

# Concrete Pavement Life Cycle Environmental Assessment & Economic Analysis: A Manitoba Case Study

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**ABSTRACT:** Life Cycle Assessment (LCA) is recognized as one of the most comprehensive ways to evaluate the environmental impacts of different strategies associated with a physical feature such as highway pavement structures, bridges and vertical structures. Alternatively, life cycle cost analysis (LCCA) is performed by different agencies including Manitoba Infrastructure (MI) to select the most cost-effective construction option or life cycle strategy. Highway agencies started to realize the need to combine the LCA and LCCA in the design, construction and management of roadway assets.

This paper presents comparisons of the environmental impacts and life cycle costs of various alternative strategies for a portland cement concrete (PCC) pavement project in Manitoba to demonstrate the opportunity to optimize the cost, pavement performance and environmental impacts. A matrix of 10 different strategies that include alternative PCC mix, pavement design, and maintenance and rehabilitation (M&R) treatments have been used to contrast both the life cycle costs and environmental impacts with MI's past practice (base case). The presented analysis is expected to assist highway agencies to better understand and weigh not only the economics of alternative strategies, but also the environmental implications of alternative roadway materials, design, construction, and maintenance and rehabilitation practices.

## 1 INTRODUCTION

### 1.1 *Background*

Environmentally sustainable design, construction, preservation and maintenance practices can assist in preserving our natural environment. LCA is acknowledged as one of the most comprehensive ways to evaluate the environmental impact of activities associated with a physical feature or to compare the environmental impacts of different strategies for a given analysis period. The Athena Pavement LCA software allows users to analyze and compare the environmental implications of multiple roadway design scenarios taking into consideration materials production, construction, and M&R treatments. It is also the first commercially available software capable of modeling pavement vehicle interactions (PVI), so designers have the option of considering roadway roughness and deflection on predicted roadway traffic fuel consumption and associated environmental impacts.

LCCA has long been performed by different agencies to select the most cost-effective construction option or life cycle strategy among the feasible alternatives. The life cycle approach to pavement management decisions has also continued to grow in asset financing, as agencies search for effective ways to allocate their budget to maintain an aging infrastructure network. Consequently, several new LCCA tools have been developed that can account for uncertainty in the decision-making process and the costs accrued to users of a roadway facility (Tighe 2001, Salem et al. 2003, Lee et al. 2011).

## *1.2 Objectives and scope*

The objectives of this paper are to show, using the Athena Pavement LCA tool the environmental impacts of various PCC mixes and pavement design scenarios, and to explain the performance reasons for the current MI specification changes and future considerations. Furthermore, this study evaluates the life cycle costs associated with each material and design scenario. These include the agency cost of initial construction and future M&R activities as well as the user costs from excess fuel consumption due to PVI.

This case study uses a concrete pavement section constructed in 2015 on the northbound direction of Provincial Trunk Highway (PTH) 75 divided highway, in Manitoba. This project was the first project where the new MI specification was used (listed as Scenario 6 of this case study). The other analysis scenarios include a matrix of alternative PCC mix designs based on varying cement/aggregate, fly ash and slag compositions, varying reinforcing steel type, size and quantity, and rehabilitation practices based on the expected extension of pavement's initial service life from the usual initial service life due to the construction of more durable pavement. These variations, alone and in combination, facilitated the comparison of the life cycle environmental impacts and costs for 10 alternative scenarios relative to a base case. The environmental impacts and life cycle costs presented in this paper reflect the total for the entire project i.e., 11.02 km x 2 traffic lanes plus shoulders.

It should be noted that the empirical approach of linking PCC proportioning and slab design (10 alternative scenarios) to pavement performance, which in turns affect the M&R and PVI, is intended to demonstrate the potential impact of those concrete mixes and slab design. A more robust assessment will require actual long term field performance data for each of these scenarios which is out of the scope of this paper but could be investigated further in future studies.

## 2 PAVEMENT LCA SOFTWARE

### *2.1 Overview*

In the Athena Pavement LCA tool, first released in 2011, users may enter their project specific roadway cross section designs (subbase, base and surface layers) and overall length or select from a library of sample regional PCC or asphalt concrete (AC) roadway designs and customize to their intended analysis scenario including the life cycle period. In May 2016, a web-enabled version of the tool was released (<http://pavementlca.com>). The Pavement LCA tool follows the guidance and frameworks as set out by the US Federal Highways Administration (FHWA) (see FHWA 2015 and FHWA 2016). The software has been made available free of charge to all with support from the Athena Sustainable Materials Institute's members, collaborators and supporters.

### *2.2 Data sources*

Pavement materials, energy and transportation data were derived from proprietary Athena Institute databases as well as publicly and commercially available life cycle inventory (LCI) databases and environmental product declarations (EPDs). The materials data typically represent national or industry averages for the extraction, processing and manufacture of materials and products. Canadian regional energy grids and transportation distances are then applied to manufacturing process energies and material sourcing distances to arrive at regional data profiles. The current web-enabled version contains recent EPD results for Canadian portland cement, North American slag cement and updated Canadian regional energy and electricity grid profiles.

### *2.3 Analysis outputs*

In the Athena Pavement LCA software, users can quickly describe roadway design, M&R and (optionally) PVI parameters through a few input screens and then can view a comprehensive set of life cycle impact assessment results comprised of: energy and raw material flows plus emissions to air, water and land. The software also enables side-by-side comparison of different options across life cycle stages. The life cycle impact assessment results are based on the US

EPA's TRACI characterization model (<https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci>) and cumulative resource use metrics.

The total operating energy may also be included in the LCA if the user inputs an estimate for annual operating energy consumption by fuel type. The software will calculate total energy, including pre-combustion energy (the energy used to extract, refine and deliver energy) and the related emissions to air, water and land over the life cycle of the roadway project, and can subsequently compare the life cycle operating and embodied energy and other environmental effects of various design options, allowing the user to better gauge construction, reconstruction and M&R trade-offs.

### 3 PAVEMENT LIFE CYCLE COST ANALYSIS (LCCA)

The LCCA model used in this study follows the guidelines of Federal Highway Administration (FHWA) for life cycle cost analysis of pavements (Walls & Smith 1998). The details of the model are presented in previous work by Swei et al. (2013) and Swei et al. (2015). The model was validated against Minnesota's LCCA tool by Akbarian et al. (2017). For the analysis presented in this paper, the deterministic LCCA model has been implemented without considering the sources of uncertainty. In addition, the road user costs are accounted for based on fuel consumption by vehicles. The initial and maintenance agency costs are calculated based on the quantity of each activity in the bill of materials and operations of each scenario, and according to the local (average) item costs for these activities. Moreover, the impacts of material and design decisions on the user cost due to PVI are evaluated for vehicles throughout the pavement life cycle. The deflection-induced excess fuel consumption is evaluated using previously developed model as a function of top layer thickness, stiffness, relation time, subgrade stiffness, pavement width, temperature, vehicle axle load, and speed (see Louhghalam et al. (2014) and Akbarian (2016) for details of model, experimental development, calibration, and validation). The impact of roughness-induced PVI on vehicle fuel consumption is evaluated through the calibrated Highway Development and Maintenance Management (HDM-4) model developed by the World Bank as a function of surface roughness in terms of the International Roughness Index (IRI) (Chatti & Zaabar 2002). The parameters for this analysis include annual IRI, vehicle type and traffic volume, and IRI after construction and maintenance. The cost of excess gasoline and diesel consumption are assumed to be equal, at a value of \$0.95 CAD per liter.

### 4 CASE STUDY PROJECT DETAILS

#### 4.1 *Project description*

As mentioned earlier, a PCC pavement constructed in 2015 on the northbound lanes of PTH 75 in Manitoba is used as a case study in this paper. The project is located approximately 30 km south of Winnipeg and has a total length of 11.02 km. For the 50-year analysis presented in this paper, distances from site to the stockpile, plant to the site and from equipment depot to the site were assumed to be 30 km. The current 1-way annual average daily traffic (AADT) is 3,900 inclusive of 650 heavy vehicles (trucks) and an annual growth rate of 2%.

The existing roadway consisted of 100 mm AC (bituminous) surface layer over a 250 mm PCC and 125 mm granular base. The pavement reconstruction consists of reclaiming the existing bituminous layer, rubblizing the existing PCC, placing 100 mm drainable stable granular base, topped with 255 mm PCC and diamond grinding the new PCC surface (5 mm loss). Shoulder construction includes widening with granular base and bituminous (100 mm thick)/gravel surfaces. The cross section of the new roadway is shown in Figure 1.

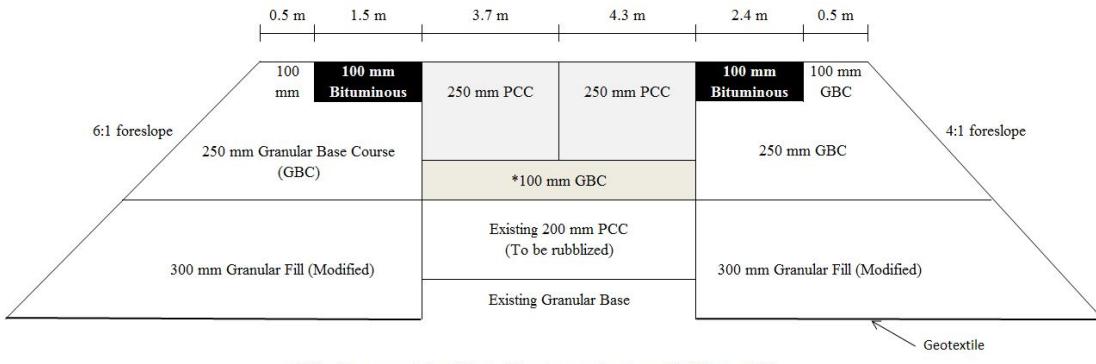


Figure 1: Roadway cross section (not to scale)

#### 4.2 Life cycle strategy

MI performs LCCA for a 50-year period to select a pavement strategy. MI's rigid (PCC) pavement life cycle strategy, which is based on local performance experience, is shown in Table 1. These periodic treatments and their lives have been used for the analysis presented in this paper. It should be noted that Pavement ME Design program may be used to predict the pavement performance and rehabilitation schedule. However, the globally calibrated performance and distress models in the Pavement ME Design program are found to be inadequate for Manitoba local conditions. MI is currently working on the local calibration of the Pavement ME Design performance and distress prediction models as well as the field verification of the LCCA strategy to determine if the life cycle rehabilitation activities are realistic.

Table 1: Life cycle strategy for PCC pavements in Manitoba

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

#### 4.3 Concrete pavement construction and concrete mix design

Recently, MI has revised the concrete mix design, dowel and tie bar configurations for the rigid pavement structure to make it more durable and economical. Changes include reduction of the cement content by implementation of optimized gradation, increase of fly ash content, use of drainable stable base (DSB) under the rigid layer, use of non-corrosive (zinc clad or stainless) steel dowel and tie bars, use of smaller diameter dowels and tie bars, reduction of number of dowels per joint, and reduction of tie bars length and spacing. This paper presents the comparison of life cycle environmental impacts and costs of these changes, except the DSB whose specification is still under evaluation, with the base case (MI's past practice before adoption of these changes) scenario. Additional comparison includes environmental impacts of optimized concrete slab design using thin concrete pavement (TCP) methodology, addition of slag in the concrete mix (to produce fly ash/slag cement ternary mix) and a hypothetical extension of initial pavement service life.

#### *4.3.1 Supplementary cementing materials (SCMs) and ternary mixes*

The aim of mixture proportioning is to find the combination of available and specified materials to ensure that a mixture is cost effective and meets all performance requirements. In the case of sustainable design, minimizing the pavement's environmental footprint over the life cycle must be one of the performance requirements. Cementitious content should be kept as low as possible without compromising mixture performance, both in the fresh and hardened states.

The two most commonly used SCMs in PCC paving are fly ash and slag cement. The amount of fly ash that can be used is often limited by concerns of delayed setting times and lower early strength gain. Its dosage varies from 15 to 40% by mass of cement. Slag cement may be used in pavements in dosages up to 50% but is limited by concerns of slow early strength gain, especially when placed during cooler ambient temperatures, and of scaling resistance.

Ternary concrete mixtures include three different cementitious materials. The optimum mixture proportions for ternary blends will depend on the final use of the concrete, construction requirements and seasonal restrictions. As with other concrete, cold weather will affect the early strength gain and mixture proportions may need to be adjusted to assure job-site performance. In low water-cementitious materials ratio (w/cm) applications such as paving, mixtures with 15% fly ash and 30% slag cement have been used successfully. For example, in 1998, airfield PCC pavements were constructed at the Minneapolis Airport using a ternary mix consisting of portland cement with 35% slag and 10% class C fly ash. The pavement has been performing very well.

MI previously allowed a maximum of 15% fly ash; this was recently increased to 20% (maximum). For ternary concrete mixes, agencies typically use a combination of 15% fly ash and 25% slag by mass of total cementitious (portland cement and SCMs) materials. This ternary mix scenario was added to the analysis to see if MI should consider ternary mixtures in the future, from environmental and performance standpoints, since it has already been shown that ternary mixtures improve concrete durability in the field (Taylor 2014).

#### *4.3.2 Optimization of aggregate gradation*

Another technique to reduce the total cementitious materials content in the PCC mixes is optimization of aggregate size and proportion. The tarantula curve, which provides an envelope for the desirable amount of material retained on each sieve, is the newest technique of mixture optimization (Ley et al. 2012). The curve has been independently validated by concrete pavement contractors and shows that over time, concrete mixtures have evolved to fit within the recommended limits of the Tarantula curve (Ley et al. 2014). This technique allows a reduction in paste content by use of an intermediate size aggregate, while still allowing sufficient paste volume to fill voids and provide workability. Benefits reported by contractors include: reduced shrinkage, lower cost, greater strengths and improved workability.

MI's PCC mix design for pavements had been based on the individual gradation of coarse and fine aggregates. In 2015, MI adopted the tarantula aggregate gradation band in the specification and increased the maximum size of the aggregate from 19 mm to 25 mm for gravel. The optimized gradation and reduced strength requirement allowed for a reduction of the total cementitious material content from 355 kg/m<sup>3</sup> to 307 kg/m<sup>3</sup> of concrete. Figure 2 shows how the pre-2015 and 2015 aggregate gradations fit into the tarantula aggregate gradation band (tarantula curve).

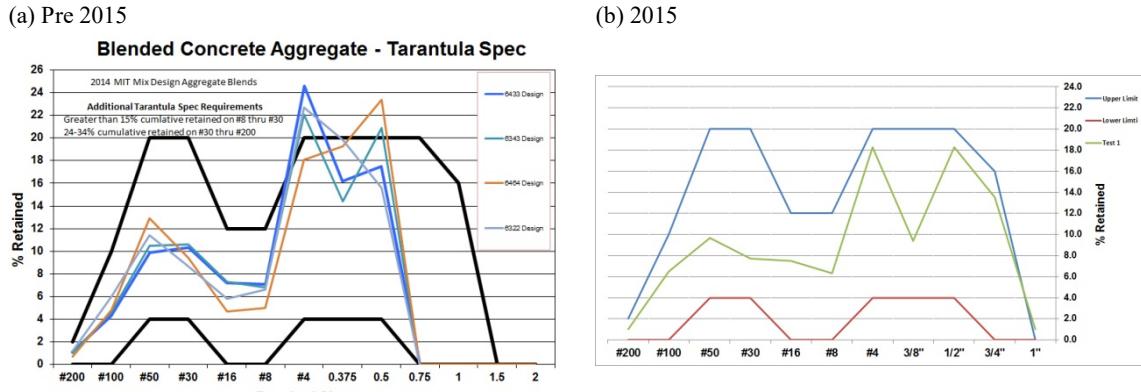


Figure 2: Aggregate gradation in tarantula curve

#### 4.3.3 Modifications to pavement structure (dowels and tie bars)

Dowel detail and joint design are new innovative concepts evolving in concrete pavement engineering today. Due to a decreasing transportation funding and a rising focus on sustainability, highway agencies are looking for ways to minimize initial construction costs and to use alternative construction materials.

Current trends in concrete pavement joint design include reducing the number of dowel bars and placing dowels directly under the wheel paths only as opposed to the conventional dowel placement at 300 mm interval throughout the transverse contraction joints. Placing dowels at 300 mm (or even 450 mm) off the outside edge of pavement and at 450 mm (or even 600 mm) off the longitudinal joint instead of typical 100-150 mm eases construction and can also help reduce interference from the adjacent tie bars.

MI had been constructing jointed plain concrete pavements (JPCP) using epoxy coated steel dowels and tie bars. Traditionally, 38 mm (diameter) x 450 mm (length) dowels were placed at 300 mm interval along the transverse contraction joints (26 dowels per 8 m wide transverse contraction joint). The size of tie bars was 19.5 mm (diameter) x 915 mm (length) and four tie bars were used along a 4.5 m long longitudinal joint. For the 11.02 km long case study road section, the total steel requirement was calculated to be 276 tonnes. MI has experienced corrosion of both dowels and tie bars resulting in deterioration of both transverse and longitudinal joints including the separation of longitudinal joints. Hence, MI has been exploring alternative reinforcing dowels and tie bar materials and configurations. MI recently revised the JPCP specifications for dowels and tie bars.

The new JPCP specifications require the use of stainless steel or zinc clad dowels and stainless steel tie bars. Based on economical and technical analysis of dowel size requirements, longevity and location of wheel paths (where about 90% of wheel load repetitions occurs), the size of dowels has been changed to 32 mm with a requirement to place only four dowels in each wheel path i.e., total 16 dowels per transverse contraction joint (two lanes). The new requirements for stainless steel tie bars are 16 mm (diameter) x 750 mm (length) and five dowels per 4.5 m long longitudinal joint. The estimated steel quantity is 126 tonnes for the 11.02 km long case study road section i.e., 54% reduction in steel quantity from that was used in the past. However, the LCA tool does not contain data for stainless steel. Therefore, all dowels and tie bars are modeled as galvanized steel (a limitation of the Pavement LCA tool) to estimate the effect of changes in steel quantity.

#### 4.3.4 Optimized concrete slab design using thin concrete pavement (TCP) methodology

This design procedure configures slab size so that each slab is loaded by only one wheel or a set of wheels (i.e., 50% of each axle load) at the same time. This significantly reduces the top tensile stresses of the slabs. Research shows that minimizing the critical top tensile stress will allow for thinner concrete slabs with smaller slab dimensions (length and width). Research also shows that fiber reinforced concrete slabs contribute to a longer service life (Covarrubias et al. publication date is unavailable). This concept was developed by a Chilean company, TCPavements, in 2007. A mechanistic software, OptiPave, has been developed to design concrete pavement using

this methodology. This design software predicts cracking, faulting and initial IRI, which is similar to the AASHTOWare Pavement ME Design program, and allows for the prediction of pavement performance over time. Typically, slabs are 70 mm thinner (on average) for higher trafficked roadways relative to traditionally designed pavements using the AASHTO 1993 method and no dowels or tie bars are used. Slab length and width are typically between 1.4 m to 2.5 m for the TCP (Covarrubias & Covarrubias 2008). In the analysis for this paper, a slab size of 2.0 m is used. The initial slab thickness is assumed to be 205 mm to obtain a net thickness of 200 mm after 5 mm loss due to diamond ground texturing of new concrete surface. The thickness designs for the JPCP and TCP using Pavement ME Design and TCPavements programs, respectively, are beyond the scope of this paper because of the inadequacy of Pavement ME Design performance/distress prediction models for the local condition and no local access to TCPavements software.

## 5 ANALYSIS AND RESULTS

### 5.1 Alternative analysis scenarios

Eleven cases (base case plus 10 alternative cases) are run in the Athena Pavement LCA software to estimate the environmental impacts of changes in one or more attributes. These alternative scenarios including their rationales are listed in Table 2. The base case represents a past standard mix design using 355 kg of cementitious material per m<sup>3</sup> of concrete, of which 15% was fly ash. The base quantity of steel is 276 tonnes. The proportion of coarse and fine aggregates is 61:39. MI's regular M&R strategy is used to estimate the post construction environmental impacts. Subsequent analysis cases include increase of fly ash content, addition of slag cement to produce a ternary mix, reduction of steel quantity, modification of M&R cycles and reduction of PCC slab size (TCP) from this base case.

Table 2: Alternative analysis scenarios and their rationales

Case #	Case description	Analysis rationale
Base	355 kg cementitious, 15% fly ash, 0% slag, 276 t steel , regular M&R	Impacts of past practice
1	355 kg cementitious, 20% fly ash, 0% slag, 276 t steel, regular M&R	Effect of additional fly ash
2	355 kg cementitious, 15% fly ash, 25% slag, 276 t steel, regular M&R	Effect of slag/ternary mix, if used
3	307 kg cementitious, 15% fly ash, 0% slag, 276 t steel, regular M&R	Effect of reduced cementitious material (tarantula optimization)
4	355 kg cementitious, 15% fly ash, 0% slag, 126 t steel, regular M&R	Effect of reduced steel
5	307 kg cementitious, 20% fly ash, 0% slag, 276 t steel, regular M&R	Combined effect of reduced cementitious and increased fly ash
6	307 kg cementitious, 20% fly ash, 0% slag, 126 t steel, regular M&R	Combined effect of reduced cementitious and steel, and increased fly ash (new spec.)
7	307 kg cementitious, 15% fly ash, 25% slag, 126 t steel , regular M&R	Combined effect of new spec. and slag/ternary mix, if used
8	307 kg cementitious, 15% fly ash, 25% slag, 126 t steel , extended M&R	Effect of extended M&R
9	355 kg cementitious, 15% fly ash, 0% slag, 0 steel, TCP, regular M&R	Effect of short concrete panel (TCP)
10	307 kg cementitious, 15% fly ash, 25% slag, 0 steel, TCP, extended M&R	Effect of reduced cementitious, TCP, ternary mix and extended M&R

Case 6 represents MI's current standard mix design, construction and M&R cycles. This mix design optimizes the aggregate blend to reduce cementitious material content with the use of larger maximum size and intermediate sized aggregates. However, there is a negligible change in the proportion of coarse and fine aggregates from the previous concrete mix design i.e., the base case. Cases 2 and 7 are intended to show the effects of ternary concrete mix as compared to the previous and new (current specification) mixes, respectively. Case 8 shows the effect of the-

oretical extension of initial pavement service life (extended M&R) due to the use of ternary concrete mix or other means (e.g., pavement designed for a longer service life). For this case, the timing of the M&R treatments are arbitrarily delayed by 5 years from the regular M&R treatments shown in Table 1. Case 9 shows the influence of short concrete panel i.e., TCP design as compared to the base case. Case 10 shows the influence of TCP, ternary cement and reduced cementitious with a theoretical extension of initial pavement service life (i.e., extended M&R).

To estimate the environmental impacts due to traffic use, the PVI analysis considered vehicle operating speed of 100 km/h, an initial IRI of 0.665 m/km (after diamond grinding of new pavement surface), a terminal IRI of 2.5 m/km that triggers a rehabilitation diamond grinding and a post-rehabilitation (diamond ground) IRI of 1.0 m/km. The subgrade resilient modulus is 30 MPa. The concrete density and elastic modulus are 2.320 t/m<sup>3</sup> and 28,600 MPa, respectively. The PVI analysis assumed 15 mm loss in concrete thickness per each periodic diamond ground treatment, except the diamond grinding of new concrete surface. The environmental impacts and life cycle costs presented in this paper reflect the total for the entire project (11.02 km).

## 5.2 Environmental impacts of base case

The LCA tool calculates the environmental impacts for several impact indicators and energy use metrics due to the manufacturing (material production and transportation), construction (equipment use and transportation), maintenance (M&R) and traffic use phase excess fuel consumption (due to roadway roughness and deflection). Table 3 summarizes the varying impact indicator and resource use metric results for the base case. A discussion of all these impact indicators is beyond the paper size (page) limitation for this symposium, and therefore the analysis focuses solely on the global warming potential (GWP) or climate change effects (see EPA 2016).

Table 3: Base case environmental impacts

Activities		Manufacturing	Construction	Maintenance & rehab	Use phase excess fuel consumption due to PVI		Total life cycle
Impact category indicators and resource use metrics	Measurement units				PVI effects (IRI)	PVI effects (deflection)	
Global Warming Potential	t CO <sub>2</sub> eq	8,086.9	6,358.5	9,500.6	1,632.7	3,701.6	29,280.3
Acidification Potential	t SO <sub>2</sub> eq	34.9	57.3	77.9	10.4	33.1	213.5
HH Particulate	t PM2.5 eq	13.9	3.4	5.6	0.5	1.9	25.3
Eutrophication Potential	t N eq	3.7	3.8	5.4	0.7	2.2	15.8
Ozone Depletion Potential	t CFC-11 eq	0.0	0.0	0.0	0.0	0.0	0.0
Smog Potential	t O <sub>3</sub> eq	653.5	1,922.9	2,515.9	357.8	1,111.9	6,561.9
Total Primary Energy	GJ	104,625.2	92,399.2	127,513.0	23,777.3	53,792.8	402,107.4
Non-Renewable Energy	GJ	95,722.9	92,360.2	126,125.1	23,772.2	53,770.4	391,750.9
Fossil Fuel Consumption	GJ	91,656.2	92,216.0	125,025.9	23,753.7	53,687.5	386,339.2

Figure 3 presents the base case percent contribution to GWP of the different activity stages. The percent contribution of material manufacturing, construction and maintenance (M&R) is a function of the roadway design, its construction and life cycle rehabilitation strategy, which together are categorized as embodied effects as opposed to the use phase effects of PVI. Figure 3 shows that the total embodied effect contributes 82% of the total life cycle environmental impact with the remaining 18% attributed to the effects of PVI. It should be noted that diamond grinding is usually considered a rehabilitation treatment and hence the effect of the initial diamond grind of the entire newly built roadway is reported in the maintenance effects instead of

initial construction effects. Therefore, the M&R effects are somewhat overstated, which is another limitation of the software. Another reason that the M&R effects perhaps appear unusually significant for a PCC roadway is that MI's M&R schedule calls for a diamond grind of the entire roadway surface at year 25 and 40, which may not be a typical practice elsewhere.

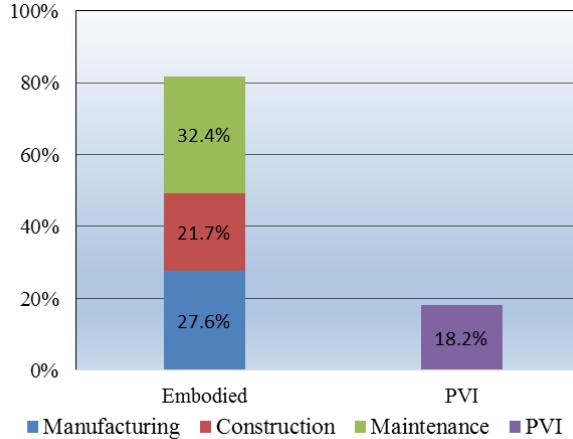


Figure 3: Percent contribution to GWP for the base case

### 5.3 GWP impacts across scenarios

Figure 4 contrasts the GWP impact across the various cases while Table 4 shows the variation (percentage change) from the base case within activity stages.

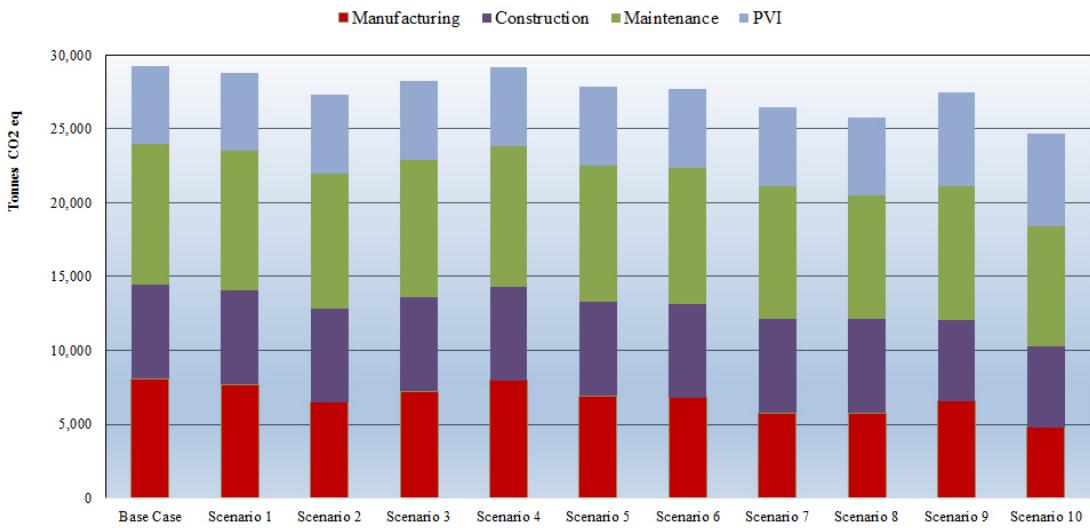


Figure 4: Comparison GWP of different scenarios

Table 4: Variation of GWP of different scenarios from the base case

Scenarios	Base	1	2	3	4	5	6	7	8	9	10
Manufacturing	N/A	-4.6	-19.6	-10.5	-1.3	-14.6	-15.9	-28.9	-28.9	-18.6	-40.7
Construction	N/A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-14.2	-14.2
Maintenance	N/A	-0.9	-3.9	-2.1	0.0	-2.9	-2.9	-5.4	-11.4	-4.7	-14.3
Embodied	N/A	-1.9	-8.1	-4.4	-0.4	-6.1	-6.5	-11.9	-14.3	-11.9	-23.2
PVI	N/A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.4	19.5	17.4
Life Cycle	N/A	-1.6	-6.7	-3.6	-0.4	-5.0	-5.3	-9.7	-12.0	-6.2	-15.8

### *5.3.1 Material manufacturing*

An increase in fly ash content of the base mix from 15% to 20% (Scn. 1) results in a 4.6% reduction in manufacturing GWP while 25% replacement of portland cement by slag (Scn. 2) in the base mix results in a 19.6% reduction in GWP from the base case. A reduction of cementitious material in the mix design from 355 kg/m<sup>3</sup> of concrete to 307 kg/m<sup>3</sup> (Scn. 3), due to the optimization using tarantula aggregate gradation, results in a 10.5% reduction in the GWP from the base case. The combined effect of concrete mix design change (Scn. 5) is 14.6% GWP reduction from the base case. The large reduction in steel quantity from 276 tonnes to 126 tonnes (Scn. 4) showed a net reduction of the GWP of only 1.3% as compared to the base case because of an equivalent and offsetting increase in concrete quantity use. The adoption of new pavement structure, concrete mix design and steel type and placement resulted in a total 15.9% reduction in GWP (Scn. 6). Use of ternary concrete mix could reduce the GWP by 28.9% (Scn. 7) while the use of the thin concrete panel could reduce the GWP by 18.6% (Scn. 9) as compared to the base case. Lastly, the use of thin concrete panel in combination with a ternary mix (Scn. 10) could reduce the manufacturing GWP by up to 40.7% as compared to the base case.

### *5.3.2 Initial construction*

Since there was no change in initial construction quantity and equipment use for Scenarios 1 to 8 from the base case, there is no change in GWP related to construction for these cases. A 14.2% reduction in GWP as related to initial construction is possible with the use of TCP.

### *5.3.3 M&R activities*

The new specification (Scn. 6) adopted by MI reduces the GWP during the M&R phase by 2.9% due to changes in portland cement content. Comparing the GWP results between Scenario 7 and 8 indicates that the five year extension (delay) in the M&R schedule (timing) could provide (11.4% - 5.4% =) 6.0% reduction in GWP as compared to the regular (standard) M&R schedule. When compared to the base case, there is a possible 11.4% GWP reduction by delaying the M&R treatments by five years. A five year delay in the M&R schedule in combination with use of TCP could provide a 14.3% reduction in GWP relative to the base case.

### *5.3.4 Pavement vehicle interaction*

Since the roadway roughness and deflection remained the same as the base case for Scenarios 1 to 7, there is no change in GWP. A small (1.4%) reduction in GWP is expected for Scn. 8 due to fuel savings as the initial pavement remains smoother and experiences less deflection for longer period (five years additional service life to reach the terminal IRI) as compared to all other cases. However, employing the thin concrete panel (TCP) resulted in a 19.5% increase in PVI related GWP due to higher expected deflection as compared to the base case.

### *5.3.5 Overall GWP impacts*

As depicted in Table 4, MI can expect a 6.5% reduction of the embodied GWP; i.e., excluding PVI effects, with the adoption of the new concrete mix design and steel configurations (Scn. 6) relative to the base case. Including the PVI, the overall life cycle GWP reduction is estimated to be 5.3% relative to the base case. Another (9.7% - 5.3% =) 4.4% (Scn. 7 - Scn. 6) reduction in GWP may be possible with the use of ternary concrete mix while further (12% - 9.7% =) 2.3% (Scn. 8 – Scn. 7) reduction in GWP may be possible by extending the initial pavement service life by five years; i.e., by constructing more durable pavements. Overall, a 15.8% reduction in GWP is possible with the use of new concrete mix, ternary mix, thin concrete panel and extension of initial pavement service life by five years relative to the base case.

## *5.4 Comparison of agency costs*

The initial construction costs, maintenance costs, and salvage values for the given cases are computed and the net present values (NPV) are presented in Figure 5(a) together with the percentage reduction in total agency cost as compared to the base case scenario. Figure 5(b) provides a percent contribution of the agency costs for different scenarios. It is observed that initial construction drives the LCCA outcome and that each environmental impact reduction strategy has an associated cost benefit. A comparison of Scenarios 8 and 10 with other scenarios in Fig-

ures 5 (a) and (b) is interesting, where the five-year delayed maintenance strategy, in pair with the 3% discount rate, have decreased the relative contribution of the M&R costs as compared to other Scenarios, while resulting in considerable overall cost reduction levels of 14% and 23%, respectively from the Base Scenario.

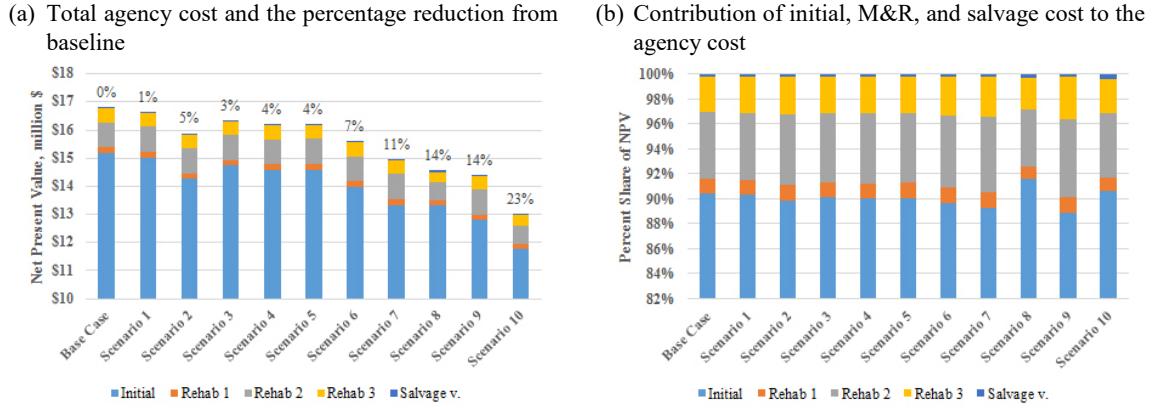


Figure 5: Agency LCCA results for the base case and the 10 scenarios

### 5.5 Comparison of user cost

Figure 6(a) and Figure 6(b) present the user costs of roughness and deflection induced PVI impacts on passenger car and truck fuel consumptions for the old (regular) and new (extended) M&R strategies. The difference in the two cases is the five-year delay of the M&R treatments for the new M&R strategy, where they occur in years 30 and 45 instead of years 25 and 40, respectively. The upward trend of user costs are associated with increasing road IRI levels and the traffic growths of passenger car and trucks. The contribution of roughness induced PVI for passenger cars dominates the associated user costs, followed by the same impact for trucks and deflection induced PVI for trucks. Figure 7 compares the overall old and new M&R user costs, which indicates that the five-year delay has almost no impact (<1%) in reducing the total user cost.

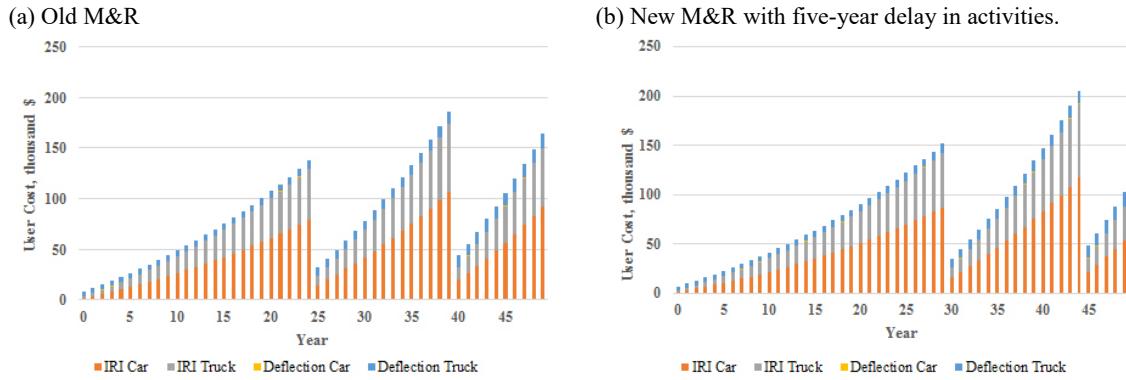


Figure 6: User cost associated with roughness and deflection induced PVI for scenarios.

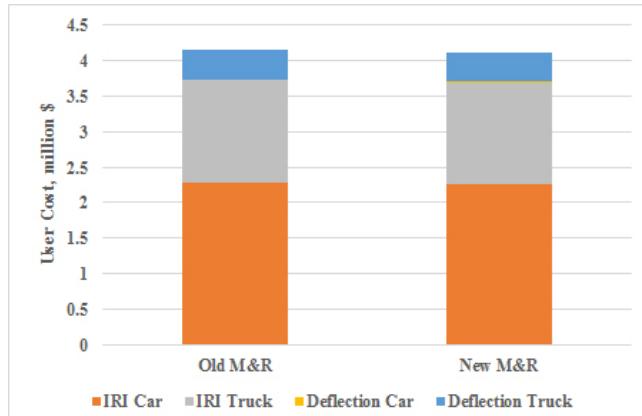


Figure 7: Total user cost associated with roughness and deflection induced PVI for passenger cars and trucks for the old and new M&R strategies

### 5.6 Comparison of total cost

The initial construction, M&R and PVI induced user costs are presented in Figure 8(a) together with the percentage reduction from the base case for each scenario. Figure 8(b) provides percentage contributions of total cost for the base case and the 10 alternative scenarios. Results indicate that the M&Rs contribute the least to the overall agency and user costs. Scenario 10, where several of the environmental impact reduction strategies are combined, shows an 18% reduction in the overall lifecycle cost. And, although the road section has a medium traffic volume, additional research can potentially justify more maintenance activities to mitigate user costs.

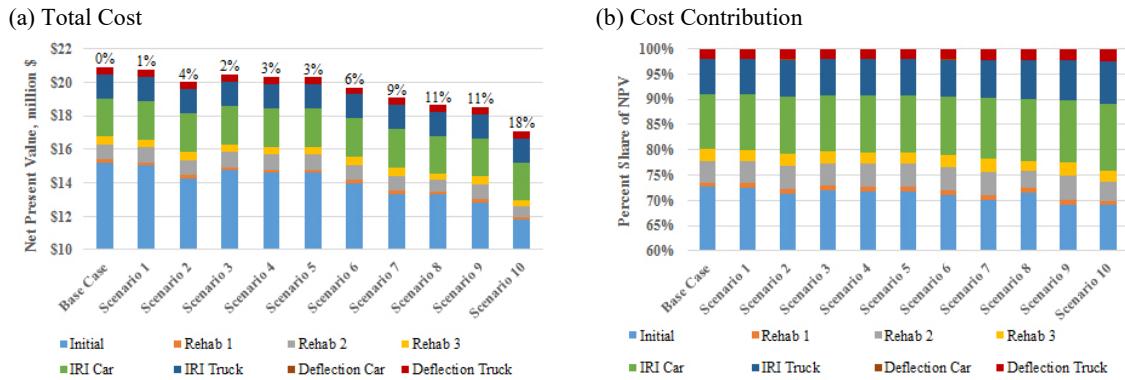


Figure 8: Total life cycle cost including agency and user associated costs

## 6 CONCLUDING REMARKS

This study demonstrates that the transportation sector can contribute significantly to the reduction of environmental impacts by adopting sustainable material, design, construction and maintenance practices and building durable infrastructures. Once a local or project specific scenario is populated, the Athena Pavement LCA software allows users to easily investigate additional alternative scenarios to understand environmental trade-offs and aid in decision making. When used in tandem with robust life cycle cost analysis software the user is additionally informed about the economic trade-offs associated with various roadway construction and life cycle management strategies.

The analysis of different scenarios showed that MI can expect about 5% reduction in overall life cycle GWP with the adoption of the new concrete mix design and dowel/tie bar configurations. Another 7% reduction in GWP may be possible by shifting to the use of ternary concrete mix and extending the pavement service life by five years. The adoption of the new concrete mix design and dowel/tie bar configurations showed a 6% reduction in total life cycle cost. With further enhancement to concrete mix and slab design, 18% reduction in the total life cycle cost is possible.

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