An LCA-Based Approach for Reducing GHG Emissions from Asphalt Pavements: An Ontario Study

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Paper prepared for the session “A Changing Climate: Pavement Resilience in the Era of a Changing Global Landscape”

2026 Transportation Association of Canada (TAC) Conference & Exhibition
Winnipeg, Manitoba

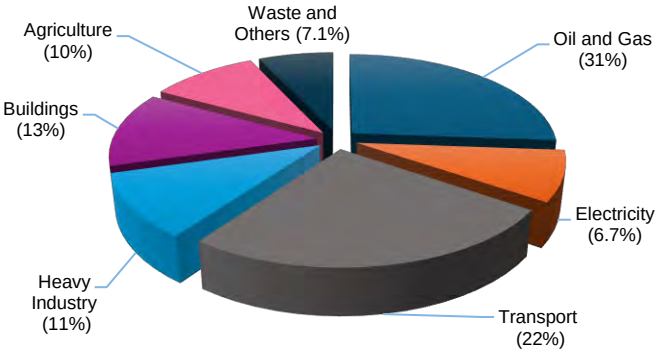
Abstract

In pavement design and management practice, the integration of life cycle assessment (LCA) has become increasingly crucial for facilitating environmental conservation and economic efficiency. However, very few studies have focused on LCA for asphalt pavements in Canada, creating a significant knowledge gap in understanding region-specific factors. This study conducted a detailed investigation using pavement LCA to quantify the greenhouse gas (GHG) emissions arising from various structural conditions of asphalt pavements. A comprehensive pavement structural design matrix consisting of 23 conventional asphalt pavement structures employed in Ontario was evaluated with various lift thicknesses and in-situ resilient modulus for roads with different traffic volumes. Additionally, the incorporation of a sustainable pavement alternative, reclaimed asphalt pavement (RAP), was examined to assess its potential to reduce GHG emissions from an environmental point of view. This study reveals that, within the system boundaries considered in this study, the manufacturing phase was the most significant contributor to total GHG emissions, often exceeding 65%. Also, the sensitivity analysis concludes that the transportation distance of materials moderately influences the GHG emissions arising from asphalt pavement. Moreover, the scenario analysis advocates for incorporating RAP contents in the granular layers of asphalt pavements, with each roadway type achieving around 4,000 kg CO_2 eq. in global warming potential (GWP) reductions on average. Thus, the outcomes of this study set a foundation for future research to analyze and develop sustainable alternatives to pursue the required resilience in asphalt pavement construction.

Introduction

Due to the ever-increasing effects of global warming, climate change exerts a profound environmental impact globally. As global temperatures continue to rise, the infrastructure foundational to the society are also confronting challenges of unprecedented scale and complexity[1, 2.] Asphalt pavement is widely used in the construction of various infrastructural facilities such as roads, highways, and airports because of its durability, low maintenance, and cost-effectiveness. According to the Canadian Technical Asphalt Association, in North America, about 94% of paved roads are surfaced with asphalt. It is estimated that Canada has just over 500 hot-mix asphalt plants, which collectively produce approximately 30 to 31 million tonnes of asphalt mixtures each year[3]. In addition, the construction of asphalt pavement involves the extraction and processing of raw materials, transportation of these materials to the construction site, and the mixing and laying of the pavement[4]. These activities collectively generate significant environmental impacts throughout the entire construction process[5].

Figure 1. Canada's GHG emissions by economic sector (2022)



Environment and Climate Change Canada reported that the transportation sector was the second largest contributor to GHG emissions in Canada, accounting for 22% of the total emissions with 156 Mt CO2 eq. released in 2022, as shown in Figure 1[6]. However, under the Paris Agreement, Canada has committed to reducing its greenhouse gas emissions by 40 to 45% below 2005 levels by 2030. Furthermore, Canada is dedicated to carrying out its expanded climate plan to reach net-zero emissions by 2050[7]. As a result, the asphalt industry is being called upon to reduce emissions to align with national and international goals for climate change mitigation and sustainability.

The issues associated with environmental emissions are critical in areas with vast road networks, such as Ontario, where the extensive interaction between urban development and road infrastructure plays a significant role in shaping the region's GHG emissions profile[8]. The dense road network in Ontario, heavily utilized for commercial and personal transportation, leads to increased use of asphalt for pavement construction and maintenance. This, in turn, contributes substantially to the overall environmental emissions. As the substantial impact of greenhouse gases becomes increasingly apparent on global climate patterns, the precise quantification of these emissions from asphalt pavement infrastructures emerges as a crucial step in environmental conservation and climate change mitigation[9].

In this scenario, LCA can be a viable option to provide a comprehensive analysis of the life cycle phases of asphalt pavement to identify significant environmental impacts[10]. Additionally, LCA supports decision-making by offering insights into the environmental benefits of alternative sustainable materials and technologies[11]. However, there has been limited focus on the LCA for asphalt pavements in Canada, which creates a significant knowledge gap, particularly in understanding region-specific factors. This study addresses the critical need for pavement-specific LCA research in Canada by providing actionable data to guide the stakeholders in adopting sustainable pavement practices.

In exploring environmentally friendly practices, one promising area can be incorporating RAP in asphalt pavement structures[12]. By incorporating RAP into pavement structures, researchers and practitioners can mitigate the environmental impacts of virgin material use and move towards a more sustainable and circular approach to pavement construction and maintenance[13]. Despite the growing global emphasis on sustainable pavement alternatives, little focus has been placed on systematically assessing the environmental benefits of using RAP in the Canadian context. This research aims to fill that gap, offering insights into how RAP can potentially reduce the carbon footprint of asphalt pavements while maintaining and enhancing pavement performance in Canada.

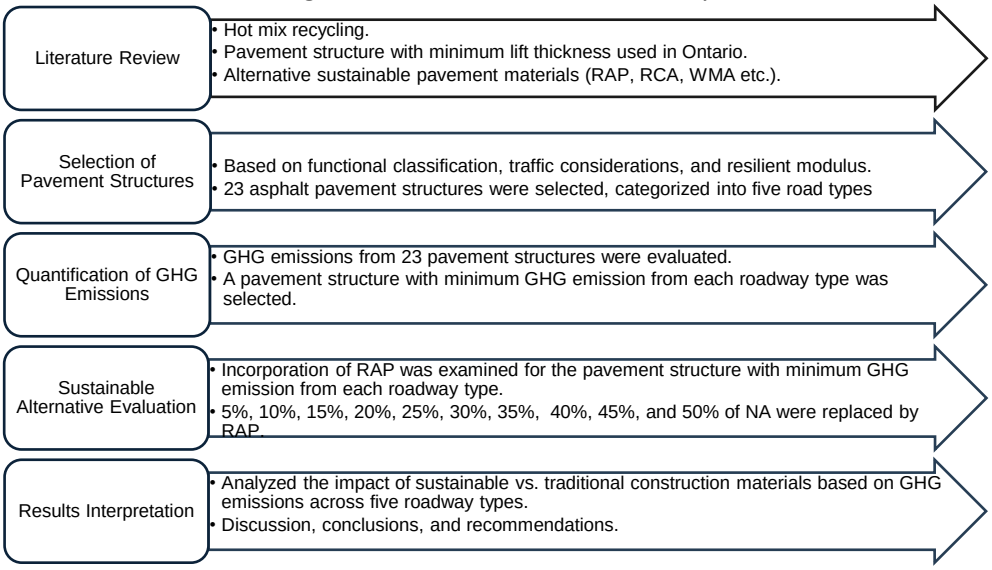
Objectives and Research Framework

The prime objective of this study was to quantify the GHG emissions obtained from various structural conditions of asphalt pavements used in Ontario. To achieve this goal, 23 asphalt pavement structures were selected based on functional classification, traffic considerations, and subgrade resilient modulus. The asphalt pavements were then categorized into five roadway types: local, collector, minor arterial, major arterial, and expressways. The outcomes provided a GHG emission range for each roadway type, which is crucial for setting standards, decision-making, and identifying sustainable alternatives in pavement infrastructure. Additionally, the study examined the contribution of the major life cycle stages to the total GHG emissions, with the intent of identifying and informing targeted reduction strategies.

The second objective was to assess the potential of a sustainable pavement alternative, RAP, in reducing GHG emissions associated with asphalt pavement structures. For this, ten different asphalt mixtures with

varying RAP percentages (5% to 50% by weight of granular materials) for each roadway type were studied. The outcomes were utilized to determine whether the emissions obtained after RAP incorporation were lower than the minimum GHG emissions for each roadway type. The research framework for this study is comprehensively structured into five sequential stages as illustrated in Figure 2.

Figure 2. Research flow of this study



LCA for Ontario Asphalt Pavements

The life cycle analysis performed in this study is a comparative attributional process-based LCA, conducted by following the 'four-stage methodology' outlined by the ISO 14040 guidelines[14] and the Federal Highway Administration's (FHWA) 'Pavement LCA Framework'[15]. This process includes defining the goal and scope, conducting the life cycle inventory, performing the life cycle impact assessment, and interpreting the results.

Goal and Scope Definition

Goal

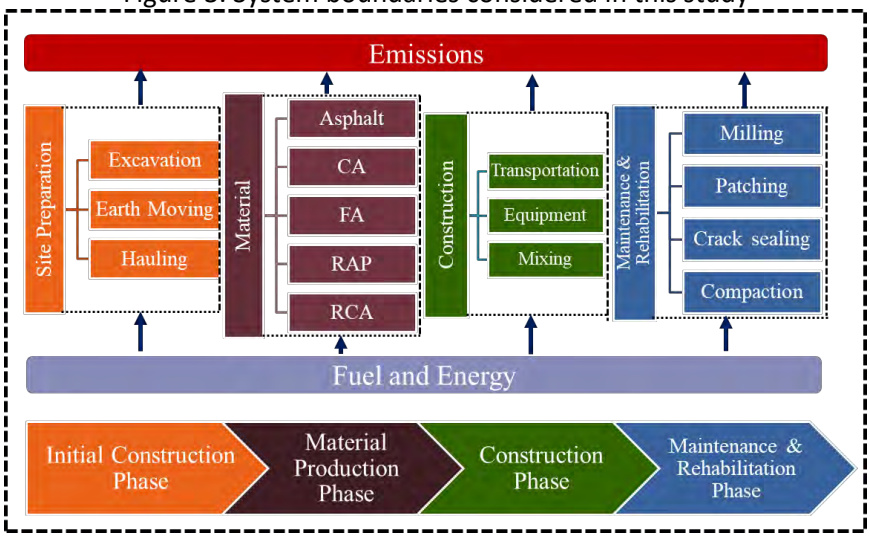
This study aimed to investigate the environmental emissions generated by various asphalt pavements in Ontario. This included analyzing the variations in GHG emissions across diverse pavement structural conditions under usual operating scenarios. Additionally, a significant aspect of this study was to investigate the incorporation of RAP in proportions of 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50% by weight of granular coarse aggregates in conventional asphalt pavement structures. The findings are intended to inform and assist highway agencies and pavement practitioners in developing sustainable pavement practices, potentially leading to the widespread adoption of eco-friendly infrastructures.

System Boundaries

The life cycle analysis was carried out using a 'cradle-to-gate' approach[15]. Figure 3 outlines the scope of the system and the main processes included in the study. Specifically, the analysis covered four key phases of the pavement life cycle:

- Initial construction, which involved site preparation tasks such as excavation, earth moving, and material hauling.
- Material transportation, including transporting materials to and from the construction location as well as between intermediate facilities.
- Processing of materials and production of mixtures at the asphalt mixing plant.
- Pavement construction, maintenance and rehabilitation.

Figure 3. System boundaries considered in this study

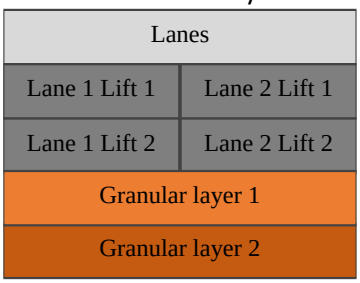


Additionally, a 'cut-off' allocation method was used to manage the RAP. This means that only the impacts associated with processing the RAP to make it suitable for use in asphalt mixtures were assigned to the system. Environmental impacts related to the demolition of the pavement and the transport of demolition materials to the recycling facility were not considered within the system boundaries of this study[16–18].

Functional Unit

The functional unit considered in this study was a typical roadway section in Ontario of 1-km length, two lanes with an individual width of 3.75 m. The service life was 30 years. The average annual daily traffic (AADT) varied according to the type of road selected, which is presented in Table 3.

Figure 4. Cross-section of the roadways considered in this study



The cross-section of a typical pavement structure adopted in the roadways is presented in Figure 4, and the details in Table 2. For pavement maintenance, typical pavement maintenance and rehabilitation strategies derived from Canadian practice for each type of roadway were considered.

Spotlight on the Pavement LCA

Pavement LCA, developed by the Athena Sustainable Materials Institute in Canada, specializes in analyzing roadway life cycles in Canadian conditions and selected regions in the US. The software includes a detailed database of materials, allowing users to customize the design of pavement surfaces, subbase, base, and shoulder materials[19, 20]. Athena Pavement LCA features options for measuring impacts like energy consumption, resource usage, and other specific environmental effects such as global warming potential (GWP), fossil fuel consumption, and acidification. For example, the GWP is calculated using CO_2 emissions along with factors for other gases based on guidelines from the Intergovernmental Panel on Climate Change (IPCC),

$$GWP(kg) = CO_2(kg) + [CH_4(kg) * 23] + [N_2O(kg) * 296] \quad (8)$$

The first step of the LCA usually concentrates on acquiring raw materials and transporting them to the site. These materials can be divided into two groups: asphalt layers and aggregate layers. To quantify emissions from the material production and manufacturing phase, Equation 1 was followed by Swarna et al., 2022,

$$CO_{2\ emissions}{}_{site\ preparation+manufacturing} = \sum_{i=material} Volume_i * Density_i * CO_{2\ emission\ rate_i} \quad (1)$$

where,

$$CO_{2\ emission\ rate\ i} = \frac{CO_{2_{emissions}}}{\$_i * \frac{\$}{mass\ material\ produced_i}}$$

Here, "$" reference to Canadian dollars, or CAD.

During the construction stage of the LCA, the focus is on the fuel consumption of equipment used in the construction process. It assumes that emissions from transportation were covered in the earlier phase, so it only accounts for the emissions from front loaders, road graders, paving machines, and other construction-specific equipment. The following Equation 2 was employed by Swarna et al., 2022 to determine the emissions from the construction stage.

$$CO_{2\ emissions\ construction} = \sum_{i=pavement\ layer} \sum_{\substack{i=construction \\ equipment}} (Volume_i * Density_i * Fuel\ consumption\ rate_i * Density\ of\ fuel_i * CO_{2\ emission\ rate\ per\ fuel\ mass_i}) / Utility\ rate_i \quad (2)$$

Additionally, the maintenance phase includes all emissions related to the maintenance and rehabilitation of pavements. The intervals for maintenance are estimated based on the type of road. Wastage factors for all imported materials are also considered. However, the Athena Pavement LCA software excludes demolition and disposal in its calculations, assuming that the long lifespan of highway pavements negates the need for demolition or disposal[1].

Life Cycle Inventory (LCI)

Project and roadway information

Several input parameters were required regarding the project and roadway to quantify the GHG emissions from asphalt pavement structures. Table 1 lists the various inputs considered for the roadway construction project in central Ontario. Two asphalt lifts with two granular layers were considered for the flexible pavement. No paved or unpaved granular shoulder was included in the analysis in order to isolate the emissions associated with the mainline pavement structure. Average distances from plant to site, from equipment depot to site, and from site to stockpile were considered to be 30 km in each case [8]. Canadian dollars (CAD) were used as the project currency, with an exchange rate of 1.3 to the US dollar, a 2.08% inflation rate, and a 1.76% discount rate for cost calculations.

Roadway layers

Table 2 shows the features typically present in the design of asphalt pavement structures. In the hot mix asphalt (HMA) surface layer, Ontario (ON) HMA Superpave 12.5 was utilized, having a density of 2.52 tonnes/m^3. ON HMA Superpave 19, with a 2.46 tonnes/m^3 density, was utilized in the HMA binder layer. ON Granular A was utilized for the base course, and ON Granular B for the subbase course. The density of ON Granular A and ON Granular B were 2.4 tonnes/m^3 and 2 tonnes/m^3 respectively.

Table 1. LCA parameters considered in this study

Project and Roadway Information	Inputs
Project Type	Roadway
Project Lifespan	30 years
Project Location	Ontario - Central
Average Distance from Plant to Site	30 km
Average Distance from Site to Stockpile	30 km
Average Distance from Equipment Depot to Site	30 km
Project Currency	CAD
USD to CAD Exchange Rate	1.3
Real Inflation Rate	2.08 %
Real Discount Rate	1.76 %
Lane Length	1 km
Number of Lanes	2
Number of Pavement Lifts	2
Number of Granular Layers	2 (Base and Subbase)
Pavement Type	Flexible Pavement
Paved Shoulder	No

Table 2. Features of roadway layers used in all pavement structures

Element Name	Layer	Material	Width (m)	Density (tonnes/m^3)
Lane 1 Lift 1	HMA Surface	ON HMA Superpave 12.5	3.75	2.52
Lane 1 Lift 2	HMA Binder	ON HMA Superpave 19	3.75	2.46
Lane 2 Lift 1	HMA Surface	ON HMA Superpave 12.5	3.75	2.52
Lane 2 Lift 2	HMA Binder	ON HMA Superpave 19	3.75	2.46
Granular Layer 1	Base	ON Granular A	7.50	2.4
Granular Layer 2	Subbase	ON Granular B	7.50	2

Asphalt pavement structures

To understand the environmental emissions from asphalt pavements in Ontario, this study examined 23 different pavement structures [22]. The details of the selected asphalt pavement structures are outlined in Table 3. These pavement structures were categorized based on their functional classifications, traffic considerations, and subgrade resilient modulus. For instance, based on functionality, the asphalt pavements were divided into five main roadway types: local, collector, minor arterial, major arterial, and expressways. Each roadway type was further segmented into distinct categories, with five pavement structures for all except expressways, which had three. Notably, each pavement structure considered in the study represents the minimum structural requirements for the specific roadway type in Ontario, respecting structural design perspectives [22]. The study assumes that the environmental emissions calculated from these baseline conditions are the lowest possible emissions these road types could produce, given their minimum pavement structural specifications.

This detailed categorization allows for a comprehensive analysis of environmental emissions from each type of pavement structure, providing insights into the emissions profile of specific roadway types. By understanding the minimum structural requirements for pavements in Ontario, the study aims to establish a baseline for GHG emissions. This baseline can then be used to evaluate if sustainable alternatives can achieve lower GHG emissions than these minimum levels, offering a pathway to more environmentally friendly paving solutions.

Table 3. Roadway design details based on function, traffic volume, and subgrade support

Roadway Type	Pavement Structure	HMA Surface (mm)	HMA Binder (mm)	Base (mm)	Subbase (mm)	Total Thickness (mm)	Subgrade Support, Mr (MPa)	AADT
Local	Local Residential (L1) 3% Commercial Vehicles	40	60	150	150	400	30	2,500

	Local Industrial (L2) 10% Commercial Vehicles	40	80	150	150	420	30	3,000
	Local Industrial (L3) 10% Commercial Vehicles	40	60	150	150	400	50	3,000
	Local Throughway (L4) 3% Commercial Vehicles	40	60	150	150	400	30	4,500
	Local Throughway (L5) 3% Commercial Vehicles	40	60	150	150	400	50	4,500
Collector	Collector Residential (C1) 3% Commercial Vehicles	40	70	150	150	410	30	5,000
	Collector Industrial (C2) 5% Commercial Vehicles	40	105	150	150	445	30	7,500
	Collector Industrial (C3) 5% Commercial Vehicles	40	115	150	150	455	30	10,000
	Collector Industrial (C4) 5% Commercial Vehicles	40	85	150	150	425	50	10,000
	Collector Industrial (C5) 5% Commercial Vehicles	40	125	150	150	465	30	15,000

Minor Arterial	Truck Routes (MI1) 7.5% Commercial Vehicles	40	135	150	150	475	30	20,000
	Non-Truck Routes (MI2) 4% Commercial Vehicles	40	80	150	150	420	50	20,000
	Non-Truck Routes (MI3) 4% Commercial Vehicles	40	105	150	150	445	30	25,000
	Truck Routes (MI4) 7.5% Commercial Vehicles	40	140	150	150	480	30	25,000
	Truck Routes (MI5) 7.5% Commercial Vehicles	40	120	150	150	460	50	25,000
Major Arterial	Truck Routes (MA1) 10% Commercial Vehicles	40	150	150	250	590	30	30,000
	Truck Routes (MA2) 7.5% Commercial Vehicles	40	130	150	250	570	50	40,000
	Non-Truck Routes (MA3) 5% Commercial Vehicles	40	135	150	200	525	30	50,000
	Truck Routes (MA4) 7.5% Commercial Vehicles	40	145	150	250	585	50	60,000
	Truck Routes (MA5)	40	185	150	250	625	30	75,000

	10% Commercial Vehicles							
Expressway	Truck Routes (EX1) 10% Commercial Vehicles	55	140	200	300	695	30	80,000
	Truck Routes (EX2) 10% Commercial Vehicles	60	150	200	350	760	30	100,000
	Truck Routes (EX3) 12.5% Commercial Vehicles	50	150	250	325	775	50	120,000

For facilitating some necessary inputs, such as operation of construction equipment, transportation of materials, energy use, etc., the databases from the Athena Sustainable Materials Institute were used. Apart from that, the public and commercially available life cycle inventory databases were also used in this study as these databases consist of the required data necessary for the analysis. For example, the materials data include national or industry averages for the extraction, processing, and manufacturing of materials and products. The energy usage in Canadian regional grids and transportation distances was then applied to the energy used in manufacturing processes and material sourcing to create regional data profiles. Ultimately, the Athena Pavement LCA database served as the base system, while all specific activities representing the detailed system were integrated directly into it for LCA calculations.

Life Cycle Impact Assessment

TRACI v2.0 impact assessment methodology was used in this study to classify and characterize the LCI data according to the characterization factors as outlined by Bare[23]. This methodology allows systematic analysis of the environmental impacts from pavement structures across a wide range of impact categories. The categories include global warming potential (GWP), acidification potential (AP), eutrophication potential (EuP), ozone depletion (OD), ecotoxicity (Ec), human health factors (HH), smog potential (SP), and fossil fuel depletion (FFD) [23]. However, although the detailed characterization was carried out, the study did not extend to the optional LCA steps such as normalization, grouping, and weighting advised by the ISO 14040 standards [14]. Finally, to model the processes within the scope of the study, Pavement LCA software was used [19].

Results and Discussion

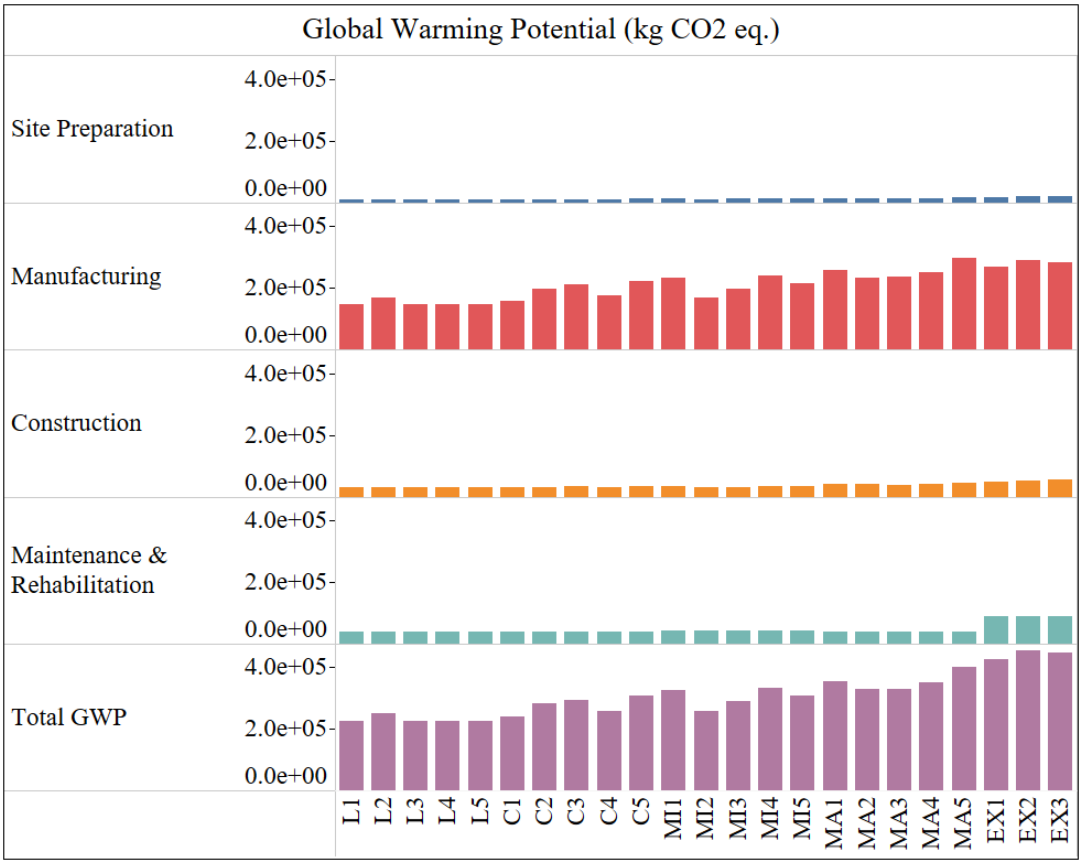
Quantification of GHG emissions by contribution analysis

The first objective of this study was to quantify the GHG emissions from Ontario roadways. As a result, during this phase, GHG emissions from 23 asphalt pavement structures were evaluated from five major

roadway types. The total GWP came from the contributions of four phases of the LCA within the system boundaries, i.e. site preparation, manufacturing, construction, and maintenance & rehabilitation.

Figure 5 provides an overview of GWP in kg CO_2 equivalent obtained from 23 asphalt pavement structures. In the case of local roads, the total GWP ranged from 2.26×10^5 kg CO_2 eq. to 2.51×10^5 kg CO_2 eq., with L1 having the lowest total GWP and L2 having the highest. The manufacturing phase was the most significant contributor to total GWP, ranging from 1.46×10^5 kg CO_2 eq. to 1.70×10^5 kg CO_2 eq. on all local pavement structures, followed by construction, and maintenance & rehabilitation. Site preparation remained consistent and was the lowest contributor to total GWP among all local road structures. In collector roads, the total GWP was lowest for C1 at 2.39×10^5 kg CO_2 eq. and highest for C5 at 3.08×10^5 kg CO_2 eq. Manufacturing remained the highest contributing phase for total GWP for all pavement structures of collector roads, with emissions highest at 2.22×10^5 kg CO_2 eq. for C5 and the lowest at 1.58×10^5 kg CO_2 eq. for C1.

Figure 5. Graphical representation of GWP across different asphalt pavement structures



In minor arterial roads, MI4 had the highest total GWP at 3.33×10^5 kg CO_2 eq., while MI2 had the lowest at 2.58×10^5 kg CO_2 -eq. The manufacturing phase was the most significant contributor to total GWP for minor arterial pavement structures. The site preparation phase added 1.31×10^5 kg CO_2 eq. in the case of MI4 to the total GWP, and it was 1.15×10^5 kg CO_2 eq. for MI2. The GWP contribution for maintenance & rehabilitation was consistent for all minor arterial roads, each contributing 4.48×10^4 kg CO_2 eq.

For major arterial roads, the total GWP varied significantly. MA5 was evaluated as the pavement structure with the highest total GWP at 4.00×10^5 kg CO_2 eq., while MA3 showed the lowest at 3.30×10^5 kg CO_2 eq. The manufacturing phase was the main contributor to total GWP, contributing 2.98×10^5 kg CO_2 eq. for MA5 and 2.34×10^5 kg CO_2 eq. for MA2. As the lowest contributor to total GWP, site preparation contributed 1.69×10^4 kg CO_2 eq. to total GWP for MA5, while in the case of MA3, it was lowest at 1.43×10^4 kg CO_2 eq.

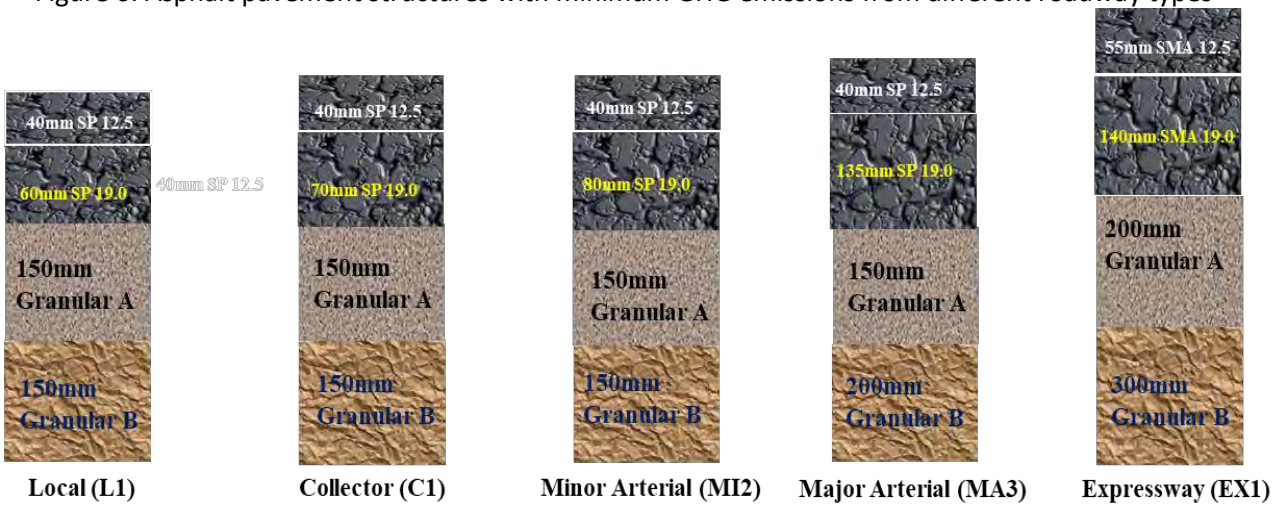
Finally, expressways showed the highest overall GWP among all road types, with the manufacturing phase being the most significant contributor. The total GWP ranged from 4.28×10^5 kg CO_2 eq. (EX1) to 4.54×10^5 kg CO_2 eq. (EX2), with a moderate GWP from EX3. The manufacturing phase contributed the most to these amounts, with EX2 and EX1 having values of 2.91×10^5 kg CO_2 eq. and 2.71×10^5 kg CO_2 eq., respectively.

The emission and contribution analysis quantified the GWP of 23 asphalt pavement structures commonly used in Ontario. This study covered five major roadway types and provided a detailed emission range for GWP within the system boundaries of this study. The analysis also revealed a clear and phenomenal trend: the manufacturing phase was consistently the most significant contributor to total GHG emissions for all roadway types, often exceeding 65%. On the other hand, site preparation generally contributed the least, around 5%. The construction and maintenance & rehabilitation phases also contribute substantially, particularly around 15% for each.

Asphalt pavement structures with minimum environmental emissions

The emission and contribution analysis identified five asphalt pavement structures from five major roadway types with minimum GWP. These pavement structures are L1, C1, MI2, MA3, and EX1, which are represented in Figure 6.

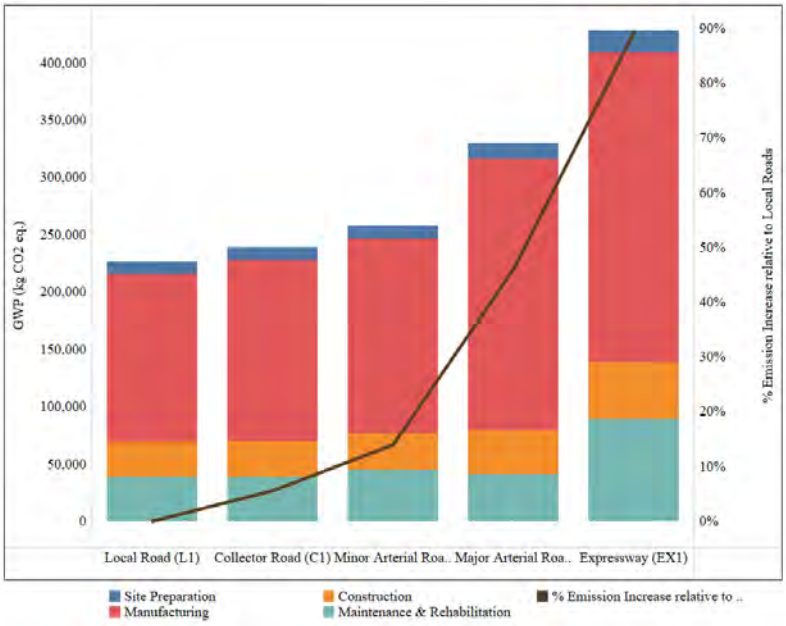
Figure 6. Asphalt pavement structures with minimum GHG emissions from different roadway types



One of the major objectives of this study was to assess the feasibility of incorporating RAP in asphalt pavement structures, and these five pavement structures assisted in evaluating this. The analysis involved incorporating RAP in these pavement structures to evaluate potential changes in GHG emissions. If the

emissions were lower in asphalt pavement structures with RAP content than those from these five pavement structures, it would validate RAP as a sustainable alternative from an environmental point of view.

Figure 7. Total GWP and percent emission increase for asphalt pavements



The total GWP emissions and the percentage emission increase for the five roadway structures are shown in Figure 7. The pattern depicts that the GWP emissions gradually increase as the roadway type shifts from local roads to expressways. Again, the percentage increase in emissions relative to local roads indicates that, although C1 showed a minor increase of 5.57% compared to the local road, L1, the minor arterial road, MI2, displayed a moderate rise in emissions of about 14%. Moreover, the major arterial road, MA3, had a more substantial increase of 46%, indicating significantly higher emissions compared to L1. The expressway (EX1) exhibited a substantial increase of around 90% in emissions relative to local road (L1). This data highlights the dire need for focused efforts to reduce GWP emissions, particularly in larger and more heavily used road types like major arterial roads and expressways.

Sensitivity analysis

Sensitivity analysis is essential in environmental impact assessment, particularly when explaining complex systems like asphalt pavement structures. It discusses the extent to which the outcomes are sensitive to changes in the value of some significant input parameters. Sensitivity analysis also helps to validate the robustness of the model by demonstrating that the results are consistent and reliable across a variety of input parameter values [8, 18].

In this study, the 'transportation distance of materials' was considered as the parameter for sensitivity analysis. The parameter was selected primarily for its significant impact in assessing the environmental footprint of pavement projects [8]. Notably, the sensitivity analysis was conducted considering a wide range of environmental impact categories to evaluate the relative sensitivity of GWP with respect to the sensitivity parameter. Therefore, by varying the transportation distance from an initial value of 10 km to

distances of up to 100 km, the sensitivity of various impact categories such as GWP, AP, HHP, EuP, ODP, SP, TPE, and FFC were assessed.

The sensitivity ratio (SR) can be defined as the ratio of the relative change in the impact assessment outcome to the relative change in the parameter value, which was calculated according to Equation 3 [18]. The higher the sensitivity ratio, the greater the effect that a change in the parameter has on the outcomes.

$$SR = \frac{\frac{\Delta Result}{Result_0}}{\frac{\Delta Parameter}{Parameter_0}} \quad (3)$$

Figure 8. Sensitivity analysis for impact categories with respect to the transportation distance of materials

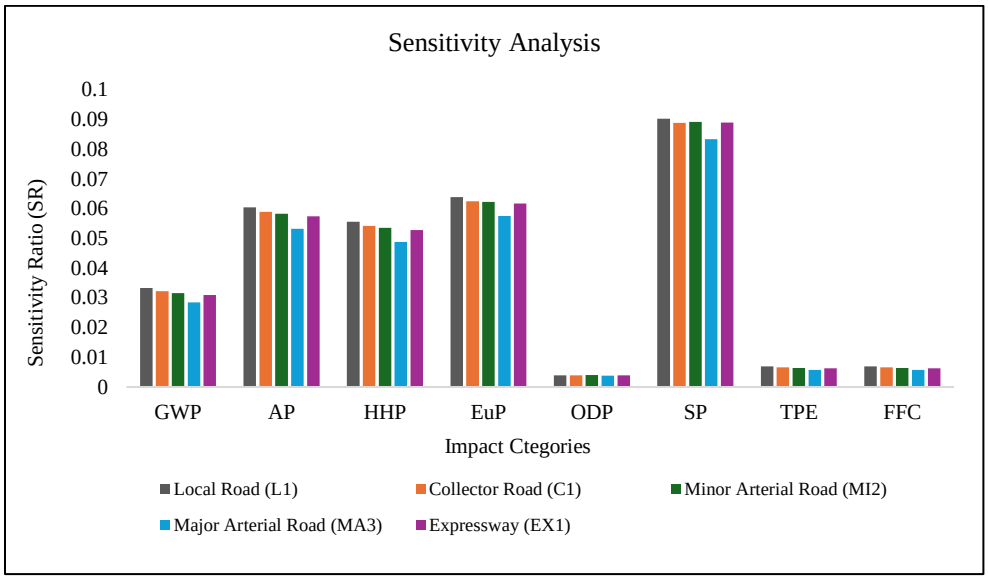


Figure 8 depicts that the highest SR, 0.0903, was observed in SP in the case of the local road, L1, which implies that SP was the most sensitive impact category regardless of the pavement structures. In contrast, ODP, TPE, and FFC exhibited one of the lowest SR values across all road types, signifying the minimal sensitivity to changes in transportation distances. Moreover, the sensitivity of GWP, AP, HHP, and EuP were moderate to transportation distance, having slight variation across road types. The sensitivity analysis also explains that the local road, L1, was the most sensitive to changes in transportation distance, followed by C1, MI2, EX1, and MA3. This consistency across road structures highlights the robustness of sensitivity analysis and the importance of considering transportation distance in environmental impact assessments for asphalt pavement structures.

Incorporation of RAP

To understand the potential environmental effects related to the RAP usage as granular material in base and subbase layer of asphalt pavement structures, ten different asphalt mixtures with varying RAP percentages, i.e. 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50% by weight of granular materials were used in this study. Table 4 represents the RAP percentages and quantities used for the five major roadway types, i.e. local roads, collector roads, minor arterial roads, major arterial roads, and expressways. The

corresponding mix type is also delineated in Table 4. For example, if 5% of natural granular material was replaced by 5% RAP content, then the respective mix was "HMA-5% RAP."

Table 4. Quantities of RAP incorporated in various road types

RAP Percentage	Mix Name	Density of RAP (tonnes/m^3)	Quantity of RAP (tonnes)		
			L1 C1 MI2	MA3	EX1
5	HMA-5% RAP	1.565	247.5	285	405
10	HMA-10% RAP		495	570	810
15	HMA-15% RAP		742.5	855	1215
20	HMA-20% RAP		990	1140	1620
25	HMA-25% RAP		1237.5	1425	2025
30	HMA-30% RAP		1485	1710	2430
35	HMA-35% RAP		1732.5	1995	2835
40	HMA-40% RAP		1980	2280	3240
45	HMA-45% RAP		2227.5	2565	3645
50	HMA-50% RAP		2475	2850	4050

Scenario analysis

The incorporation of RAP is one of the sustainable strategies frequently cited in the literature to reduce the environmental emissions of asphalt pavement structures [24, 25]. The total GWP obtained from L1, C1, MI2, MA3, and EX1 were considered as baselines for each corresponding roadway type. The result is reported as 'emission savings for roadway,' indicating how much GWP is reduced after incorporating RAP contents in the certain roadway type in kg CO_2 eq. Additionally, the percent savings for HMA-RAP mixes are indicated to show the trend of emission reduction.

Figures 9, 10, 11, 12, 13 illustrate GHG emission savings in kg CO_2 eq. and percent savings with respect to five major Ontario roadway structures with minimum GHG emissions—local road (L1), collector road (C1), minor arterial road (MI2), major arterial road (MA3), and expressway (EX1)—with varying RAP percentages ranging from 5% to 50%.

Respecting the local road, L1, the emission saving increases as the RAP content increases (Figure 9). For the HMA-5% RAP mix, the emission saving was approximately 135.23 kg CO_2 eq., which elevated significantly to over 1000 kg CO_2 eq. for the HMA-10% RAP. The trend continued with a gradual increase in savings for the increasing RAP percentage, reaching just over 6500 kg CO_2 eq. for the HMA-50% RAP mixture. Interestingly, the percent savings relative to L1 started modestly, around 0.05% with HMA-5% RAP, but steadily climbed to 1.5% at 30% RAP and peaked at around 3% with HMA-50% RAP.

A similar pattern is observed in Figure 10 for incorporating RAP in collector road, C1. The GWP for HMA-5% RAP was 2.38×10^5 kg CO_2 eq., which was 1114.25 kg CO_2 eq. (0.5%) less than the GWP obtained from C1. So, with increased RAP content, the emission savings also increased for C1. Moreover, the emission savings rose to around 3000 kg CO_2 eq. for HMA-25% RAP, which accounted for around 1.25% emission savings. The emission savings continued to rise, reaching more than 5,500 kg CO_2 eq. for HMA-50% RAP, with a percent saving of approximately 2.33%.

The minor arterial road (MI2) showed a GWP saving of about 500 kg CO_2 eq. at HMA-5% RAP in Figure 11, and it rose to 5562.34 kg CO_2 eq. at HMA-50% RAP. The percent savings increased from around 0.2% (HMA-5% RAP) to just over 2.15% (HMA-50% RAP). This indicates that higher RAP content resulted in more significant GHG emission reductions than the previous road types. For major arterial roads (MA3), the initial GWP emission saving with HMA-5% RAP was about 550 kg CO_2 eq. (Figure 12). With HMA-25% RAP, the GWP advanced to over 3050 kg CO_2 eq.; at 50% RAP, it is around 6000 kg CO_2 eq. In expressway EX1, the percent savings, beginning at about 0.2% with HMA-5% RAP, climbed steadily to around 1.2% at 25% RAP and peaked at 2.12% with 50% RAP (Figure 13). This consistent trend emphasizes the significant environmental benefits of incorporating RAP into major arterial roads and expressways.

Figure 9. GHG emission savings with respect to Local Road (L1)

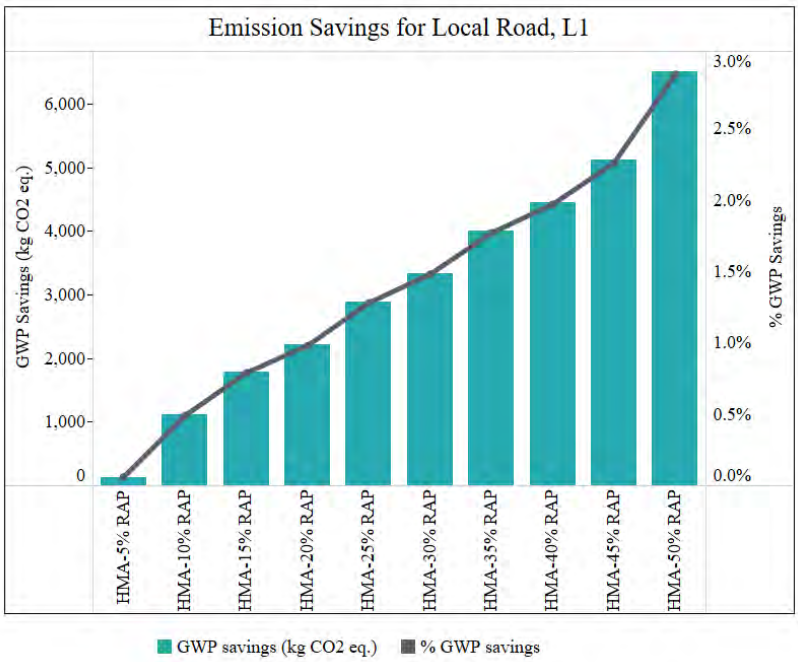


Figure 10. GHG emission savings with respect to Collector Road (C1)

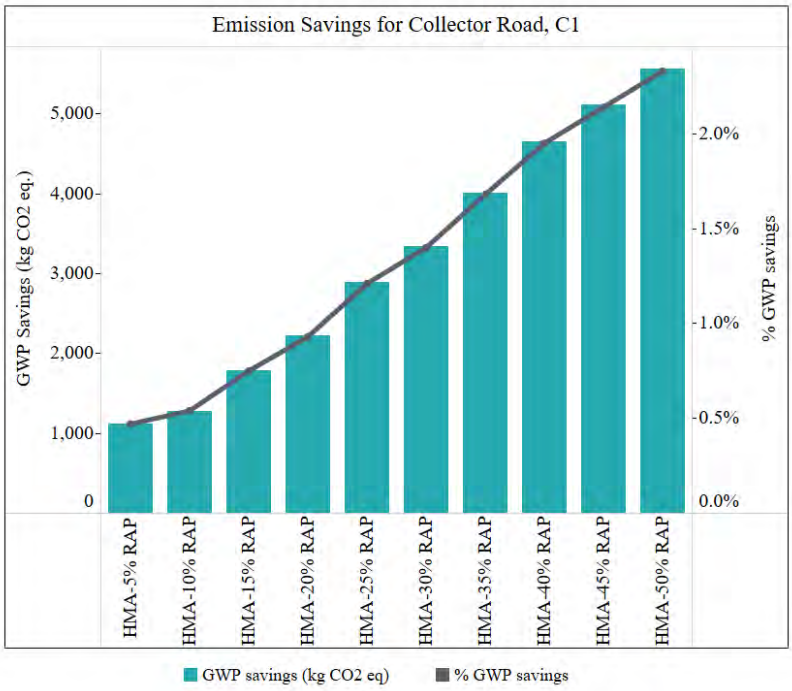


Figure 11. GHG emission savings with respect to Minor Arterial Road (MI2)

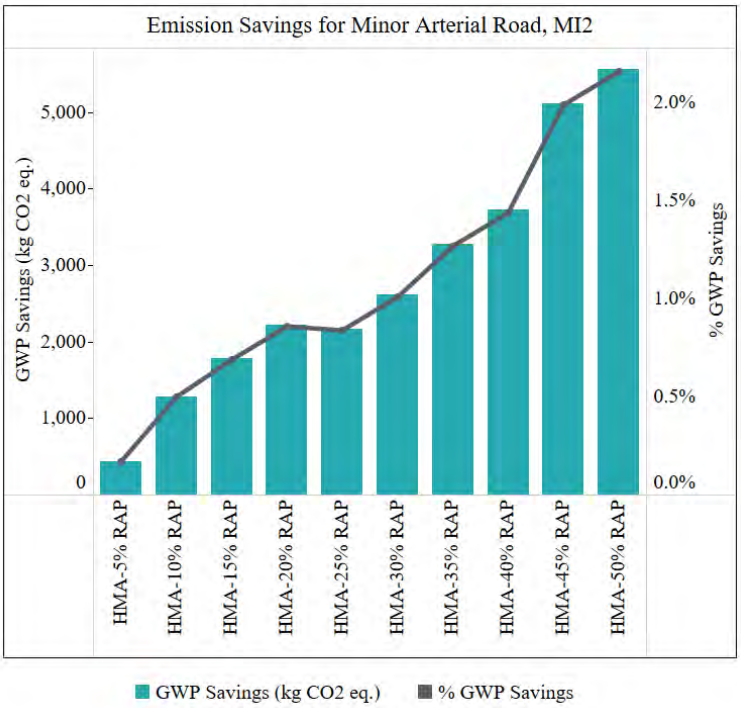


Figure 12. GHG emission savings with respect to Major Arterial Road (MA3)

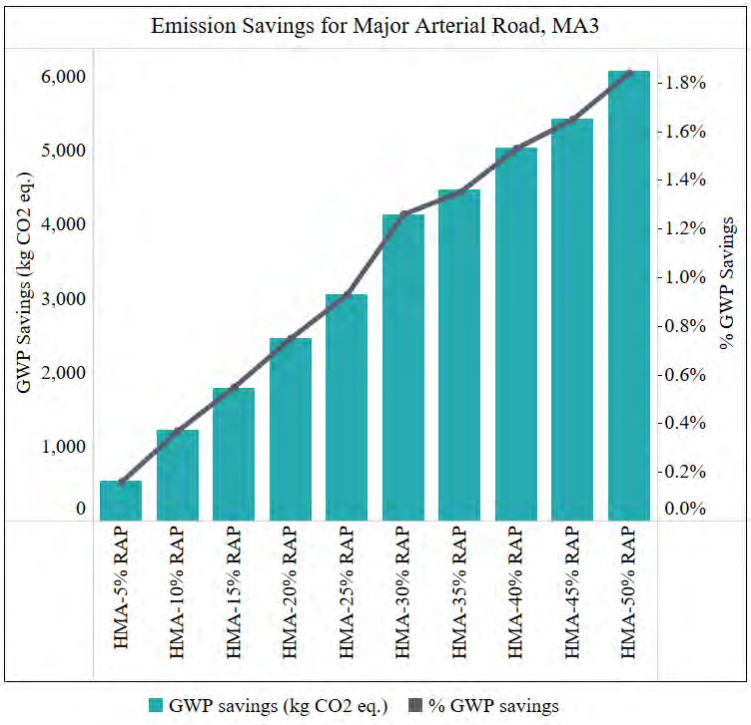


Figure 13. GHG emission savings with respect to Expressway (EX1)

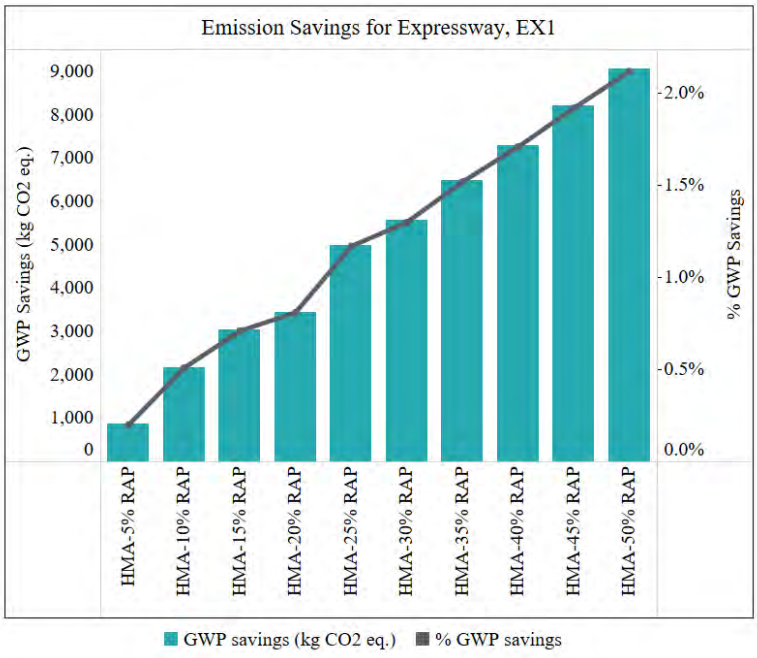


Figure 14. Percent GHG emission savings with varying RAP contents

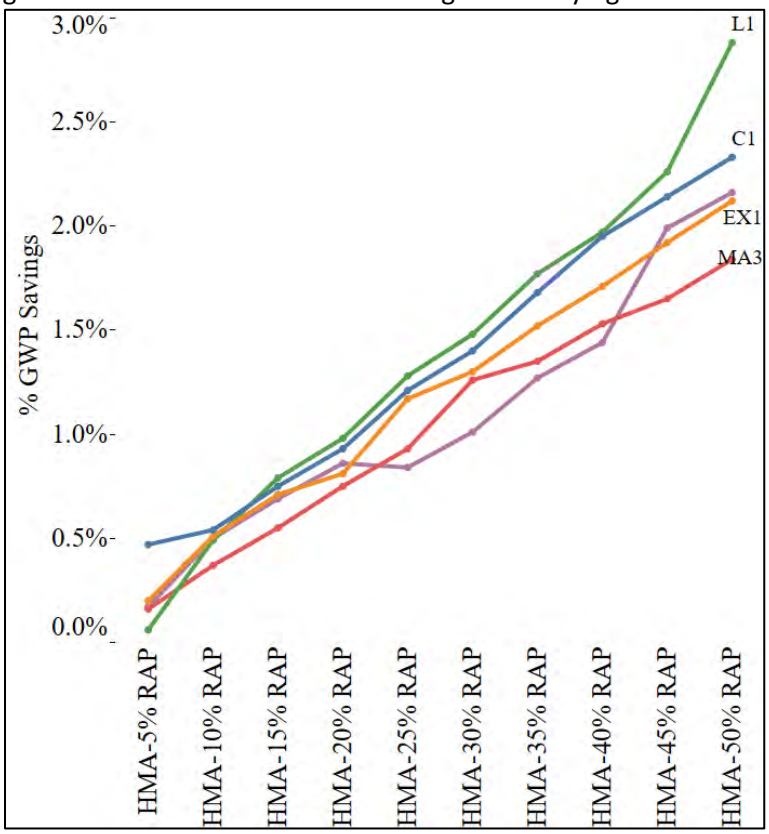


Figure 14 shows that the percentage of emission savings increased gradually with higher RAP content. Local road, L1 and collector road, and C1 showed the highest savings percentages, followed by expressway (EX1), minor arterial road (MI2), and major arterial road (MA3). These trends demonstrate the benefits of incorporating RAP into asphalt pavement structures from an environmental point of view.

CONCLUSIONS

The outcomes from this research can be concluded as follows:

- One of the significant outcomes obtained from the emission and contribution analysis is the quantification of a GHG emissions range for different roadway types in Ontario. For instance, local roads exhibited GHG emissions ranging from 2.26×10^5 kg CO_2 eq. to 2.51×10^5 kg CO_2 eq., while collector roads ranged from 2.39×10^5 kg CO_2 eq. to 3.08×10^5 kg CO_2 eq. Minor arterial roads showed a GWP range from 2.58×10^5 kg CO_2 eq. to 3.33×10^5 kg CO_2 eq., and major arterial roads from 3.30×10^5 kg CO_2 eq. to 4.00×10^5 kg CO_2 eq. Expressways, which showed the highest emissions, GWP range from 4.28×10^5 kg CO_2 eq. to 4.54×10^5 kg CO_2 eq. These ranges will set a foundation for future research to analyze and develop sustainable alternatives to pave the way toward eco-friendly pavement solutions.
- Within the system boundaries considered in this study, the manufacturing phase was the most significant contributor to total GHG emissions, often exceeding 65%. This is likely due to the intensive energy consumption and material processing of asphalt. This phase also includes activities such as the extraction and refining of raw materials, the production of asphalt binder,

and the mixing of asphalt concrete, all energy-intensive processes that emit large amounts of greenhouse gases.

- Site preparation was the least impactful phase, contributing less than 10% of total GHG emissions because it primarily involved earth moving and excavation, which usually requires comparatively less energy and generates fewer emissions than the other life cycle phases. This phase does not involve the complex industrial processes or high-energy demands observed in the other phases, resulting in lower overall environmental impacts.
- The outcomes of sensitivity analysis conclude that the transportation distance of materials significantly influences the environmental impact assessment of asphalt pavement structures. Among the impact categories, GWP showed moderate sensitivity towards the transportation distance of materials.
- The scenario analysis advocates the incorporation of RAP contents in the granular layers of asphalt pavement structures. On average, incorporating RAP resulted in significant emission savings, with each roadway type achieving around 4,000 kg CO_2 eq. in GWP reductions. Notably, these reduced emissions were obtained from the minimum structural specifications for asphalt pavement design. In practical scenarios, incorporating RAP will result in even more significant emission savings if the lift thicknesses increase.

Acknowledgements

The authors wish to thank all the members of the Advanced Road and Transportation Engineering Lab (ARTEL) who provided their valuable responses and comments to execute this study. Special thanks to J. Barzegaran, PhD candidate at Carleton University, for his assistance during brainstorming sessions.

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