Canadian Case Study for Perpetual Pavements Design

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ABSTRACT: The Ministry of Transportation of Ontario (MTO) in partnership with the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo and other partners planned and designed an ambitious research project that would validate and evaluate the structural performance of different pavement mixes and structural designs by monitoring three test sections constructed on Highway 401, Ontario, Canada. The project design did not allow for changes in traffic and environmental conditions within the three test section to ensure that the traffic load will be exactly the same among the different structural designs. Two of the three test sections were designed as very thick or perpetual asphalt pavement sections with a Rich Bottom Mix (RBM) at the bottom of asphalt layers and a perpetual asphalt pavement section without the RBM layer. A conventional asphalt pavement section was also included to act as a control section. Monitoring the three pavement test sections will be facilitated by using sensors that are capable of capturing the strain, vertical pressure, moisture content and temperature. In addition, a Preliminary structural evaluation was performed by analyzing the three designs using a Mechanistic Empirical Pavement Design Guide (MEPDG) models representing the three pavement designs. Life Cycle Cost Analysis (LCCA) was also performed for the perpetual and conventional pavement designs to evaluate the cost benefits associated with pavement designs for 70 year analysis period.

KEY WORDS: Perpetual Pavements, Structural Evaluation, MEPDG, Life Cycle Cost Analysis.

1 INTRODUCTION

The perpetual structural pavement design is currently being explored for usage in Canada and worldwide. The thick structural design can provide many potential benefits but it also has associated costs. Cold Canadian winters and warm summers impact pavement performance and make pavement design challenging. This is further complicated by a heavy dependence on trucks to transport imports and exports. Consequently, most Canadian roads are subjected to rapid deterioration due to high fatigue stresses and rapid growth of the traffic loads.

The concept of a perpetual pavement design was raised to overcome the limitation of structural capacity of the conventional pavement designs. This research project aims to evaluate the benefits to be gained by using perpetual pavement designs through monitoring the structural performance of the three test sections using various types of sensors. In addition, structural preliminary evaluation of the three test sections was implemented to show estimation for the expected structural deterioration in the test sections. Structural evaluation was performed by creating structural models using Mechanistic Empirical Pavement Design Guide (MEPDG) computer program.

Economic evaluation of the perpetual design with Rich Bottom Mix (RBM) and the conventional Design was implemented by applying a 70 year Life Cycle Cost Analysis (LCCA).

2 CONSTRUCTION OF TEST SECTIONS

The construction of test sections was accomplished in two stages. Stage one of the construction project includes preparation and instrumentation of three monitoring stations on the lane three (left lane) of the Highway 401. The stage two of the project includes construction and instrumentation of another three monitoring stations located in lane one (right lane/the driving lane) of the Highway 401 located near Wookstock, Ontario. Sensors installed are capable of collecting strain, vertical pressure, temperature and moisture content. The asphalt strain gauges (ASG) installation was designed to target the strain in the critical zones where cracks initiation is expected. In order to study the rutting phenomenon, earth pressure cells (EPC) were installed under the wheel path in order to measure the vertical pressure on the top of subgrade. Thermistor strings (TS) are installed to monitor the temperature of the different pavement layers. As the moisture content in the subgrade layer plays great role in the pavement deterioration and performance, moisture probes (MP) were installed to measure the moisture content in the subgrade layer.

In addition to these sensors, weigh-in-motion (WIM) sensors will be installed to capture the axle load of the vehicles. Thus loads, strain, vertical pressure and environmental parameters affecting the pavement performance can all be monitored and used to evaluate the pavement mixes.

Data collected from the different sensors will be used to create a numerical simulation model to predict the performance of the three pavement mixes in the future. In addition, the maintenance programs for the different mixes will be assumed according to the pavement performance to ensure extending the lifetime of each mix and grantee a minimum acceptable performance and safety level of the road. This numerical model will take into account the environmental and climatic conditions in this part of the world in order to evaluate the benefits of using these mixes in our region.

Each of the test sections is four kilometers long and they were constructed adjacent to each other to ensure consistency in traffic loading over the different sections. The pavement cross section of the three different designs is represented in figure one, two and three.

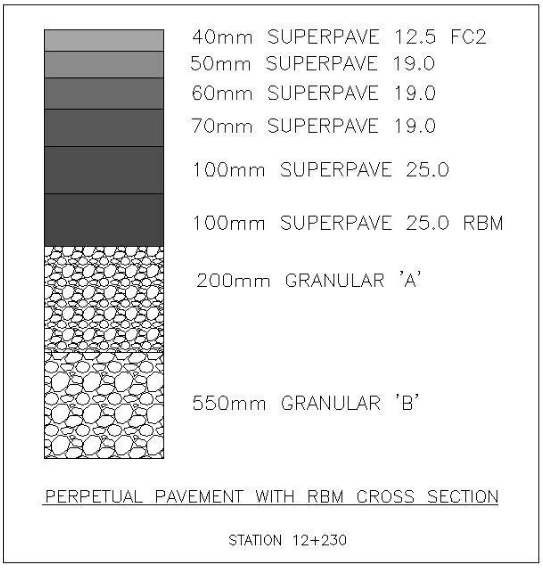


Figure 1: Cross Section of Perpetual Pavement with RBM

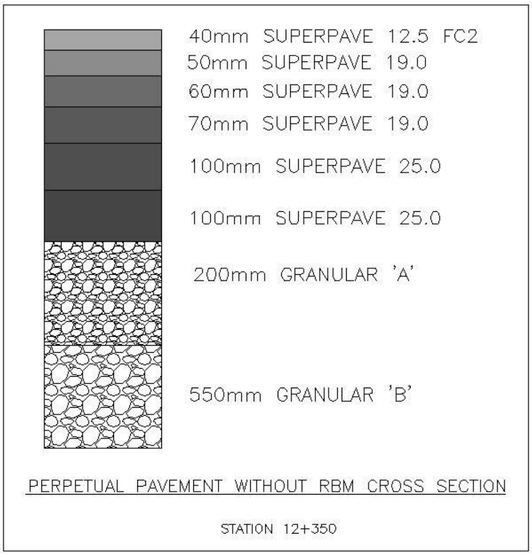


Figure 2: Cross Section of Perpetual Pavement Without RBM

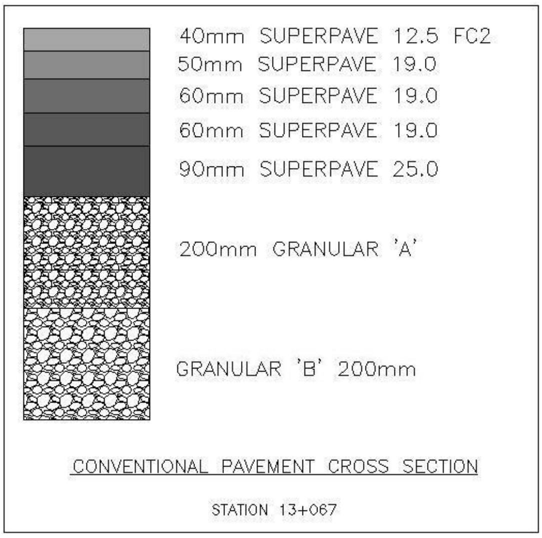


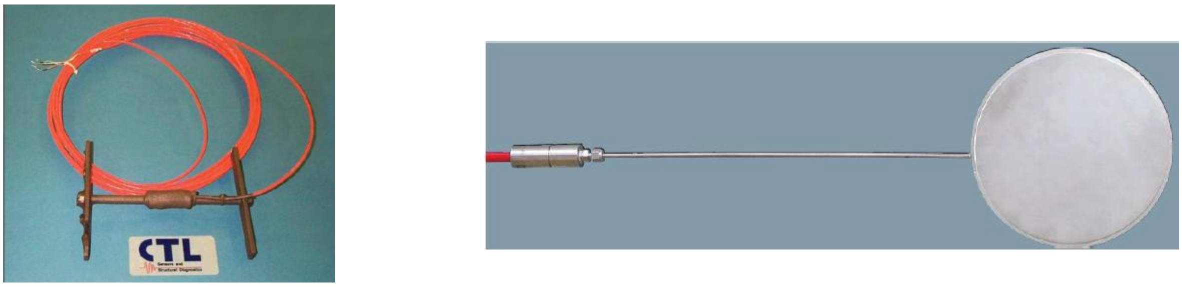
Figure 3: Cross Section of Conventional Pavement

3 INSTRUMENTATION OF TEST SECTIONS

The sensor installation was designed to provide the research team with the most accurate and pertinent data. The sensor locations in the pavement layers play a vital role in validating real time pavement performance. The location of each sensor is designed to provide engineering data that can later be used to model long term performance. The Asphalt Strain Gauges (ASGs) are installed under the left and right wheel paths where the vehicles drive over them. The sensors are installed to measure the strain values in the longitudinal direction and the transverse direction perpendicular to traffic (µx and µy respectively). The vertical location of the Asphalt Strain Gauges (ASG) is at the top and bottom of the lowest asphalt layer installed on top of the granular layers. This is the location subjected to highest tension and thus crack initiation is expected to take place from the bottom of the asphalt layers under the wheel paths. Therefore, these gauges will provide strain information necessary to determine whether cracking is likely to occur or not. Earth Pressure Cells (EPCs) are installed to determine the vertical strain on top of the subgrade layer to determine the total rutting values over time. To fulfill the installation purpose, Earth Pressure Cells (EPCs) are installed under the right wheel path on the top of subgrade layer. Moisture probes (MPs) are installed to determine the moisture content in the subgrade layer. The Moisture Probes (MPs) are installed 40 centimeters deep in the subgrade layer. The moisture content in the subgrade layer affects the frost-thaw impact cycles thus, affecting the deterioration rate of pavement sections due to fatigue cracking.

The project instrumentation plan included installation of Thermistor Strings (TSs) in the six monitoring stations. Thermistor Strings (TSs) are used to determine the temperature profile as it captures the temperature every 10 centimeters starting the pavement surface reaching the subgrade layer. Due to construction constrains, Thermistor Strings (TSs) installation in lane three was cancelled. Phase two of the project will include installation of three Thermistor Strings (TSs) in spring 2010 – one per monitoring station – in the paved shoulder.

The brands and models of different sensors used in this project were selected based on intensive literature review for construction of similar test sections in North America and Europe. Figure four shows the different sensors used in this project.



Asphalt Strain Gauges (ASG-152) Earth Pressure Cell (LPTPC-V)

Moisture Probe (CS 616) Thermistor String

Figure 4: Sensors used in project instrumentation

4 PRELIMINARY EVALUATION

The pavement structural and economic evaluation provides necessary benchmarks for performance. In short, prior to the construction and instrumentation phase, the research team needs to do a pre-engineering evaluation whereby a general performance model is assumed. The three pavement designs that were designed by the Ministry of Transportation of Ontario (MTO) for the Highway 401 instrumentation project were analyzed structurally using the newly engineered Mechanistic Empirical Pavement Design Guide (MEPDG). The mechanical and physical properties needed for the model creation were determined and calculated during this research. In addition to the structural evaluation, a Life Cycle Cost Analysis (LCCA) was performed for evaluating the three pavement designs over the entire life cycle. The maintenance and rehabilitation activities were based on state of the practice of the Ministry of Transportation of Ontario (MTO) recommendations. The maintenance and rehabilitation reports and experience of the research team provided a reliable data source for different maintenance activities and its expected cost.

4.1 Structural Evaluation

An evaluation model was created using Mechanistic Empirical Pavement Design Guide (MEPDG) software version 1.003 to mechanistically evaluate the three pavement structures, including asphalt mixtures that is used for construction of these pavements [Schwartz, 2007]. The MEPDG software is unique as it predicts the pavement performance with regard to several distress types in addition to providing roughness measurements. The MEPDG software outputs include pavement performance predications to surface down cracking, bottom up damage for fatigue (alligator) cracking, thermal cracking, rutting and International Roughness Index (IRI) values expected through the analysis time. The evaluation of both pavement structures assumed an analysis period of 50 years.

The MEPDG model was created with Level Three inputs. Mechanical and physical properties used in creating the MEPDG models such as voids in mineral aggregate (VMA), percentage of air voids, percentage of volumetric binder content and total unit weight were based on state of the art practice [D'Angelo 1998, Kandhal 1998] . The climate data file used in the model implementation was created from downloading the data monitored in the Niagara Falls, New York. This weather station is the closest weather station to the project location. The distance between the project location and the Niagara Falls, New York weather station is 160 km. This approximation in weather conditions is believed to be acceptable due to similarity of most climatic characteristics of the two areas.

The MEPDG analysis predicted that bottom up cracking for the perpetual pavement design will be minimal to that of the conventional design. This shows that the actual bottom up crack propagation is less likely to occur in the perpetual pavement structures compared to conventional asphalt pavement structure. Figure 5 shows the benefits of perpetual pavement construction specially when associated with a Rich Bottom Mix (RBM) layer. The Rich Bottom Mix (RBM) layer proved to be the most optimum solution for fatigue bottom up cracking compared to the perpetual design without Rich Bottom Mix (RBM) layer and the conventional design. The deterioration rate of the conventional design proves that this pavement design will suffer structural damage and bottom up cracks in the short term and will require a more intensive and expensive maintenance and rehabilitation program compared to the perpetual designs.

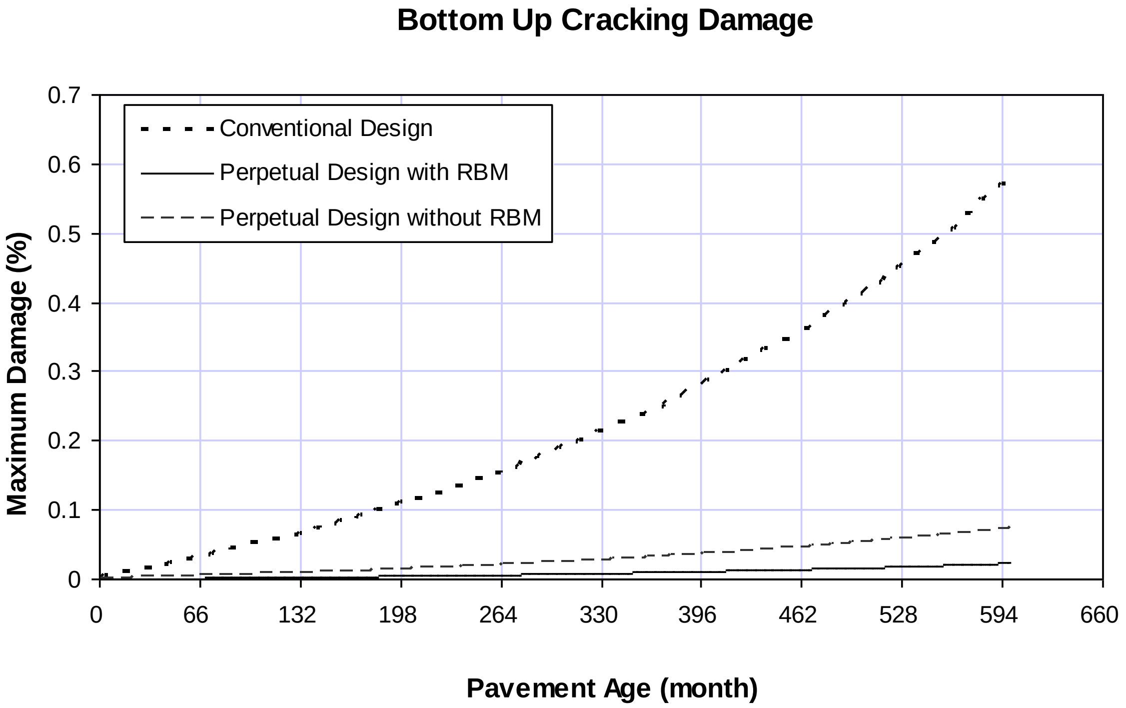


Figure 5: Bottom Up Cracking Damage

Figures 6 and 7 shows the Mechanistic Empirical Pavement Design Guide (MEPDG) rutting model results for the three pavement designs. Both perpetual pavement designs have shown better performance in rutting throughout the analysis period. Analyzing Figure 6, the base rutting in both conventional and perpetual with Rich Bottom Mix (RBM) designs is almost the same. The main factor behind the difference in the total rutting in both pavement designs is the total asphalt layers. The thick asphalt layers are showing enormous rutting resistance to the rutting phenomenon. It is also noticed that in the first five years, the base rutting is primer type of rutting and having the highest contribution to the total rutting. After the fifth year, the rate of increase in the base rutting decreases tremendously while that of the asphalt layers rutting remains in a linear trend and becomes the primer factor behind the total overall rutting. Figure 7 shows the rutting model results for the conventional pavement design and the perpetual pavement design without Rich Bottom Mix (RBM) layer. The results shows that the performance of the perpetual design without Rich Bottom Mix (RBM) layer is subjected to less rutting values compared to that in the conventional design. When comparing the two perpetual asphalt pavement designs, the rutting models created for both pavement types gave almost the same results. The charts for both pavement designs were identical but by reviewing the data a slight difference was deduced that's giving advantage to the perpetual design with Rich Bottom Mix (RBM) layer. This slight difference is showing the impact of adding 0.5% of asphalt content to the bottom asphalt layer of the design as both perpetual designs are identical with the exception of the increase in the asphalt content at the bottom asphalt layer.

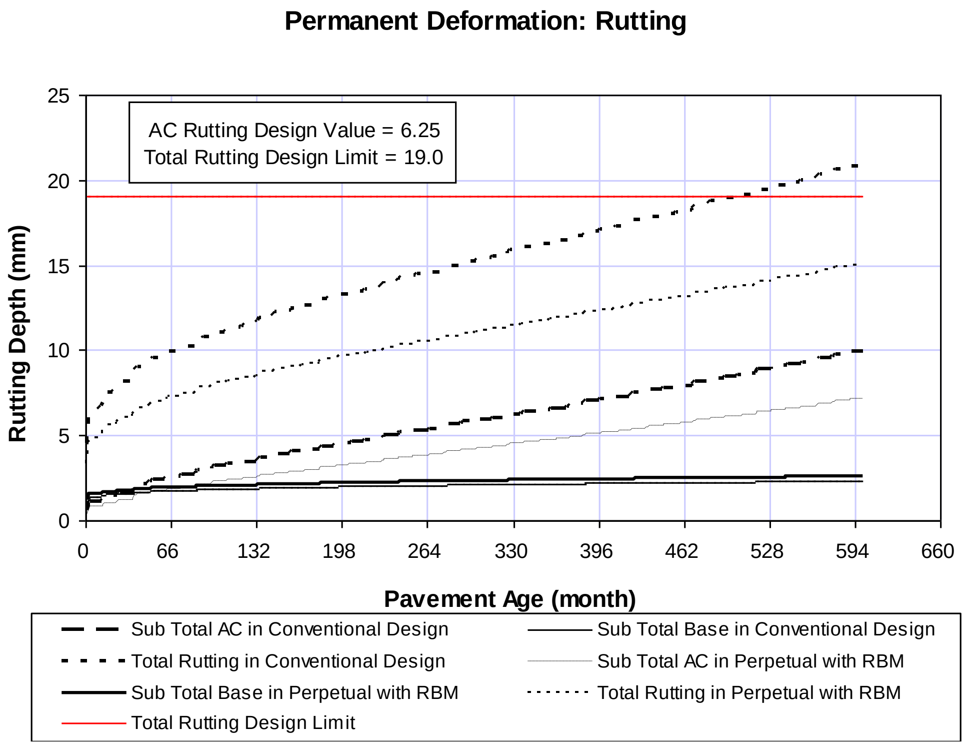


Figure 6: Rutting in Conventional and Perpetual design with RBM

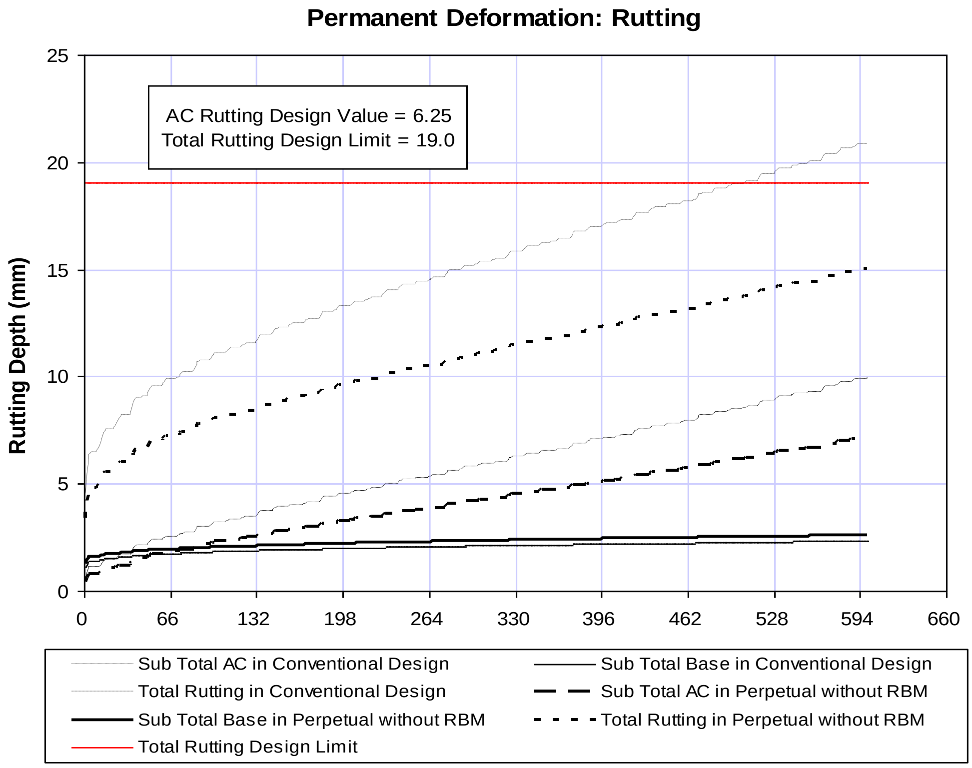


Figure 7: Rutting in Conventional and Perpetual design without RBM

Figure 8 presents the International Roughness Index (IRI) model results for all three pavement designs. It is obvious that all three pavement mixes IRI values were equal immediately after construction. The rate of deterioration of the International Roughness Index (IRI) of the conventional asphalt pavement design is higher than that of the perpetual designs. In addition, the Rich Bottom Mix

(RBM) layer provided extra resistance for the perpetual asphalt pavement design including the Rich Bottom Mix (RBM) layer compared to that without that layer. The deterioration of International Roughness Index (IRI) can be resolved by replacing the surface course every ten years approximately to maintain the IRI values.

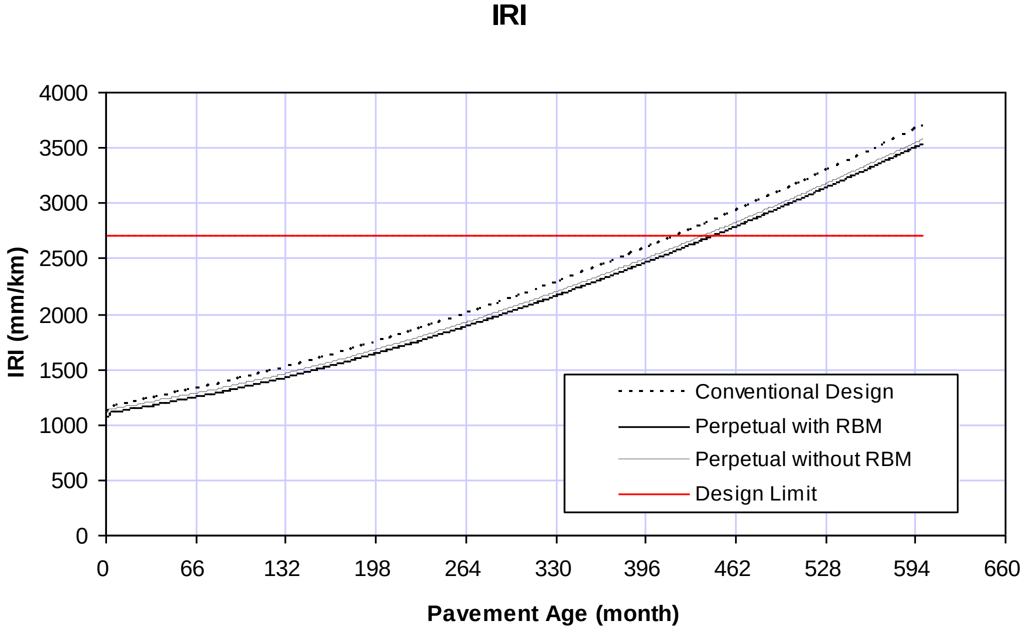


Figure 8: International Roughness Index (IRI) Model Results

4.2 Economic Evaluation

Life Cycle Cost Analysis (LCCA) was also performed to evaluate the conventional and perpetual pavement design methods. The construction difference between the two perpetual pavement designs takes place in the asphalt content of the bottom asphalt layer. The addition of 0.5% of binder content in the bottom asphalt layer is expected to have minor effect on the LCCA. To simplify the LCCA calculations, comparison and evaluation was performed on the conventional pavement design and the perpetual pavement design with RBM as a representative for the perpetual designs. Superior pavement performance predictions supported by reasonable economic analysis is essential to justify any capital investment.

It is important to highlight that the life cycle cost analysis (LCCA) procedure will be performed under the following assumptions:

1- Best possible unit cost estimates for pavement material, maintenance and rehabilitation, and labor in Ontario are obtained through the Ministry of Transportation of Ontario (MTO). The final life cycle cost analysis reports submitted to MTO in 1998 and 2006 were used for estimating the material, maintenance and rehabilitation costs [Hein 2007, Smith 1998]. However if necessary, some unit costs were assumed based on national averages.
2- The LCCA evaluation period is proposed to be 70 years for the two pavement design alternatives.
3- Preventative maintenance, scheduled maintenance, and/or rehabilitation treatments were assumed based on the recommendations of the MTO reports.
4- Inflation costs per treatment and/or maintenance activities are not used

and are assumed constant between different rehabilitation options. This is a common practice that is mostly used in LCCA.

5- User delay costs during different maintenance and rehabilitation activities were not taken into account in this LCCA due to the lack of sufficient data and to simplify the LCCA calculation.

The construction costs of the perpetual asphalt pavement and conventional asphalt pavement are presented in tables 1 and 2 respectively.

Table 1: Initial Construction Cost of Perpetual Pavement Design

(40 mm) Superpave 12.5 FC 2 Density = 2.56 t/m^3	(180 mm) Superpave 19 Density = 2.41 t/m^3	(100 mm) Superpave 25 Density = 2.34 t/m^3	(100 mm) RBM Layer Density = 2.44 t/m^3	(200 mm) Granular A Density = 3.12 t/m^3	(550 mm) Granular B Density = 2.05 t/m^3	SUM
$238,797	$744,401	$303,732	$348,920	$238,680	$253,688	$2,128,217.10
$238,797	$744,401	$303,732	$348,920	$238,680	$253,688	$2,128,217.10
					Avg	$2,128,217.10
					Sum	$4,256,434.20

Table 2: Initial Construction Cost of Conventional Pavement Design

(40 mm) Superpave 12.5 FC 2 Density = 2.56 t/m^3	(180 mm) Superpave 19 Density = 2.41 t/m^3	(90 mm) Superpave 25 Density = 2.34 t/m^3	(200 mm) Granular A Density = 3.12 t/m^3	(200 mm) Granular B Density = 2.05 t/m^3	SUM
$170,100	$515,970	$238,140	$238,680	$92,250.0	$1,255,140.0
$170,100	$515,970	$238,140	$238,680	$92,250.0	$1,255,140.0
				Avg	$1,255,140.0
				SUM	$2,510,280.0

The maintenance and rehabilitation program –presented in table 3 and 4– prepared for the conventional pavement design was prepared based on the MEPDG model results of the conventional design. As the MEPDG model have predicted faster structural deterioration rate for conventional design compared to the perpetual pavement design, the maintenance and rehabilitation program for the conventional pavement design was prepared to treat various distresses and structural deterioration of the pavement section.

The LCCA total Net Present Value (NPV) of the perpetual and conventional pavement designs is calculated using three percent discount rate for an analysis period of 70 years. The deterministic Net Present Value results at the end of the analysis period were $5,649,711 and $5,437,145 for perpetual and conventional pavement designs respectively. The LCCA results show the two pavement designs are almost having equal Net Present Values. The difference between the NPV of the two pavement designs is almost 4% which provides a slight economic advantage to the conventional pavement design. This Life Cycle Cost Analysis does not take into account the user delay cost due to the construction, maintenance and rehabilitation activities and the lane closures. These factors would to complicate the Life Cycle Cost Analysis calculation and more user delay cost data would be required to obtain a more accurate LCCA. However, the LCCA results are expected to give more advantage to the perpetual pavement design if the user delay costs were to be included in the LCCA as more frequent maintenance activities and treatments are scheduled for the conventional pavement design compared to the perpetual pavement design.

Although the construction costs of the perpetual pavement design is expected to be 70 percent more expensive compared to the conventional design, the overall LCCA NPV costs of the perpetual pavement is higher than that of the conventional design by four percent. The LCCA analysis shows the perpetual pavement design can provide several advantages over the entire life cycle of the asset.

Table 3: Maintenance Schedule of a Conventional Pavement

Maintenance Activity	Year
Rout and Crack Sealing (352 m/km)	4
Rout and Crack Sealing (352 m/km)	7
Rout and Crack Sealing (352 m/km)	10
5% Mill and Patch 50 mm	10
Rout and Crack Sealing (704 m/km)	14
20% Mill and Patch 50 mm	18
Rout and Crack Sealing (704 m/km)	21
Tack Coat	25
Mill 50 mm Asphalt Pavement	26
Superpave 12.5 FC2 - 50 mm	26
Rout and Crack Sealing (352 m/km)	29
Rout and Crack Sealing (352 m/km)	33
Rout and Crack Sealing (352 m/km)	35
20% Mill and Patch 50 mm	37
Partial Reconstruction of Pavement	40
Rout and Crack Sealing (352 m/km)	44
Rout and Crack Sealing (352 m/km)	47
Rout and Crack Sealing (352 m/km)	50
5% Mill and Patch 50 mm	50
Rout and Crack Sealing (704 m/km)	54
20% Mill and Patch 50 mm	58
Rout and Crack Sealing (704 m/km)	61
Tack Coat	65
Mill 50 mm Asphalt Pavement	66
Superpave 12.5 FC2 - 50 mm	66
Rout and Crack Sealing (352 m/km)	69

Table 4: Maintenance Schedule of a Perpetual Pavement

Maintenance Activity	Year
Rout and Crack Sealing (280m/km)	5
Rout and Crack Sealing (280m/km)	10
3% Mill and Patch 40 mm	14
Rout and Crack Sealing (560m/km)	18
15% Mill and Patch 40 mm	22
Mill 50mm Asphalt pavement	27
SMA- 50 mm	27
Tack Coat	27
Rout and Crack Sealing (280m/km)	32
Rout and Crack Sealing (280m/km)	37
15% Mill and Patch 40 mm	41
Rout and Crack Sealing (560m/km)	45
Mill 50mm Asphalt Pavement	50
SMA- 50 mm	50
Tack Coat	50
Rout and Crack Sealing (280m/km)	55
Rout and Crack Sealing (280m/km)	60
15% Mill and Patch 40 mm	64
Rout and Crack Sealing (560m/km)	68

5 CONCLUSION

The results and analysis of the structural and economic evaluation presented in this paper shows strong evidence that perpetual pavement designs are expected to have better structural resistance for different loads and stresses compared to the conventional design. The perpetual design is expected to be the most economic design on the long term, taking into account the minor maintenance and rehabilitation activities that are required to preserve the pavement condition.

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