Life Cycle Environmental Assessment Using Athena Pavement LCA Tool: A Manitoba Case Study

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Paper prepared for presentation at the Technical Session:
Sustainability and Climate Change Considerations in Pavements- Life Cycle Assessment of Pavement Projects

The 2016 Conference of the Transportation Association of Canada
September 25-28, 2016, Toronto, Ontario

ABSTRACT

Environmental sustainability is one of the four strategic priorities of the Department of Manitoba Infrastructure. Life Cycle Assessment (LCA) is acknowledged as one of the most comprehensive ways to evaluate the environmental impacts of different strategies associated with a physical feature. The Athena Pavement LCA software for highways is a tool that can be used to assess the environmental impacts of materials production, construction, and maintenance & rehabilitation activities over a given life cycle period. The software is also capable of modeling pavement vehicle interactions (PVI) to assess the environmental impact of traffic use phases of a roadway due to pavement surface roughness and deflection.

This paper presents comparisons of the environmental impacts of various alternative strategies for a concrete pavement to demonstrate the opportunity to optimize pavement performance and environmental impacts. The concrete pavement constructed in 2015 on Manitoba Provincial Truck Highway 75 (PTH 75) has been used as a case study. A matrix of alternative concrete mix, pavement design, and maintenance and rehabilitation strategies has been used to compare environmental impacts of those alternative options. The analysis presented is expected to assist Manitoba Infrastructure and other agencies to better understand and weigh the environmental implications of alternative roadway materials, design as well as construction, maintenance and rehabilitation practices and select the best strategy considering pavement performance and preservation of our natural environment.

INTRODUCTION

Background

The Manitoba Government is committed to maintaining ecological integrity by greening the government operation and promoting environmentally sustainable practices. Manitoba Infrastructure is one of the largest departments within the Manitoba Government with a vast operational mandate. Department of Manitoba Infrastructure is positioned to lead the government into “greening government operations” through the adoption of environmentally sustainable design, construction, preservation, maintenance and other operational practices. Accordingly, environmental sustainability has been adopted as one of the four strategic priorities of Manitoba Infrastructure.

Life Cycle Assessment (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, formerly known as the Impact Estimator for Highways, is loaded with a large material and construction equipment database. It has the ability to compare the impacts of different pavement designs, mix design optimization as well as alternative maintenance & rehabilitation schedules and timing on our natural environment. Thus, the software allows users to quickly and easily analyze and compare the environmental implications of multiple scenarios of materials production, construction, maintenance & rehabilitation and use phase treatments for a roadway pavement. 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 the associated environmental impacts.

Recently, Manitoba Infrastructure 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 environmental impacts of these changes, except the DSB whose specification is still under evaluation, with the base case scenario before adoption of these changes. Additional comparison includes environmental impacts of adding slag in the concrete mix (in addition to fly ash - ternary mix) and extension of initial pavement service life.

Objectives, Scope and Significance

The objectives of this paper are to show, using the Athena Pavement LCA tool, the environmental impacts of various modifications made to both concrete mix and pavement design and to explain the performance reasons for making these modifications.

For the case study, the concrete pavement constructed in 2015 on PTH 75 in Manitoba has been used. The analysis included a matrix of alternative concrete mix designs based on changes in cement/aggregate, fly ash and slag contents, pavement designs based on changes in steel contents, and rehabilitation practices based on the extension of initial pavement service life due to more durable pavement. This allowed for the comparison of environmental impacts from eight alternative scenarios with the base case.

The analysis presented in this paper is expected to assist Manitoba Infrastructure and other agencies to better understand and weigh the environmental implications of alternative roadway designs, construction, maintenance and rehabilitation practices, and pavement service life. It will also provide an understanding of the reasons for doing such analysis before the selection of a strategy to ensure an optimal strategy that include life cycle costs, pavement performance and environmental impacts.

PAVEMENT LCA SOFTWARE

Overview

In the Athena Pavement LCA tool, users may enter their specific roadway designs (base, subbase and surface layers and length of the roadway) or select from a library of sample regional portland cement concrete (PCC) or asphalt concrete (AC) roadway designs and customize to their situation. The software has undergone significant enhancements and improvements since being initially released in 2011 Beta version as a Windows desktop application. In May 2016 a web-enabled version of the tool was released. The software is free to the roadway design community with support from the Athena Institute’s members, collaborators and supporters.

Data Sources

Pavement materials, energy and transportation data was derived from proprietary Athena Institute databases as well as public and commercially available Life Cycle Inventory (LCI) databases. The materials data 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 comes loaded with updated LCA results for Canadian portland cement, American slag cement and updated Canadian regional energy and electricity grid profiles.

Analysis Outputs

In the Athena Pavement LCA software, users can quickly describe roadway parameters through a few easy input screens and then can view results in a variety of ways. The inventory results are comprised of: energy and raw material flows plus emissions to air, water and land. The software reports a comprehensive set of life cycle impact assessment results, resource use metrics and enables easy side-by-side comparison of different design options across pavement life cycle stages.

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, and can subsequently compare the life cycle operating and embodied energy and other environmental effects of various design options, allowing the user to better understand trade-offs.

CASE STUDY PROJECT DETAILS

Project Description

PCC pavement constructed in 2015 on the northbound PTH 75 in Manitoba is used as a case study in this paper. The project is located approximately 30 km south of Winnipeg (from 2.9 km north of PR 305 to 0.5 km north of PR 210) for a total length of 11.02 km. For the 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 with 650 heavy vehicles (trucks) and 3,250 light duty vehicles. The traffic growth rate is 2% (typical).

The existing roadway consisted of 100 mm bituminous over a 250 mm concrete and 125 mm granular base. The new pavement construction consists of milling the existing bituminous, rubblizing the existing concrete, placing 100 mm granular base (DSB layer), 255 mm concrete, diamond grinding the new concrete (5 mm loss) and shoulder widening with bituminous (100 mm thick) and gravel surfaces. The cross section of the new roadway is shown in Figure 1.

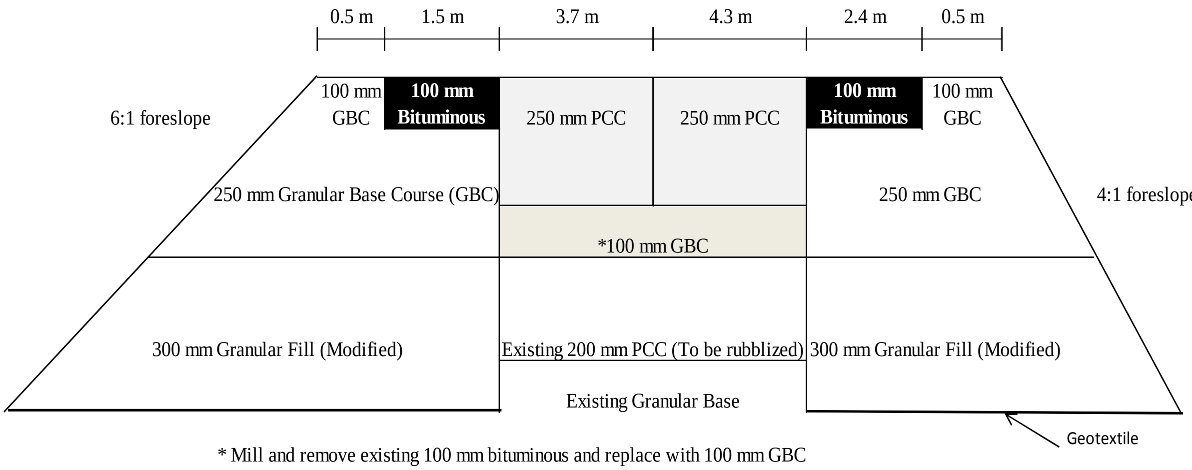


Figure 1: Roadway Cross Section (Not to Scale)

Life Cycle Strategy

Manitoba Infrastructure performs life cycle cost analysis for a 50-year period to select a pavement strategy. Manitoba's rigid pavement life cycle strategy is shown in Table 1. These treatments and their lives have been used for the analysis presented in this paper.

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

Concrete Pavement Construction and Concrete Mix Design

Manitoba Infrastructure is currently reviewing their concrete pavement specifications. Several changes have been adopted over the last few years with hope to make concrete pavements more economical and durable. Some other changes are still under review. This paper focuses on the impacts of changes in concrete mix design through the adoption of tarantula aggregate gradation band and reduction of cement content, increase of fly ash content and adding slag in the concrete mix (in addition to fly ash - ternary mix). On the pavement structural side, changes include the use non-corrosive steel dowels and tie bars, and reduction in dowels and tie bars quantities.

Supplementary Cementing Materials (SCMs) and Ternary Mixes

The aim of mixture proportioning is to find the combinations of available and specified materials that will 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 pavement 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 state. The selection of the cementitious system should be to maximize SCM contents while preventing alkali silica reaction (ASR), resisting freezing and thawing distress, and meeting other specified requirements. The quality of the paste, including the w/cm ratio and air void system, should be selected based on the environment to which the mixture will be exposed. The two most commonly used SCMs in concrete paving are fly ash and slag cement. Table 2 provides a summary of the side effects and interactions of SCMs in concrete mix (Taylor 2014).

Fly ash is a byproduct of the combustion of pulverized coal in thermal power plants. The rock embedded in the coal melts in the furnace and is carried up the stack in the flue gases. As it rapidly cools, small glassy spheres are formed that are collected before the flue gases are emitted to the air. Dosage of fly ash is typically between 15 and 40 percent by mass of cement. The amount of fly ash that can be used is often limited by concerns of delayed setting times and lower early strength gain.

Slag cement is made from iron blast-furnace slag, the material left after extraction of iron from iron ore. When quenched from the molten state and ground to the fineness of cement, it is an extremely effective SCM. It is generally used in pavements in dosages up to 50 percent but is limited by concerns of early strength gain, especially when placed during cooler ambient temperatures, and of scaling resistance. As with fly ash, usage tends to be regional because of limitations on the cost effectiveness of transporting it long distances when it is not available locally.

Ternary concrete mixtures include three different cementitious materials. The optimum mixture proportions for ternary blends, as with other concrete, will be dependent on the final use of the concrete, construction requirements and seasonal considerations. 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 W/CM applications such as paving, mixtures with 15 percent fly ash and 30 percent slag cement component have been used successfully. For example, in 1998, airfield concrete pavements were constructed at the Minneapolis Airport using a ternary mix consisting of portland cement with 35% slag and 10% class C fly ash. Performance of this pavement has been excellent.

Table 2: Summary of the Benefits, Side Effects and Interactions of SCMs (Taylor 2014)

Properties	Supplementary Cementitious Material			
	Class F Fly Ash	**Class C Fly Ash**	**Slag Cement**	**Silica Fume**
Workability	Significantly Improved	Improved	Neutral/Improved	Improved at low dose (<5%), decreased at high dose
Air Void System	May be difficult to entrain air with high LOI	Neutral	Neutral	May be difficult to entrain air
Setting	Delayed	Slightly Delayed	Slightly Delayed	Accelerated
Incompatibility	Low Risk	Some Risk	Low Risk	Low Risk
Strength Gain	Slower but continues longer	Slightly slower but continues longer	Slightly slower but continues longer	Accelerated Initially
Stiffness	(Related to Strength Gain)			
Heat Generation	Lower	Slightly Lower	Slightly Lower	Higher
Shrinkage	Neutral	Reduced	Neutral	Increased
Permeability	Improved over time	Improved over time	Improved over time	Improved
ASR	Improved	Improved at sufficient dosage	Improved at high dosages	Slightly Improved
Sulfate Attack	Improved	Improved at sufficient dosage	Improved at high dosages	Neutral
Corrosion Resistance	Slightly Improved	Slightly Improved	Improved	Improved

Manitoba Infrastructure used to allow a maximum of 15% fly ash; this was recently increased to 20% (maximum). For ternary concrete mix, agencies typically use a combination of 15% fly ash and 25% slag by mass of total cementitious (portland cement and SCMs) materials.

Optimization of Aggregate Gradation

Another technique used in concrete mix design optimization is through aggregate gradation and proportioning to reduce the total cementitious content of the mix, using the tarantula curve (Ley et al. 2012). The Tarantula curve provides an envelope in which a desirable amount of material retained on each sieve is reported. The curve varies from the Haystack in that for most fractions, the upper and lower bounds are broadened, except for those on the #8 and #16 sieves that are reduced. 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). Essentially this will allow a reduction in paste content by use of an intermediate 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.

Manitoba's concrete mix design had been based on the individual gradation of coarse and fine aggregates. In 2015, Manitoba adopted the tarantula aggregate gradation band in the specification and increased the maximum size of the aggregate from 19 mm to 25 mm. This resulted in a reduction of the total cementitious material content from 355 kg/m^3 (typical) to 307 kg/m^3. Figure 2 and 3 show how the Pre-2015 and 2015 aggregate gradations fit into the tarantula aggregate gradation band (tarantula curve).

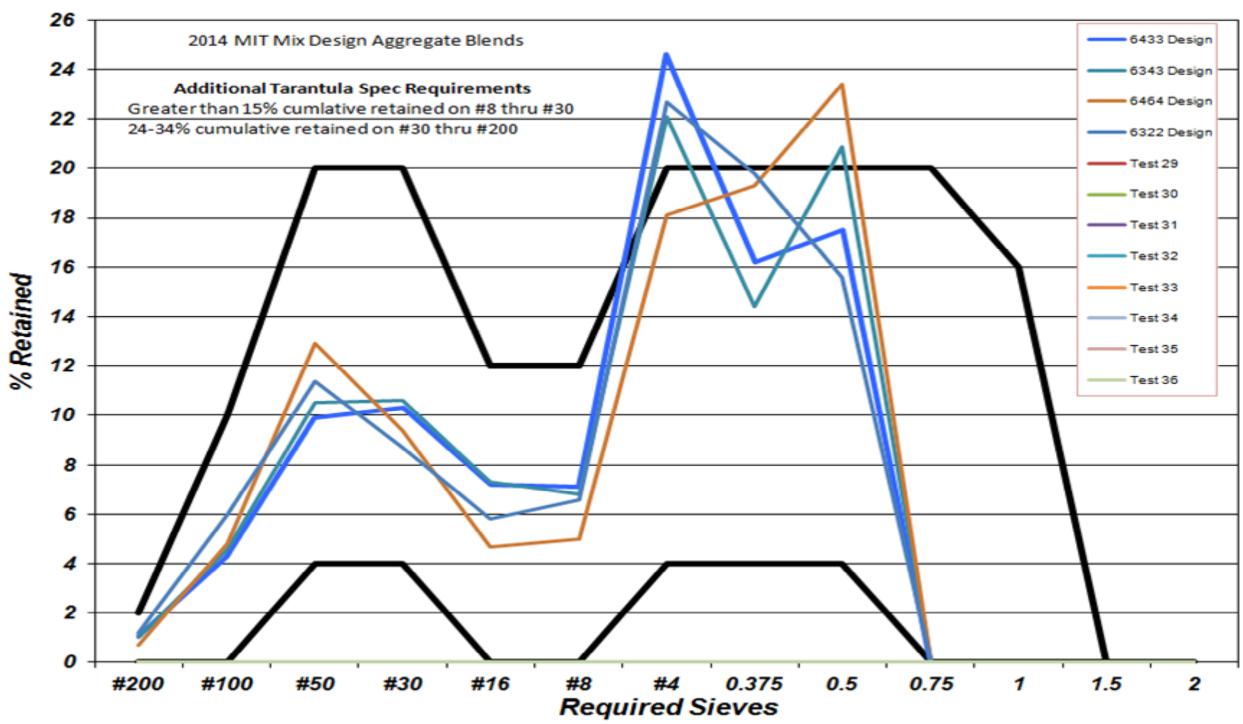


Figure 2: Pre-2015 Aggregate Gradation in Tarantula Curve

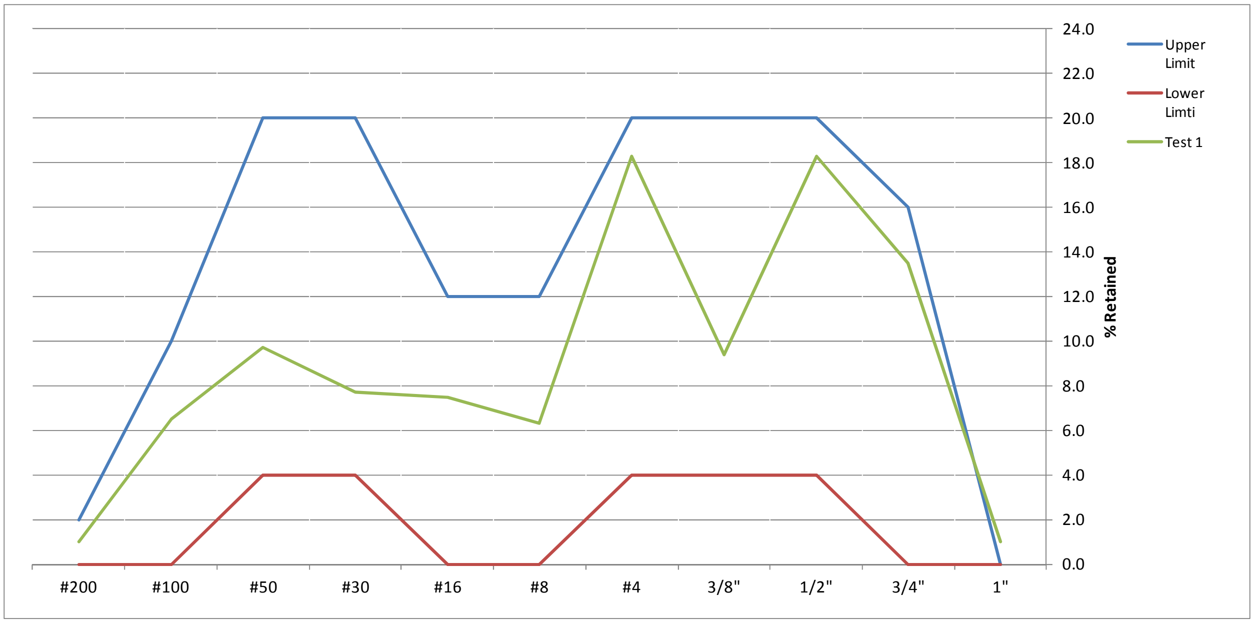


Figure 3: 2015 Aggregate Gradation in Tarantula Curve

Modifications to Pavement Structure (Dowels and Tie Bars)

Dowel detail and joint design is one of the most innovative concepts evolving in concrete pavement engineering today. Due to decreased transportation funding and a rising focus on sustainability, owners and agencies are looking for ways to minimize initial construction costs and to look more closely at alternative construction materials.

In highway applications, the focus has been mainly on geometry (round, elliptical), alternative materials (stainless, galvanized, epoxy coated), standardization of dowel baskets assemblies (staking methods), and the potential impact of dowel bar misalignment (Snyder 2011).

Dowel bar optimization is a fairly new concept, however, with engineering tools such as finite element analyses packages like EverFE (http://www.civil.umaine.edu/EverFE/), concrete pavement engineers can now actively engineer these design details given their specific project details and constraints.

Current trends in highway dowel design are looking at a reduction in the number of dowel bars. Also the placement of dowel bars in the wheel path in contrast to the conventional placement of dowel bars at 300 mm on center. Moving the dowels off the edge of pavement with the outside dowel moving from 150 mm to 300 mm (or even 450 mm) off the longitudinal joint, helps with constructability and can also help with interference from the adjacent tie bars if they are used.

The cost savings of reducing the number of dowel bars varies by doweling technology specified, quantity ordered, local availability, and other factors, but the cost reduction is on the order of five dollars per dowel bar. If as many as six dowel bars might be removed in each and every doweled transverse joint in a Jointed Plain Concrete Pavement (JPCP) design, the resultant savings can be substantial, not to mention the positive impacts on sustainability of the pavement. Even the reduction of two dowels per joint may prove worthwhile.

Manitoba had been constructing JPCP using epoxy coated steel dowels and tie bars. The dowel bars were 38 mm in diameter, 450 mm long and were placed at 300 mm interval along the transverse joints (26 dowels per 8 m wide transverse joint). The tie bars were 19.5 mm diameter and 915 mm long. Total four ties were used along a 4.5 m long longitudinal joint. For an 11.02 km road section under this case study project, the total steel requirement is calculated to be 276 tonnes. Manitoba has experienced corrosion of both dowel and tie bars resulting in transverse and longitudinal joints deterioration including the longitudinal joint separation. Because of the observed corrosion and joint deterioration issues, MI explored alternative reinforcing dowels and tie bars, and revised the JPCP specification for dowels and tie bars few years ago.

The current JPCP specifications requires use of the stainless steel or zinc clad dowels and stainless steel tie bars. Considering economical and technical aspects of dowel size requirements, longevity and location of wheel paths (where about 90% of the wheel load repetitions occurs), the dowel size has been changed to 32 mm with a requirement to place 4 dowels in each wheel path i.e., total 16 dowels per transverse joint (two lanes). The current requirements for stainless steel tie bars are 16 mm diameter, 750 m long and five dowels per 4.5 m long longitudinal joint. The estimated steel quantity is 126 tonnes for the 11.02 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 to estimate the effect of changes in quantity.

ANALYSIS AND RESULTS

Alternative Analysis Scenarios

Nine cases (base case plus eight alternative cases) were run in the Athena Pavement LCA software to show the environmental impacts and effects of actual or possible changes in one or more attributes. These alternative scenarios including their rationales are listed in Table 3. The base case represents a past standard mix design using 355 kg of cementitious material per m^3 of concrete, of which 15% was fly ash but no slag. The quantity of steel was 276 tonnes. The proportion of coarse and fine aggregates was 61:39. Manitoba’s regular (standard) maintenance & rehabilitation (M & R) cycles are used to estimate the environmental impacts during the use phase (after initial construction) of the newly constructed roadway. Subsequent analysis cases include modification to the fly ash, slag (to produce a ternary mix), steel and M & R cycles from this base case.

Case 6 represents Manitoba’s current standard mix designs, construction and M & R. Although this mix design optimizes the aggregate blend to reduce cementitious material contents with the use of large maximum size and intermediate sized aggregates, there was a negligible change in the proportion of coarse and fine aggregates from the previous concrete mix design.

Cases 2 and 7 are intended to show the effects of ternary concrete mix as compared to the previous practice (base case) and the new practice. Case 8 shows the effect of possible 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). In this case, the timing of the M and R treatments were arbitrarily delayed by 5 years from the regular M and R treatments shown in Table 1.

To estimate the environmental impacts due to traffic use, the PVI analysis considered vehicle operating speed of 100 km/h, initial international roughness index (IRI) of 0.665 m/km, pre diamond ground (terminal) IRI of 2.5 m/km and post 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^3 and 28,600 MPa, respectively. The analysis assumed 15 mm loss in concrete thickness during the second and third diamond ground treatments.

Table 3: Alternative Analysis Scenarios

Case #	Case Description	Case ID	Analysis Rationale
Base	355 kg cementitious, 15 % fly ash, 0% slag, 276 tonnes steel and regular M & R	355CE-15FA-0SL-276DT-RR	Impacts of past practice
1	355 kg cementitious, 20 % fly ash, 0% slag, 276 tonnes steel and regular M & R	355CE-20FA-0SL-276DT-RR	Effect of additional fly ash
2	355 kg cementitious, 15 % fly ash, 25% slag, 276 tonnes steel and regular M & R	355CE-15FA-25SL-276DT-RR	Effect of slag/ternary mix, if used
3	307 kg cementitious, 15 % fly ash, 0% slag, 276 tonnes steel and regular M & R	307CE-15FA-0SL-276DT-RR	Effect of reduced cementitious material (tarantula optimization)
4	355 kg cementitious, 15 % fly ash, 0% slag, 126 tonnes steel and regular M & R	355CE-15FA-0SL-126DT-RR	Effect of reduced steel
5	307 kg cementitious, 20 % fly ash, 0% slag, 276 tonnes steel and regular M & R	307CE-20FA-0SL-276DT-RR	Combined effect of reduced cementitious and increased fly ash
6	307 kg cementitious, 20 % fly ash, 0% slag, 126 tonnes steel and regular M & R	307CE-20FA-0SL-126DT-RR	Combined effect of reduced cementitious and steel, and increased fly ash (new spec.)
7	307 kg cementitious, 20 % fly ash, 25% slag, 126 tonnes steel and regular M & R	307CE-15FA-25SL-126DT-RR	Combined effect of new spec. and slag/ternary mix, if used
8	307 kg cementitious, 20 % fly ash, 25% slag, 126 tonnes steel and regular M & R	307CE-15FA-25SL-126DT-ER	Effect of extended M and R

Environmental Impacts of Base Case

The LCA tool provides estimates of environmental impacts in terms of several impact indicators (attributes) 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) as shown in Table 4. Comparisons of all these impact indicators are beyond the scope of this paper. Therefore, the subsequent analysis presents comparisons of the global warming potential (GWP).

Table 4: Base Case Environmental Impacts

Activities		*Manufacturing*		*Construction*		*Maintenance*		*Use Phase - Excess Fuel Consumption due to PVI*		*Total Life Cycle*
Sustainability/ Climate Change Indicators	Measurement Units	Material	Transportation	Equipment	Transportation	Material and Equipment	Transportation	PVI Effects (IRI)	PVI Effects (Deflection)	Total
Global Warming Potential	tonnes CO_2 eq	7,662.4	445.7	5,849.4	509.1	9,326.9	178.6	1,632.7	3,701.6	29,306.3
Acidification Potential	tonnes SO_2 eq	31.4	4.2	52.7	4.6	76.4	1.6	10.4	33.1	214.4
HH Particulate	tonnes PM2.5 eq	14.1	0.2	3.1	0.3	5.6	0.1	0.5	1.9	25.8
Eutrophication Potential	tonnes N eq	1.5	0.3	3.5	0.3	4.9	0.1	0.7	2.2	13.4
Ozone Depletion Potential	tonnes CFC-11 eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Smog Potential	tonnes O_3 eq	398.2	141.7	1,768.9	154.0	2,435.7	54.0	357.8	1,111.9	6,422.1
Total Primary Energy	GJ	104,569.3	6,438.9	85,001.1	7,398.0	126,412.7	2,594.7	23,777.3	53,792.8	409,984.8
Non-Renewable Energy	GJ	104,314.0	6,436.2	84,965.3	7,394.9	126,341.2	2,593.6	23,772.2	53,770.4	409,587.9
Fossil Fuel Consumption	GJ	84,558.5	6,426.1	84,832.7	7,383.4	122,281.1	2,589.5	23,753.7	53,687.5	385,512.4

Figure 4 shows the distribution of GWP among different activities for the base case in terms of percentages of total GWP from pavement design option, construction and M & R (% of Dgn-Const-Rehab) as well as percentages of the total life cycle GWP that includes the PVI effects. The embodied effect (material and equipment) includes the effects of material manufacturing and equipment use. The embodied transportation effect includes effects of material and equipment transportation.

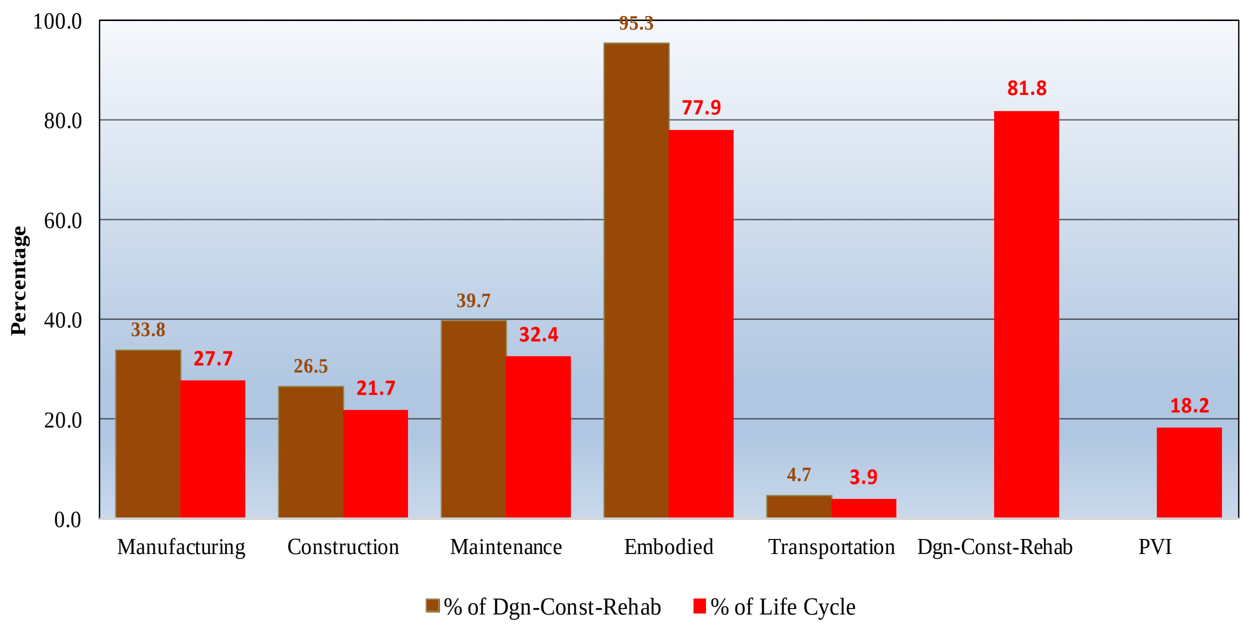
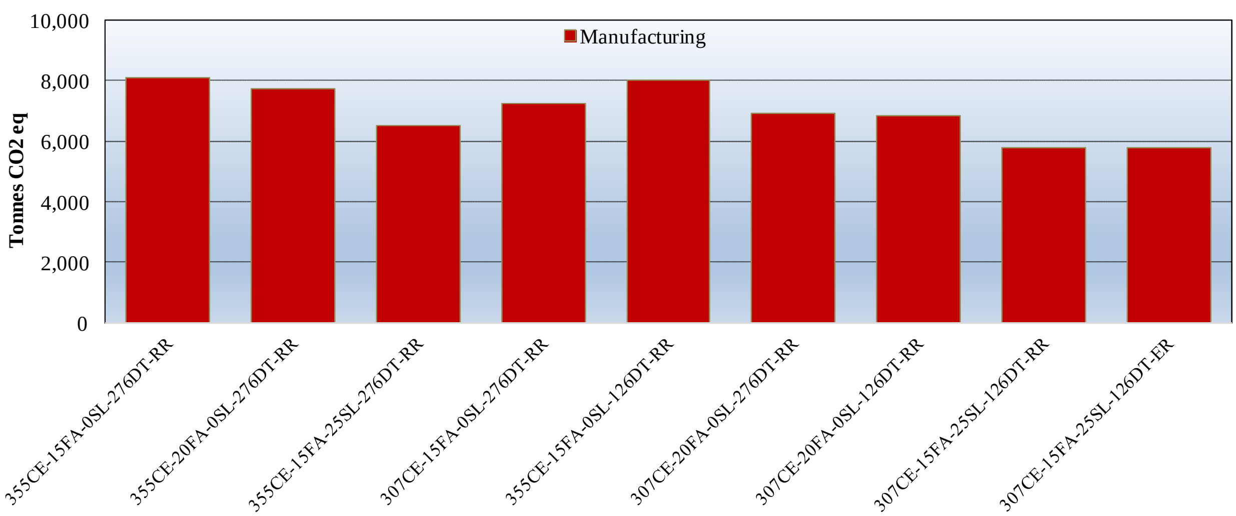


Figure 4: Distribution of GWP for the Base Case

As shown in Figure 4, the highest impact is due to the use phase M & R treatments. The embodied effect due to material and equipment contributes to 78% of the total life cycle environmental impact. The PVI contributes to 18% of the total life cycle environmental impact. The impact of material and equipment transportation is small.

Comparison of Environmental Impacts Due to Material Manufacturing

Figure 5 shows comparisons of environmental impacts from various case studies due to the material manufacturing (material production and transportation). An increase in fly ash content from 15% to 20% (i.e., increase by 5%) in the base mix (previous concrete mix design) results in a 4.6% reduction of GWP while 25% replacement of portland cement by slag in the base mix results in a 19.6% reduction of GWP as compared to the base case. A reduction of cementitious material from 355 kg/m^3 of concrete to 307 kg/m^3 (with tarantula aggregate gradation blend and 5% increase of fly ash proportion) is expected to provide 10.5% reduction of the GWP. The combined effect of concrete mix design change is 14.6% reduction of the GWP from the base case. However, the big reduction of steel quantity from 276 tonnes to 126 tonnes showed only 1.3% reduction of the GWP as compared to the base case resulting in a total 15.9% reduction of the GWP due to the adoption of new pavement structure and concrete mix design. Use of ternary concrete mix could reduce the GWP by 28.9% as compared to the base case.

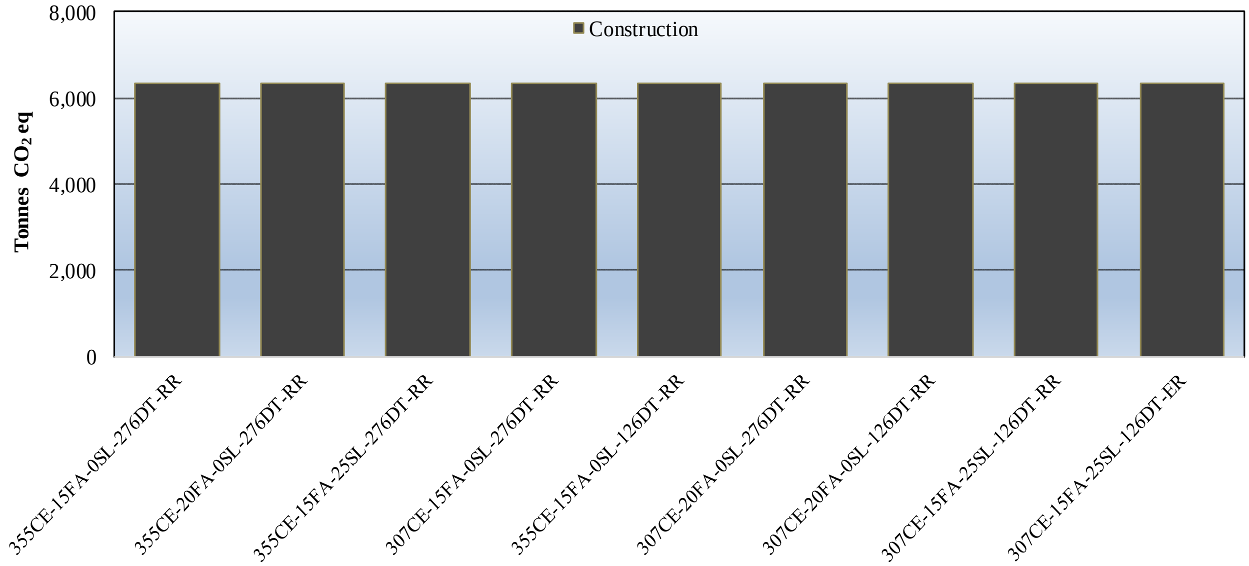


% Change from the Base Case								
N/A	-4.6	-19.6	-10.5	-1.3	-14.6	-15.9	-28.9	-28.9

Figure 5: Comparison GWP Due to Manufacturing

Comparison of Environmental Impacts Due to Initial Construction

Since there was no change in initial construction quantity and equipment use, there is no change in environmental impacts (GWP) related to construction as shown Figure 6.

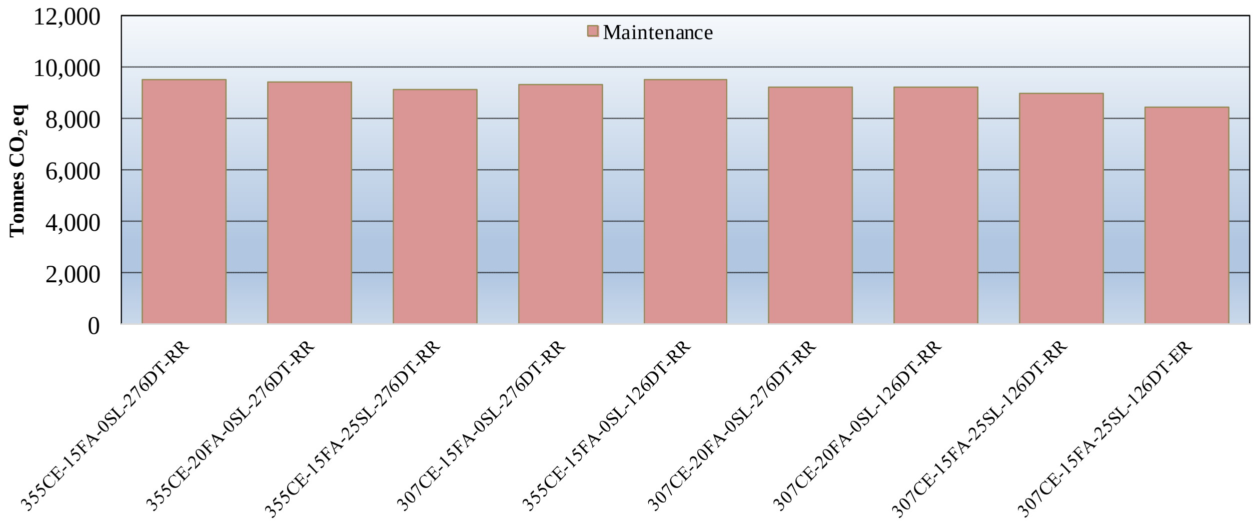


% Change from the Base Case								
N/A	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 6: Comparison GWP Due to Initial Construction

Comparison of Environmental Impacts Due to M & R Activities

The comparisons of environmental impacts from various study cases due to the life cycle M & R strategy (material, equipment and transportation) is shown in Figure 7. The variations of the GWP are due to the variations in concrete mix design only for alternative cases 1-7 as there was no change in equipment use and their transportation when compared to the base case. The highest environmental benefits are related to the replacement of cement with slag and reduction of portland cement content during the M & R phase. A comparison of the GWP between cases 7 and 8 shows that five years extension (delay) in the M and R schedule (timing) could provide (11.5% - 5.4% =) 6.1% reduction of the GWP as compared to the regular (standard) M and R schedule. As compared to the base case, there is 11.5% reduction of the GWP for five years delay in the M & R treatments.

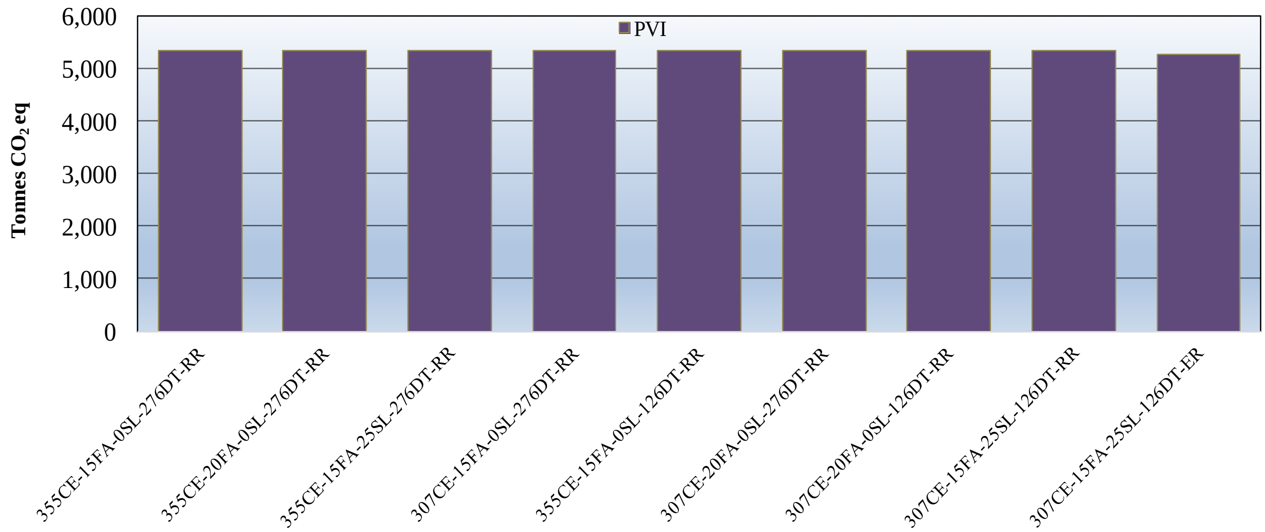


% Change from the Base Case								
N/A	-0.9	-3.9	-2.1	0.0	-2.9	-2.9	-5.4	-11.5

Figure 7: Comparison GWP Due to the M and R Treatments

Comparison of Environmental Impacts Due to Pavement Vehicle Interaction (PVI)

The comparisons of environmental impacts from excess fuel consumption due to roadway roughness and deflection are shown in Figure 8. Since the roadway roughness and deflection remained the same as the base case for alternatives 1 to 7, there is no change in the GWP. A reduction of the GWP by 1.4% is expected due to fuel savings as initial pavement remains smoother and experiences smaller deflection for longer period (five years additional service life to reach the terminal IRI) as compared to all other cases.

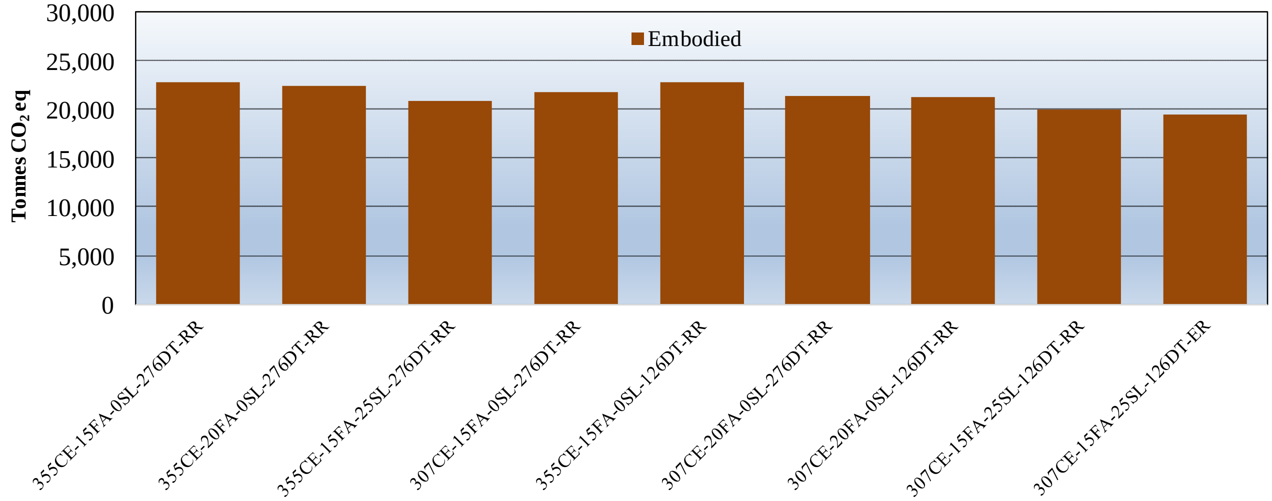


% Change from the Base Case								
N/A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.4

Figure 8: Comparison GWP Due to PVI

Comparison of Environmental Impacts Due to Embodied Materials and Equipment Effect

Figure 9 shows comparisons of the total GWP due to materials manufacturing and equipment use (excluding transportation). As shown in the figure, additional 5% replacement of portland cement with fly ash provides 2% reduction of the GWP while a replacement of portland cement with 25% slag is expected to provide an 8.6% reduction of the GWP related to material productions when compared to the base case. The reduced cement quantity resulted in a 4.6% reduction of the GWP from the base case. The effect of steel quantity reduction is shown to be small. The adopted new concrete mix and steel configurations in Manitoba is expected to reduce the GWP by 6.8% as compared to the base case from material manufacturing perspective. The 2.4% difference between cases 7 and 8 is related to the reduced “salvage value” of the effects of the final maintenance steps. Cases 1 to 7 have partial and full depth repairs and diamond grinding at year 40, lasting 15 years, therefore 2/3 of the effects contribute to the results. In case 8, the final step was moved to year 45, therefore only 1/3 of the effects contribute to the results.

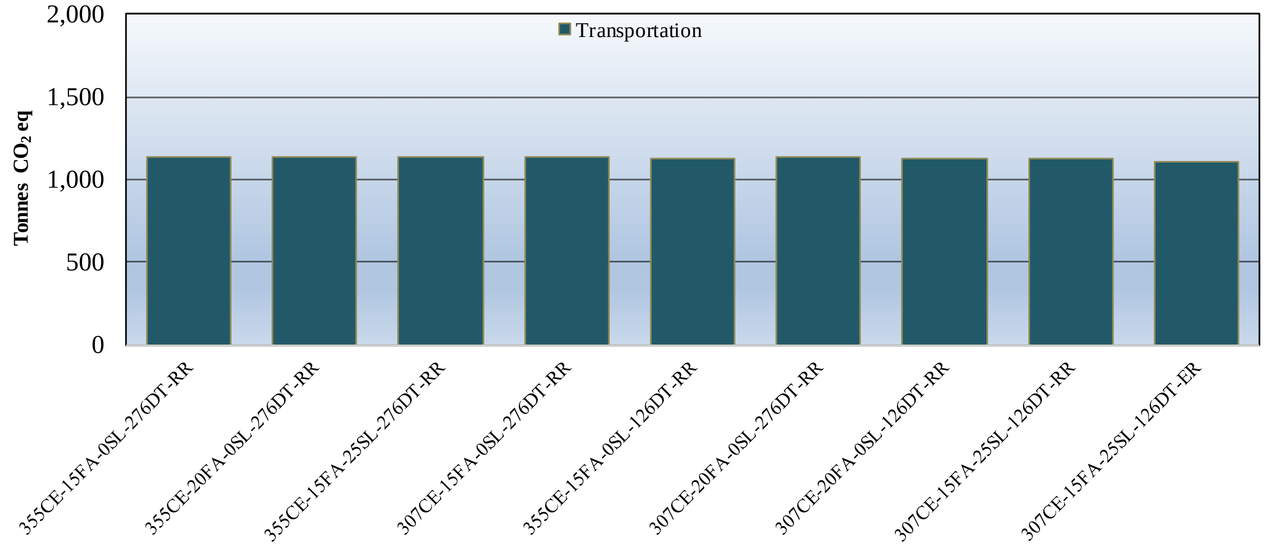


% Change from the Base Case								
N/A	-2.0	-8.6	-4.6	-0.4	-6.4	-6.8	-12.5	-14.9

Figure 9: Comparison GWP Due to Embodied (Materials and Equipment) Effect

Comparison of Environmental Impacts Due to Materials and Equipment Transportation

Figure 10 shows the comparisons of environmental impacts due to embodied material and equipment transportation effects during manufacturing, construction and M& R phases. Figure 10 shows a small increase in the GWP when there is a reduction in the cementitious material content from 355 kg/m^3 to 307 kg/m^3 of concrete and the corresponding reduction of the quantity water (W/CM remained unchanged). This increase is related to the transportation of other materials (to make up total mass per cubic meter of concrete). Quantity wise, the largest change among the analysis cases is the reduction of steel from 276 tonnes to 126 tonnes resulting in the highest reduction of the GWP related to the transportation. The extended (delayed) M & R due to increased durability of the initial pavement showed 2.7% reduction in the GWP as compared to the base case.

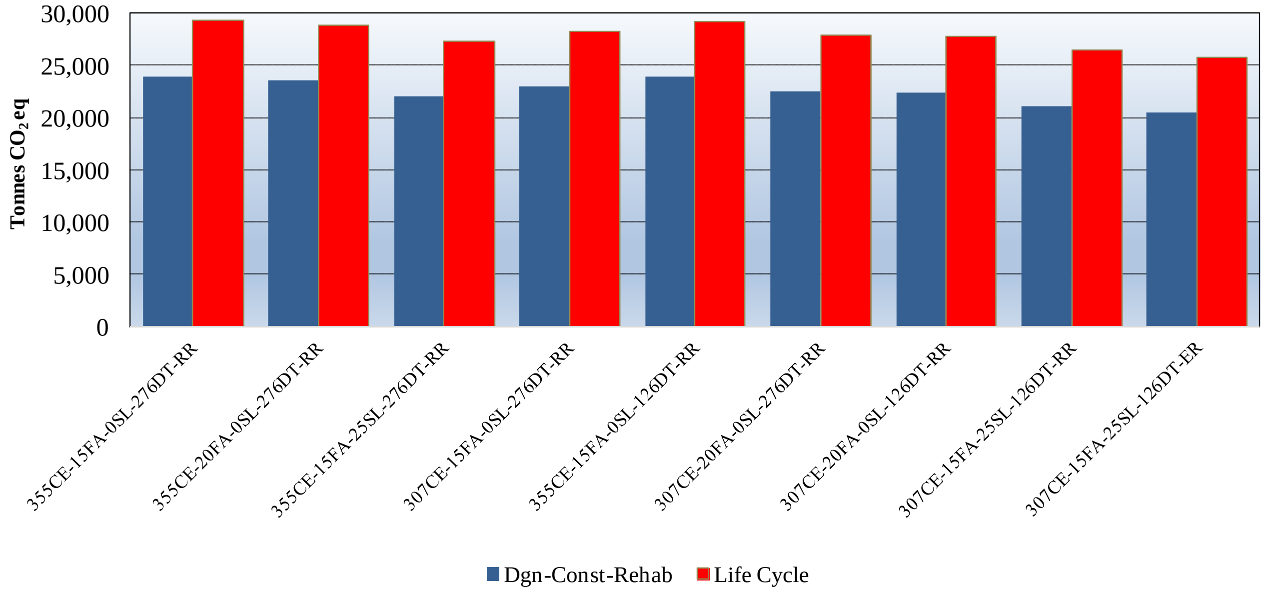


% Change from the Base Case								
N/A	0.0	0.0	0.3	-1.1	0.4	-0.7	-0.8	-2.7

Figure 10: Comparison GWP Due to Materials and Equipment Transportation

Comparison of Combined Environmental Impacts

The comparisons of total environment impacts from design, construction and M & R (Dgn-Const-Rehab) as well as the total life cycle impacts including the traffic use (pavement vehicle interaction) effects are presented in Figure 11. As shown in the figure, Manitoba can expect a 6.5% reduction of the GWP, excluding the excess fuel consumption due to the PVI, with the adoption of the new concrete mix deign and steel configurations. Including the PVI, the overall life cycle GWP reduction is estimated to be 5.3% from base case. Another (9.8% - 5.3% =) 4.5% reduction of the GWP may be possible with the use of ternary concrete mix and another (12.0% - 9.8% =) 2.2% reduction of the GWP may be possible by extending the initial pavement service life by five years i.e., by constructing more durable pavements.



Attributes	% Change from the Base Case								
Design, Construction, Rehabilitation	N/A	-1.9	-8.2	-4.4	-0.4	-6.1	-6.5	-11.9	-14.3
Total Life Cycle	N/A	-1.6	-6.7	-3.6	-0.4	-5.0	-5.3	-9.8	-12.0

Figure 11: Comparison Dgn-Const-Rehab and Total Life Cycle Impacts

CONCLUDING REMARKS

The study analysis presented in this paper showed that transportation sector can greatly contribute to the reduction of environmental impacts by adopting sustainable material, design, construction and maintenance practices and building durable infrastructures. The Athena Pavement LCA software is a great tool to perform a comparative analysis of alternative options and to aid decision making in combination with the life cycle costs.

The analysis presented showed that Manitoba can expect about 5% reduction of the GWP with the adoption of the new concrete mix design and dowel/tie bar configurations. Further significant reduction of the GWP may be possible with the use of ternary concrete mix and extension of pavement service life.

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