developed for the PMS ranging in length from several hundred metres to several kilometers.

For each Analysis Segment, the HDM-4 model framework predicts a variety of unique pavement surface distress types ranging from fatigue cracking and thermal cracking to rutting. These pavement surface distresses are weighted and then combined to provide an overall pavement roughness condition or IRI in each future OM&R year.

5.2 Probabilistic Model Development

It is important to recognize that the IRI condition within each Analysis Segment is represented by many 50 m long data reporting sections, each of which is represented by an average IRI condition. The range of 50 m average IRI values together comprise the IRI CDF for that segment. A graphical example of this is shown in Figure 6 which represents an Analysis Segment of approximately 2.85 km in length and includes approximately 57 individual 50 m average IRI reporting sections.

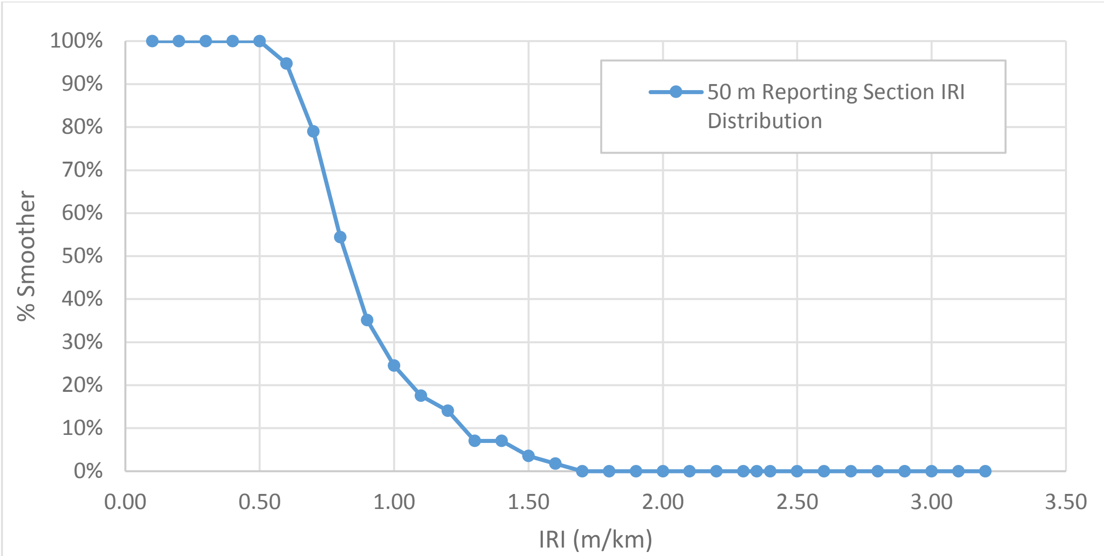

Figure 6: Example of 50 m Roughness Distribution for One Segment

There is a unique IRI distribution curve similar to that shown in Figure 6 for each of the 57 pavement Analysis Segments.

As the APPMs are defined in terms of CDFs for mainline IRI condition, it is necessary to predict an expected cumulative distribution for each Analysis Segment in each OM&R year. It was observed that the distributions of 50 m sections within each Analysis Segment typically follow a sigmoid or "S" shape. This type of curve generally correlates to a Gompertz continuous probability distribution. The Gompertz Distribution is often used for analysis of survival, where survival in this case represents the percentage of roadway with less rutting or less roughness than specified.

The equation of the Gompertz Distribution is shown as Equation 2:

$$Proportion\ Smoother\ than\ IRI\ x = 1 - e^{-e^{-(b-cx)}} \qquad \text{Equation 2}$$

Where 'e' is the base of the natural logarithm (2.71828…) and b and c are parameters that scale and shape the Gompertz Distribution. For each pavement management segment, the parameters b and c are unique and determined by best-fit to the actual CDF (minimum error between fit curve and data). An example of a best-fit curve is shown in Figure 7, where the 2015 roadway condition data are plotted with the Gompertz best-fit distribution.

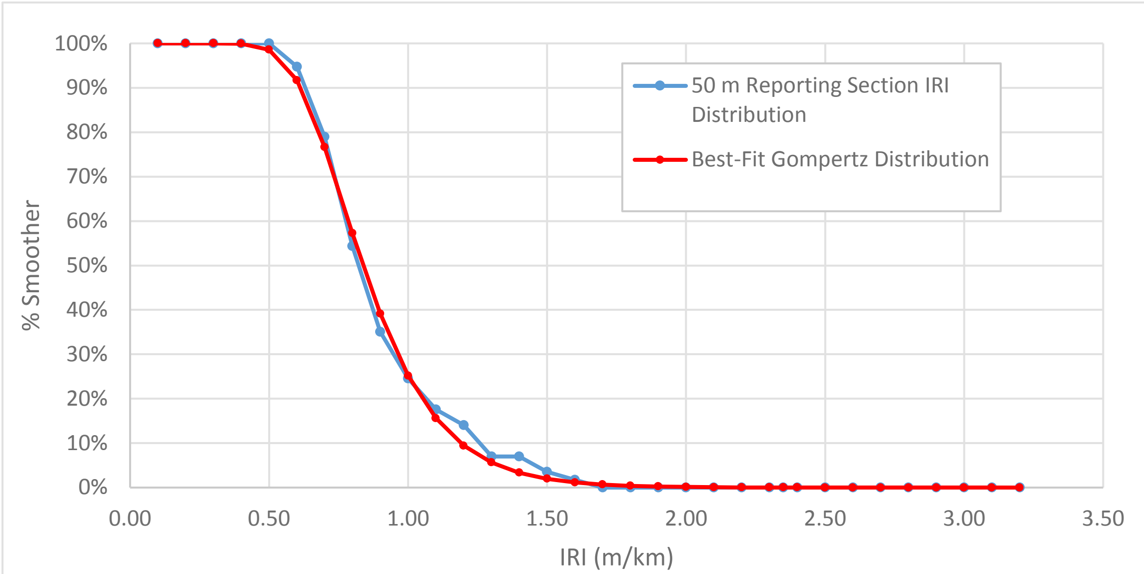

Figure 7: Example of a Gompertz Distribution Best-fit for One Segment

In order to model the cumulative distribution for future OM&R years, it is then necessary to estimate how the parameters b and c from Equation 2 are influenced as the asset ages. Further analysis and observation shows that the Gompertz parameter c is a function of the standard deviation of all the average 50 m IRI reporting segments. An example of this correlation for IRI is shown in Figure 8.

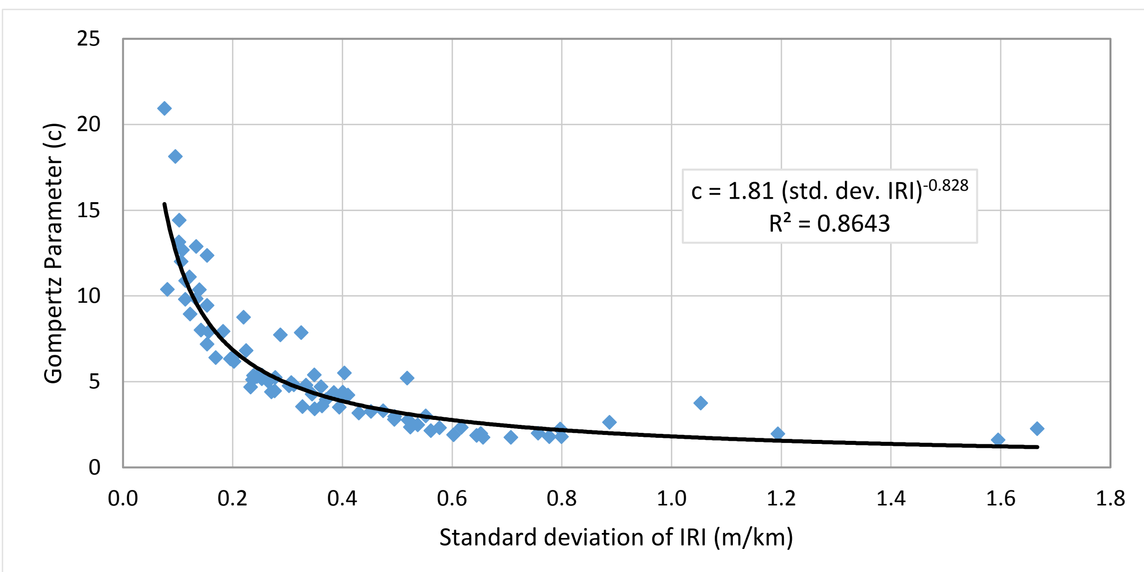

Figure 8: Relationship between Gompertz Parameter c and Standard Deviation of IRI

In addition, the relationship between Gompertz parameters b and c control the scale of the distribution. It was observed that parameter b divided by parameter c (b/c) is a function of the average of all the 50 m IRI reporting segments. An example of this relationship for the IRI KPM is shown in Figure 9.

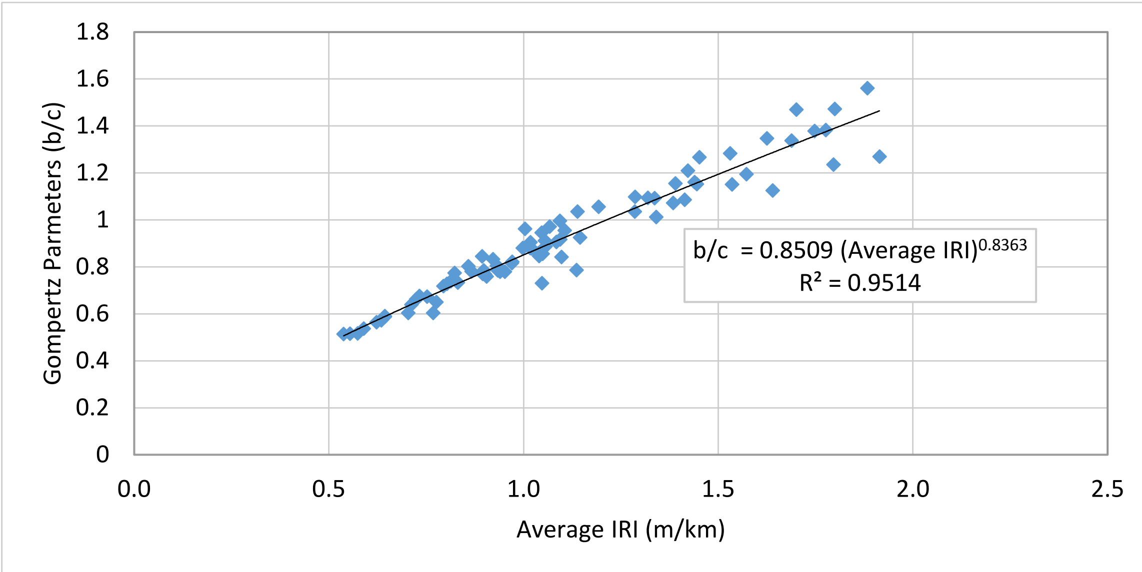

Figure 9: Relationship between Gompertz Parameters b and c and Average IRI

Once the relationship between Gompertz parameters b/c is known, b can be determined from the previously determined value for c (Figure 8).

In conclusion, it was determined that the percentage smoother than (or IRI less than) a given value can be determined as long as the average and standard deviation IRI is known. Based on this procedure, a unique set of Gompertz parameters (and therefore CDF) could be determined from the average and standard deviation of the 50 m reporting segments for each of the 57 Analysis segments.

The distribution of each Analysis Segment was then weighted by length to estimate the CDF for the entire length of the mainline pavements, the condition upon which the KPM is evaluated. This step was important in determining if a composite CDF could be determined from the aggregated distributions of each Analysis Segment.

5.3 Forecasting Future Condition

As discussed in the previous section of this paper, the ability to predict the future IRI condition distributions is contingent on the ability to model the average and standard deviation of the 50 m reporting segments in each Analysis Segment.

As the HDM-4 models do not specifically include the forecasting of the standard deviation of IRI, a base-line standard deviation increase was determined from the 2014 and 2015 roadway condition datasets. Comparing the 2014 and 2015 datasets, it was determined that the standard deviation of IRI increased by about 4.3% during that time period. This value was therefore assumed to be the annual increase in standard deviation, however it will require confirmation and calibration as future data sets are obtained.

An example of the IRI and standard deviation of IRI progression for the remainder of the OM&R period (for a "do-nothing" condition) is provided in Figure 10.

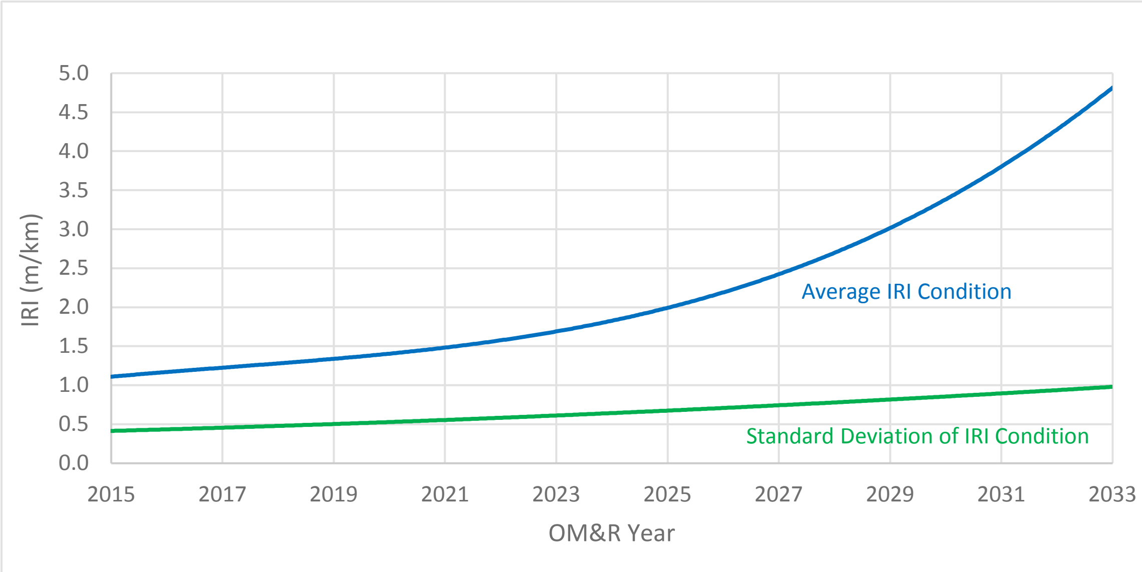

Figure 10: Increase in Average IRI and Standard Deviation of IRI in Each OM&R Year

Having established an IRI progression model predicting annual average IRI and annual standard deviation of average IRI, a Gompertz Distribution for cumulative IRI could then be forecasted for each specified roughness interval. However, it would be arduous to model each of the 18 specified points of the cumulative distribution, for each of the remaining 19 years. This would require 342 condition limits just for IRI (18 limits multiplied by 19 years). Therefore, for modelling purposes, the distribution has been simplified to five points as shown in Figure 11. The five points along the CDF provide a good fit to the complete Gompertz best-fit distribution.

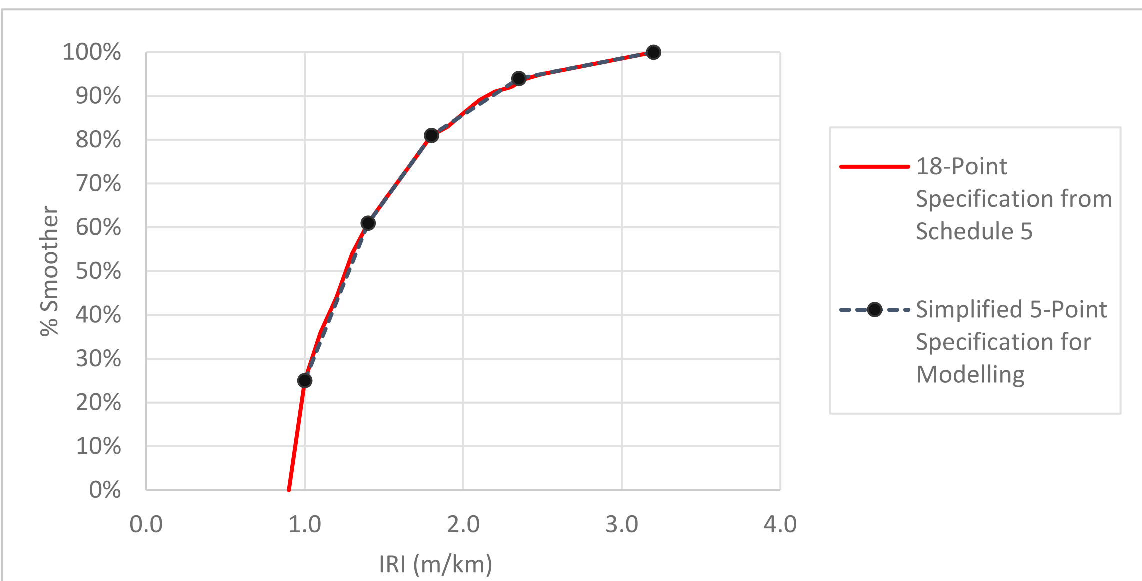

Figure 11: Schedule 5 and Simplified Specification for Roughness (smoothness)

Having simplified the model to a manageable criteria, the IRI distribution could now be projected for future years with the Gompertz parameters determined from the average IRI and standard deviation of

IRI. The resulting forecast distribution of roughness is shown in Figure 12 as a weighted average across all 84 Analysis Segments.

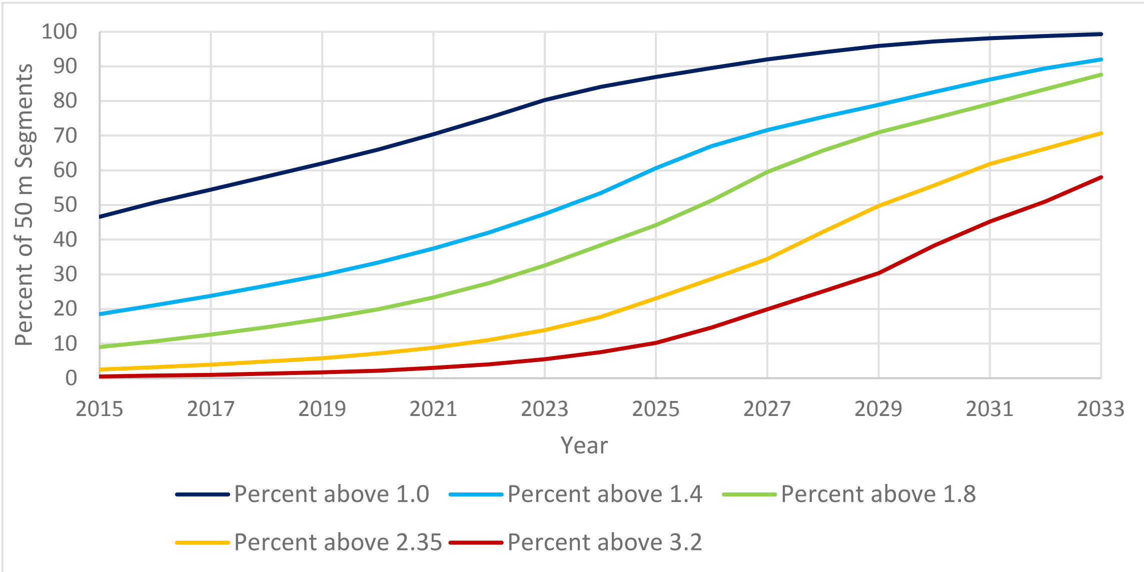

Figure 12: Projection of Roughness Distribution for the Simplified Specification for the "Do-Nothing" Condition

Further examination of Figure 12 shows that if you were to place a vertical line at any OM&R year, and plotted the Percent of 50 m Segments against the five IRI roughness models, you would obtain an annual IRI distribution curve similar to that in Figure 11. A unique set of these curves exists for each analysis segment.

5.4 IRI Model Calibration

The general calibration process of the regional HDM-4 models follows the HDM-4 Volume 5, Level 2 methodology (Bennett and Paterson, 2000). Level 2 calibration uses direct measurements of local conditions to verify and adjust the local prediction capability of the model. Calibration concentrates on the initiation of surface distress modes, rutting and roughness projection, maintenance impacts, and the consequences of environmental impacts (namely climate and local or project-specific geotechnical conditions).

Calibration was completed using the three sets of roadway pavement condition data collected in January 2014, January 2015, and September 2015. A base-line condition was extracted from the January 2014 dataset and used to forecast the January 2015 and September 2015 condition. The models were then calibrated so that the September 2015 forecasted IRI condition matched the measured September 2015 IRI condition.

There were a number of unique conditions that needed to be considered when competing the calibration. The first was the inclusion of several lane-km of open-graded friction course along the project length. This asphalt concrete mix type notably had a different deterioration model than areas surfaced with a more conventional mix type. Another consideration addressed specific areas of sensitive geotechnical conditions, such as light-weight fills or other ground improvement types. These area also had notably different deterioration model characteristics than areas constructed in more "typical" geotechnical conditions.

6.0 MULTI-STRATEGY LIFE-CYCLE COST ANALYSIS AND OPTIMIZATION

6.1 Introduction of Multi-Strategy LCCA

As noted previously, the objective of this assignment was to provide an OM&R program based on achieving the lowest NPV solution. The selection of the lowest NPV cost strategy to meet the specified criteria however, is a complex optimization problem. There are two primary causes of the complexity:

- It is not immediately apparent which of the specified pavement performance criteria will govern in each year; and
- A treatment triggered to resolve a certain specified exceedance (e.g., too much roughness above 1.4 m/km), will have a consequential effect on other criteria. That is, this same treatment, applied across the full lane width, would also improve roughness at other levels (percent rougher than 1.0 m/km, 1.8 m/km, etc.), improve rutting, improve the PDI, and extend the remaining life.

To resolve these issues, a multi-strategy LCCA approach was taken where a set of pre-determined intervention treatments are triggered (or applied) to a range of Analysis Segments in each OM&R year as they may be required for that section (because the maximum IRI of 3.2 m/km is exceeded or the maximum rut of 10 mm is exceeded). Each intervention treatment provides some benefit towards meeting the overall distribution for each KPM for the project. A strategy is defined as the combination of treatments that could be applied to any Analysis Section of roadway. Examples of this concept are shown in Figure 13.

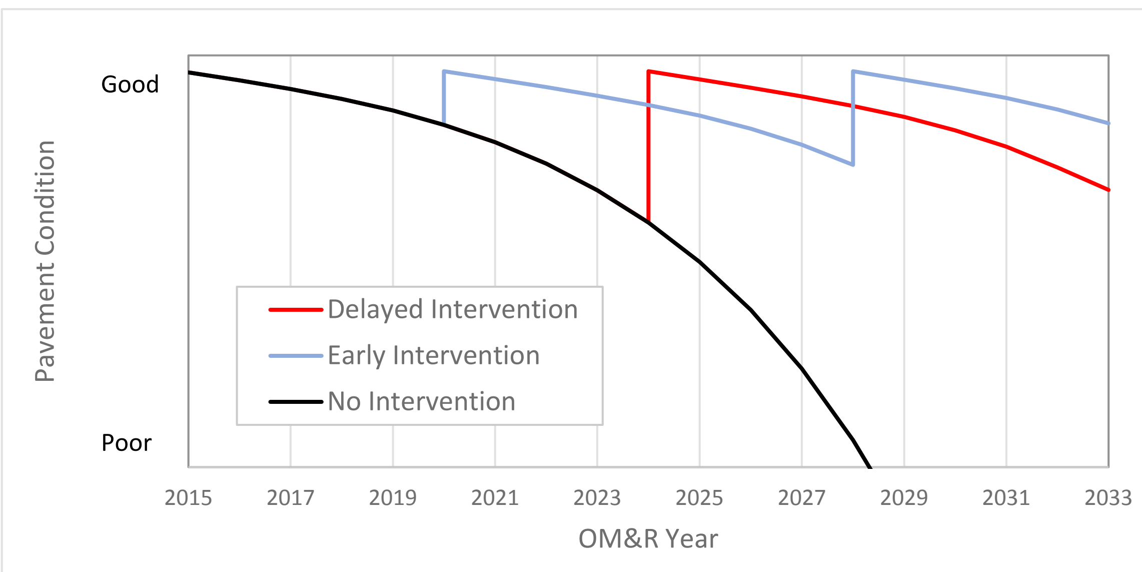

Figure 13: Examples of Strategies

In practice, many more strategies exist; the first intervention could vary by several years, and the subsequent intervention could also vary by several years for each possible first intervention. This creates many combinations of feasible strategies, each with unique cost, and unique benefit. The cost of each strategy is simply the cumulative costs of all predicted OM&R activities, discounted to present day dollars, and represented in terms of NPV. The benefit is measured in terms of meeting the condition limits for the section (IRI and rut maximums), and a contribution towards meeting the overall specified distributions (for example, having enough roadway with IRI less than 1.4 m/km to be compliant).

To account for the hundreds (or even thousands) of potential OM&R strategies generated to find the lowest compliant NPV cost strategy, Tetra Tech used an automated multi-strategy generation process. This process is completed by defining a set of business rules under which a strategy can be triggered, its associated costs and the resultant conditions.

These business rules are required to automate the development of the many LCCA alternatives, and include the following parametric data: Analysis Constraints, Treatments and Costs, Condition Triggers, Condition Resets, and Discount Rate.

A brief description of each of the parametric data is provided in the following sections.

6.2 Multi-strategy LCCA Parametric Inputs

Analysis Constraints

The analysis constraints are integral to the LCCA. They define the boundary conditions for the analysis. Analysis constraints are parameters such as:

- How long the analysis will go into the future (the analysis period for SFPR is 19 years), a 20-year OM&R period that has 19 years remaining;
- Pavement Analysis Segments included;
- Treatments to be included (i.e., structural overlays, mill and inlays, localized treatments, etc.);
- KPM to be modelled (IRI, rutting, cracking, PDI, RSL); and
- A method to measure benefits. In this case, the benefit is defined as meeting all of the performance criteria in each concession year while spending as little as possible. The benefit's value was calculated as an inverse of the cost; $1000 times the segment length minus the PV cost. The strategy for a given Analysis Segment with the maximum benefit will therefore have the lowest cost. The segment length is used to weight the benefit proportionally to the cost because the pavement management segments are of varying length.

Treatments and Costs

FTG and Tetra Tech developed a range of potential maintenance and rehabilitation treatments from structural overlays, to mill and inlays, to localized crack treatments, to localized IRI/Rut treatments, each of which has its own cost and benefit. For example, structural overlays provide a significant benefit to the pavement correcting profile and rut, as well as additional strength and improving overall level of service. Structural overlays however typically include the adjacent shoulder and often the adjacent travel lanes, whether the overlay was required or not, increasing the overall cost of the treatment. Mill and inlay treatments also improve roadway profile and rut, however do not contribute the same amount of additional strength as overlays. Mill and inlays however, can be isolated to a single travel lane without impacting adjacent shoulders and adjacent travel lanes, provided a reduced overall cost.

Triggers

The feasibility of applying a treatment on a given pavement management segment is usually limited by physical or other constraints. For example, a treatment should never be applied in the absence of any surface distress and an overlay or mill and inlay should not be considered if the pavement is too severely distressed. So that only feasible strategies are explored, a set of "triggers" are developed.

A treatment meeting the trigger criteria does not mean that it will be done; it simply means that a strategy will be generated so that the costs and benefits can be compared to determine if it is the lowest NPV strategy.

Development of Treatment Condition Resets

With the selection and application of any given treatment, the resultant performance of a road will improve. For example with a 50 mm mill and inlay, ruts would be filled, surfacing cracking would be removed, and roughness would decrease. Therefore, to predict performance over time and account for and compare possible interventions, the performance models have to adjust the individual distress data to reflect the application of the treatment. These changes to the value of the analysis variables as a result of the application of a treatment are called resets.

6.3 Example Multi-Strategy LCCA Output

An example output from the multi-strategy LCCA is provided in Figure 14. Each bubble in Figure 14 represents a unique compliant strategy (combination of maintenance and rehabilitation activities) for a single pavement analysis segment. For this one pavement analysis segment, more than 80 unique compliant strategies were generated.

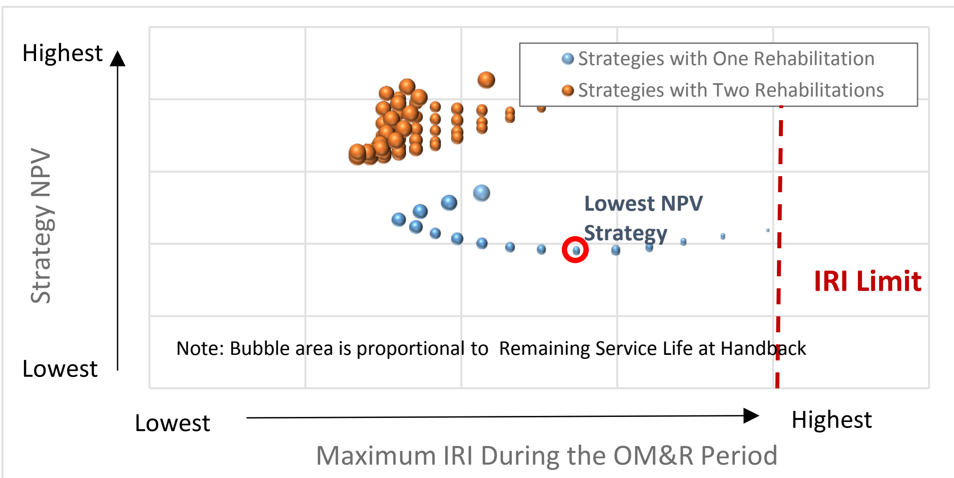

Figure 14: Examples of Multi-Strategy LCCA Output

The information provided in Figure 14 can be interpreted as follows:

- The color of the bubble represents the number of future rehabilitations: blue = 1, orange = 2;
- The y-axis represents the total NPV of the each strategy;
- The x-axis indicates the maximum IRI achieved over the OM&R, with the red dashed line representing the IRI limit; and
- The size of the bubble is proportionate to the RSL at Hand-back.

Figure 14 therefore provides a quick and easy method for assessing cost, benefit and risk (how close to the IRI threshold each strategy gets, and how much RSL each strategy provides). A multi-strategy LCCA profile similar to Figure 14 exists for each of the 84 pavement analysis segments.

7.0 DEVELOPMENT OF FUTURE OM&R PROGRAM

7.1 OM&R Program Overview

Following the objective of achieving the lowest NPV OM&R program, a program optimization algorithm was developed specifically for this project that followed the general procedure:

- **Step 1:** Identify and select the highest benefit strategy that was generated for each pavement Analysis Segment. This strategy with the highest benefit has the lowest cost since the benefit was defined as a function of cost. This results in an initial selection of no rehabilitation (lowest cost, but non-compliant) for any segment.
- **Step 2:** Next, the optimizer checks if all condition criteria are met in each year. If yes, the selection is optimal.
- **Step 3:** Determine the condition criteria that is the most exceeded. Determine the specific pavement management segment contributing the most to this criteria being exceeded.
- **Step 4:** For the specific pavement management segment from Step 3, select the next strategy with lower benefit (higher cost and improved condition).
- **Step 5:** Repeat from Step 2.

The preceding algorithm identifies an initial selection of a single strategy for each analysis segment that meets the specified condition criteria. After that, a second round of optimization is completed, where the algorithm continues to check the remaining strategies to identity if a higher benefit strategy exists. If a higher benefit strategy is found, the optimizer selects this strategy as the lowest NPV, and unselects the previous strategy. This procedure repeats for each selected strategy.

These procedures combined result in an optimal OM&R plan for the mainline pavement elements. The results from this OM&R optimizer is a multi-year capital expenditure profile, similar to that shown in Figure 15.

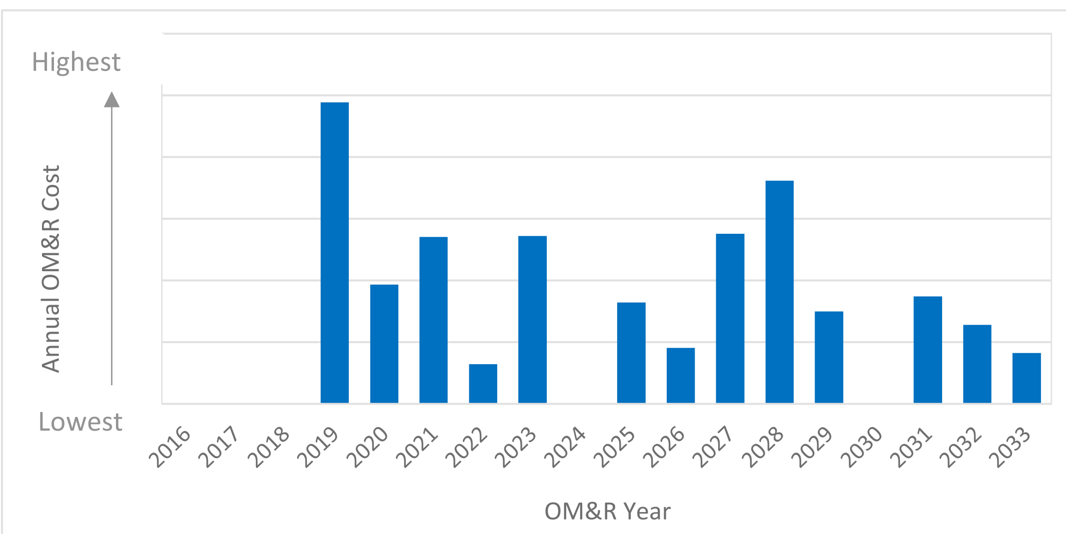

Figure 15: Examples OM&R Program

In each year, this optimized OM&R program provides a detailed maintenance and rehabilitation program along the length of the projects mainline Highway Running Surfaces. The information in this program provides FTG with the following specific deliverables:

1. A network level annual capital expenditure profile for each remaining OM&R year;
2. A project level five-year OM&R program; and
3. An annual works program detailing actual maintenance and rehabilitation works that should be completed in the following construction season.

7.2 Demonstration of KPM APPM Compliance

As part to the OM&R program optimizer, the algorithm provides a plot showing: the "do-nothing" strategy, showing how the roadway would deteriorate if no OM&R program was implemented, and the optimized program, showing compliance with the five-point IRI distribution model. Figure 16 shows an example of this output.

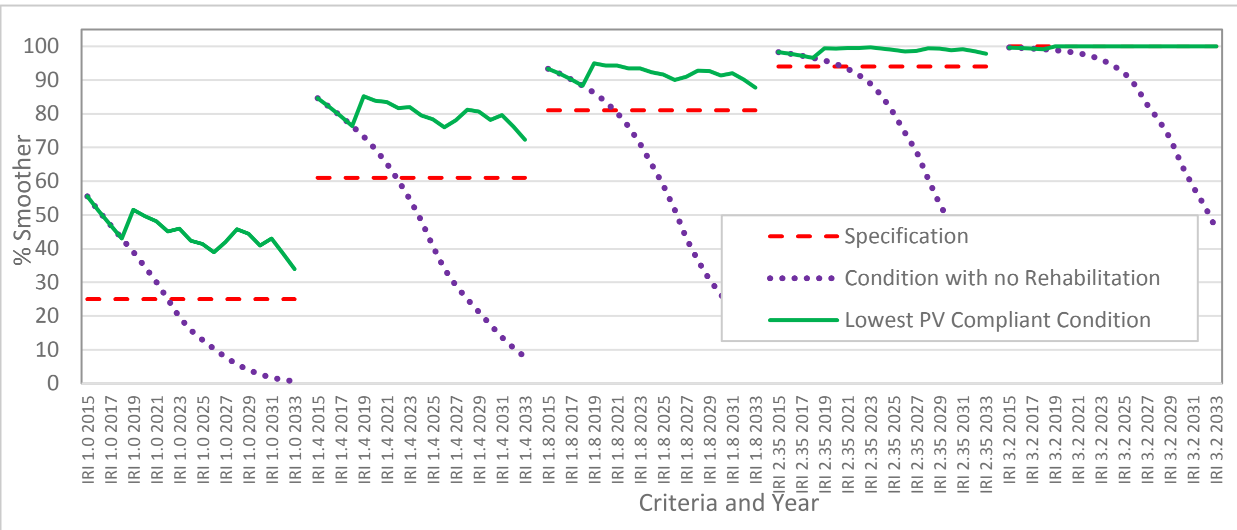

Figure 16: Demonstration of IRI Compliance

The IRI condition Figure 16 in each operation year is shown for the five IRI distribution points modelled (1.0 m/km, 1.4 m/km, 1.8 m/km, 2.35 m/km, and 3.2 m/km). The IRI performance limit is represented by the red dashed line. In other words, IRI compliance requires the green line stay above the red line. The "do-nothing" strategy (dashed purple line) demonstrates that the mainline IRI distribution would fall into non-compliance as early as 2019, which is the first year operational compliance is required by BCMoTI.

Figure 16 demonstrates that the predicted condition for roughness is better than the specified criteria through the length of the 20-year Concession for the lowest PV compliant condition.

8.0 CONCLUSIONS

In conclusion, the objectives of this pavement management system development were met, where:

1. A method for determining the annual IRI CDF in each OM&R year needed was developed; and
2. A method for optimizing the timing and time of pavement rehabilitation/restoration interventions for the purpose of achieving low NPV needed was developed.

Although focused primarily on the IRI KPM and how it is integrated into the PMS, it is important to recognize that a similar process was undertaken for all KPMs and Hand-back requirements. The final deliverable was a fully functioning customized PMS that provides the following:

1. A network level annual capital expenditure profile for each remaining OM&R year;
2. A project level five-year OM&R program; and
3. An annual works program detailing actual maintenance and rehabilitation works that should be completed in the following construction season.

9.0 REFERENCES

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