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Environmental impacts of road pavement rehabilitation

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ABSTRACT

Road pavement generates significant environmental impacts through the production, transportation, construction, and maintenance stages. Recycling methods can be used to reduce the demand for virgin materials, but these alternatives are not environmentally benign either. Using life cycle assessment of a real case study near Chatham, Ontario, we model the trade-offs of a road rehabilitation project over a 30-year service life, subject to three scenarios. These scenarios use differing quantities of resources and blends of reclaimed asphalt pavement (RAP). Results show use of RAP with cold in-place recycling substituting virgin materials improves the environmental performance of most indicators, including climate change. These gains are only slightly diminished by the additional transportation of machinery, which we show through sensitivity analysis is likely to improve as the method becomes more commonplace. This research fills a gap in knowledge for understanding the potential improvements for pavement rehabilitation supply chains.

1. Introduction

Roads provide an important function of connecting people and facilitating the movement of goods and services that contribute to our life quality. Roads contribute to the economic growth and social development of the country. By 2030, annual passenger traffic will exceed 80 trillion passenger-kilometres – a 50 % increase compared to 2015 while global freight volumes are anticipated to grow by 70 % in the same period (World Bank, 2021). This is relevant to the global climate challenge because of the high levels of environmental emissions embodied in the resources used to build road pavement (Chowdhury, Apul, & Fry, 2010), and also the energy used to move and construct these heavy materials (Daigle, 2010; Shirkhani et al., 2018). Understanding the challenge of providing safe infrastructure while reducing environmental impacts remains an open science illustrated by the increase in research papers analysing novel recycling methods and material composites (Badeli, Carter, Doré, & Saliani, 2018; Graziani, Iafelice, Raschia, Perraton, & Carter, 2018).

There are various methods to obtain asphalt mix like Hot Mix Asphalt (HMA) or Cold Mix Asphalt (CMA). Additionally, a variety of surface recycling methods exist, including Hot In-Place Recycling (HIR), Cold In-Place Recycling (CIR), Full-Depth Reclamation (FDR), and combinations of these, which all have their unique environmental emissions profiles. In this research, we focus on the environmental impacts associated with rehabilitating asphalt pavement roads using scenarios based on a mix of recycling approaches each with their advantages. These are defined and explained below in the Methods section.

We explore trade-offs between multiple environmental indicators for these road pavement rehabilitation methods. The purpose of

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this comparison is to identify environmental impact hotspots within the life cycle of road pavement – covering extraction of natural resources, transportation, production, and finally pavement construction – and measure the opportunity for reducing the environmental impacts through improving the circularity of pavement materials. The comparison allows us to weigh relative merits of reducing extraction of natural resources, reducing waste spoil, and decreasing the transportation of heavy materials to and from the construction site. We hope to provide meaningful answers to quantitatively support environmental decision-making for future road reconstruction projects and the potential for increased material circularity.

One common tool for such analyses is life cycle assessment (LCA). LCA is a quantitative decision-support tool that estimates the environmental flows from and to natural sources and sinks throughout the life of a product or process (Guinée et al., 2011). LCA may include environmental flows associated with raw material extraction, processing, transport, use, and waste management. In some applications, the full set of life cycle stages are necessary for understanding the sustainability of a product. In the case of pavement, LCA typically considers processes up to, and including, installation of the pavement, maintenance (e.g., crack sealing) and processes at the end of its life. Impacts associated with the use stage are often not taken into consideration (International EPD System, 2018).

A number of reports and research articles have outlined pavement life cycle frameworks (J. T. M. Harvey, J.; Ozer, H.; Al-Qadi, I. M.; Saboori, A.; and Alissa Kendall, 2016; Huang, Bird, & Heidrich, 2009). The first road pavement LCA published in a scientific journal was Horvath and Hendrickson (1998) according to the literature review of Santero (2010). Over this quarter century both LCA methodologies and pavement rehabilitation technology have advanced significantly (Vega A, Santos, & Martinez-Arguelles, 2020), not to mention the urgency of mitigating global environmental challenges such as climate change (Kouchaki-Penchah, Bahn, Vaillancourt, & Annie Levasseur, 2022) and biodiversity loss (Thomas Elliot, Goldstein, Gómez-Baggethun, Proença, & Rugani, 2022). However, one common area of concern is the difficulty of comparing different road utility. Performance and service life of roads differ, making a direct comparison difficult (AzariJafari, Yahia, & Ben Amor, 2016; Santero and Horvath, 2010).

Yet more have documented various material compositions including novel reclaimed substances such as crushed glass and steel slag (Uzarowski, 2015), and the processes and longevity of the pavement that subsequently change (Chiu, Hsu, & Yang, 2008; Islam, Kalevela, & Rivera, 2021). Outside academic realms, asphalt Environmental Product Declarations are becoming a marketing tool for construction companies (Downer, 2020), and as such, Product Category Rules (PCRs) exist for the ways in which asphalt life cycle assessments should be conducted (EPD Australasia, 2019; International EPD System, 2018). Industry-led research in Canada has played a role in focusing attention on environmental and economic optimisation of material demands (Workman, 2016). Academic review articles have collected and synthesised findings on life cycle approaches to pavement (AzariJafari et al., 2016; Santero, 2010) while others have focused on appraising asphalt recycling technologies in general (Reis, Quattrone, Ambros, Grigore Cazacliu, & Hoffmann Sampaio, 2021) and with respect to specific performance of cold in-place recycling (Xiao, Yao, Wang, Li, & Amirkhanian, 2018), and hot in-place recycling in Ontario, Canada (Yang, Ddamba, Ul-Islam, Safiuddin, & Tighe, 2014). Meanwhile, the additives used in some of those partially reclaimed asphalt composites have also drawn attention for their potential environmental impacts, in particular as a result of weathering and runoff events (Dorchin, 2013; Pandey, Taylor, Shaver, & Lee, 2003).

The use of novel asphalt compositions containing reclaimed materials, reducing input and spoil haulage have the potential to reduce environmental impacts over the life cycle of the pavement. However, due to the variety of materials and their unique environmental profiles, it is important to assess and compare pavement recycling approaches across a set of indicators. This avoids burden shifting, which can occur when a product system is assessed to reduce an environmental impact but increases impacts in one or more other categories. Pavement has a raft of environmental impact categories, including two global contemporary issues: climate change, which is affected by, for example, transportation of heavy materials to the construction site; and water systems due to the use and depletion of water in the extraction and manufacturing stages (Anastasiou, Liapis, & Papayianni, 2015; Rosado, Vitale, Penteado, & Arena, 2017). Subsequently, we proceed to build up three pavement product systems, each with a specific recycling process, material demands and longevity, and compare their "cradle-to-gate" life cycle impacts for a set of climate and water-specific indicators.

It is presumed that recycling materials in road rehabilitation, such as with CIR, leads to lower environmental impacts through reduced demand on virgin materials, transportation energy, and minimizing spoil. Workman (2016) concluded that CIR "reduces greenhouse gas emissions, uses less energy, makes good use of existing damaged pavement, requires a short amount of construction time, and reduces the use of non-renewable resources". However, due to the difficulty of comparing service life of roads rehabilitated via different processes, and considering the technology maturity curve of these emerging rehabilitation methods, it is difficult to know how they compare over similar function units.

2. Methods

2.1. Goal and scope

The functional unit is 1 lane-km of existing rural (class 1) road over a 30-year service life. The road is a 4.4 km section of Communication Road running between Highway 401 and Drury Line in south-western Ontario (Canada) near the city of Chatham. The lane width is 3.75 m. The existing pavement is Hot Mix Asphalt (HMA) with a bulk density of 2420 kg/m^3. In 2021, Communication Road had annual average daily traffic of 5180, including 15 % trucks, and 6 million 80 kN 20-Year Equivalent Single Axel Loads. Existing pavement structure is assumed to be 235 mm HMA with 670 mm granular subbase with 0.2 and 0.09 layer coefficients respectively or pavement structural number 4.2 (Miller Group, 2021). Three scenarios are considered for the rehabilitation of the existing pavement: Mill & Fill (MF), cold in-place recycling with 100 % RAP & bitumen emulsion (RAP100), and full-depth reclamation with 50 % RAP & bitumen emulsion (RAP50). The scenarios differ in the depth to which the existing pavement is milled, the material mix and equipment used to rehabilitate the pavement, and the quantity of spoil removed, and the estimated service life of the rehabilitated surface. Each scenario is finished with the same 50 mm HMA wearing course (Giani, Dotelli, Brandini, & Zampori, 2015; Workman, 2016). It is expected that the lower demand for virgin materials and the production thereof will result in improved environmental performance for the RAP scenarios compared to the MF scenario.

A 30-year time horizon is considered, during which time the road is assumed to be need resurfacing at different frequencies depending on the estimated service life of type of the rehabilitation used in each scenario. The details of each scenario and their respective inventories are described in section 2.2.

2.2. Scenarios and inventory

2.2.1. Mill & Fill

The Mill & Fill scenario (MF) is our business-as-usual case. The road is milled to a depth of 40 mm, and the surface is replaced with 50 mm of Hot Mix Asphalt (HMA). Assuming the structural layer coefficient for HMA is 0.44, the MF pavement has a structural number of 4.7 (Miller Group, 2021). The HMA is produced on-site using portable equipment. The equipment and materials are sourced from the Miller Huron Construction pit, 11 km from Communication Road. Milled material (spoil) is trucked to the Miller Huron Construction pit to be stockpiled. This is Reclaimed Asphalt Pavement (RAP) and forms part of the material input to future road resurfacing. End-of-life pavement milling and transportation of that RAP to the storage pile is within the system boundary (Giani et al., 2015). When the RAP reaches the stockpile, it leaves the system boundary (it may or may not be used as RAP in HMA at plant). Crushed aggregate is extracted and dried ready for market. The system process is used to capture the upstream impacts of aggregates. The type and quantity of materials used in HMA are shown in Table 1, calculated from NRCan (2005) and personal communications with Miller Group (2021).

These materials used in HMA are sourced from a variety of aggregate and asphalt stockpiles and transported to the Miller Huron Construction pit. The materials are then transported a further 11 kms from the pit to the construction site (Communication Road).

The fuels used on the construction site by heavy equipment is assumed to be 484 L diesel (18800 MJ) per lane-km for all scenarios (NRCan, 2005). In addition to heavy on-site equipment, 9.2 L (367 MJ) of diesel and heavy fuel oil per tonne of HMA is required for operating the portable HMA plant (NRCan, 2005). The type and volume of these fuels are shown in Table 2 calculated from Miller Group (2021). These fuels are sourced from Waddick Fuels (Chatham) and transported 16 kms to storage tanks located at the Miller Huron Construction pit. Trucks (14-tonne) transport the fuel 11 kms from there to the equipment and vehicles on the job site at Communication Road.

The spoil is transported to the RAP stockpile at the Miller Huron Construction pit for potential use in future HMA. It reaches the end of its first product life cycle at the stockpile. It begins its second product life when the RAP is an input to future HMA (International EPD System, 2018). These processes are shown in Fig. 1.

Over the life of the rehabilitated pavement, periodic maintenance is needed to repair surface damage. This process of crack sealing uses a mastic made of virgin bitumen and additives and occurs throughout the life of the pavement in each scenario with different frequencies. The amount of crack sealant is 2.23 tonnes per lane-km per maintenance cycle, estimated from Decker (2003) and InfraGuide (2003).

This estimation assumes the crack sealant density is 1.2 kg per litre. Surface cracking occurs four times during the 30-year service life with a surface density of 500 linear metres of cracks per lane-km of road with crack width of 10 mm, with crack depth of 25 mm. These cracks are filled and an overband of 76 mm by 1.6 mm was used to determine the amount of crack sealant per kilometre ("Asphalt Sealcoating and Crack Filling Calculators," 2022).

Table 1
Specifications of materials for HMA.

Flow	Unit	Quantity/lane-km
HMA mix (input)	T	436
RAP	T	77
Virgin Aggregate	T	359
Virgin bitumen (input)	T	18
Spoil (output)	T	363
HMA (output)	T	454

Table 2
Energy use per tonne of HMA by portable plant.

Fuel	Volume (L)	Higher heating value (L/MJ)	Energy (MJ)
Diesel	5.8	38.8	226
Heavy fuel oil	3.4	41.8	141
Total	9.2		367

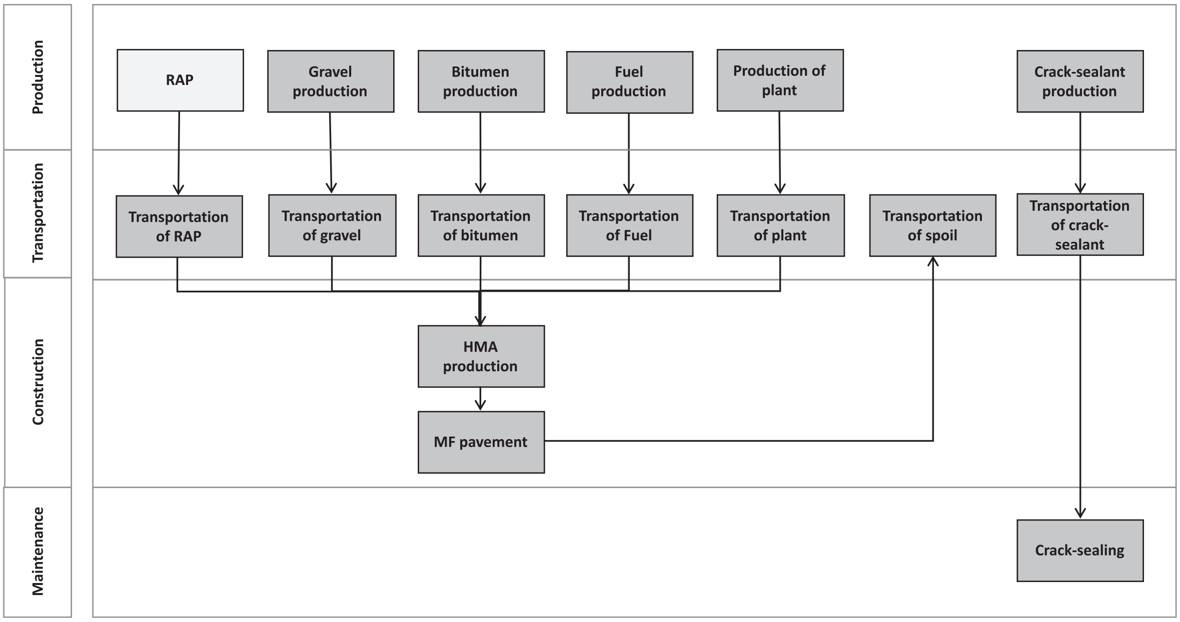

Fig. 1. Diagram of life cycle stages and processes considered in the Mill & Fill product system. No impacts are associated with RAP.

2.2.2. 100 % RAP with bitumen emulsion

In this scenario (henceforth RAP100) the road is rehabilitated using CIR.

First the existing HMA pavement is milled to 120 mm depth, leaving 115 mm of existing HMA. The milled pavement is collected, crushed, and screened for size, mixed with bitumen emulsion. This is then spread and compacted, and after curing the new HMA wearing course is laid (Workman, 2016).

No virgin aggregate is used, so less material is trucked to the construction site. The specialized heavy machinery needed for CIR and FDR, however, are sourced from a greater distance. As the milled surface is recycled there is no waste spoil to remove from the site. A 50 mm wearing course of HMA is overlaid (Workman, 2016). Assuming the layer coefficient for CIR is 0.38, the RAP100 pavement has a structural number of 5.9 (Miller Group, 2021).

The CIR constituents and their quantities are shown in Table 3, calculated from NRCan (2005) and personal communications with Miller Group (2021).

The bitumen emulsion required for RAP100 is produced by McAsphalt and transported 92 km from the McAsphalt Stanley Terminal to the construction site. This cationic slow set emulsion is composed of bitumen, water and emulsifier, and is produced using 105 MJ electricity per tonne of bitumen emulsion output (NRCan, 2005). Constituents of this bitumen emulsion are given Table 4.

CIR on-site equipment is assumed to use 187 L per hour at full load (Wirtgen, 2018). We assume the milling is done at a rate of 10 m per minute, or 100 min per lane-km. This allowed us to calculate 312 L of diesel per lane-km. These processes are illustrated in Fig. 2.

Table 3
Specifications of materials for RAP100.

Flow	Unit	Quantity/lane-km
Milled pavement	T	1089
RAP100 mix (input)	T	1171
RAP	T	1089
Bitumen emulsion	T	23
Water	T	59
Spoil	T	0
HMA wearing course (input)	T	454

Table 4
Bitumen emulsion constituents.

Flow	Unit	Quantity/tonne bitumen emulsion
Bitumen	T	0.62
Emulsifier	T	0.01
Water	T	0.37

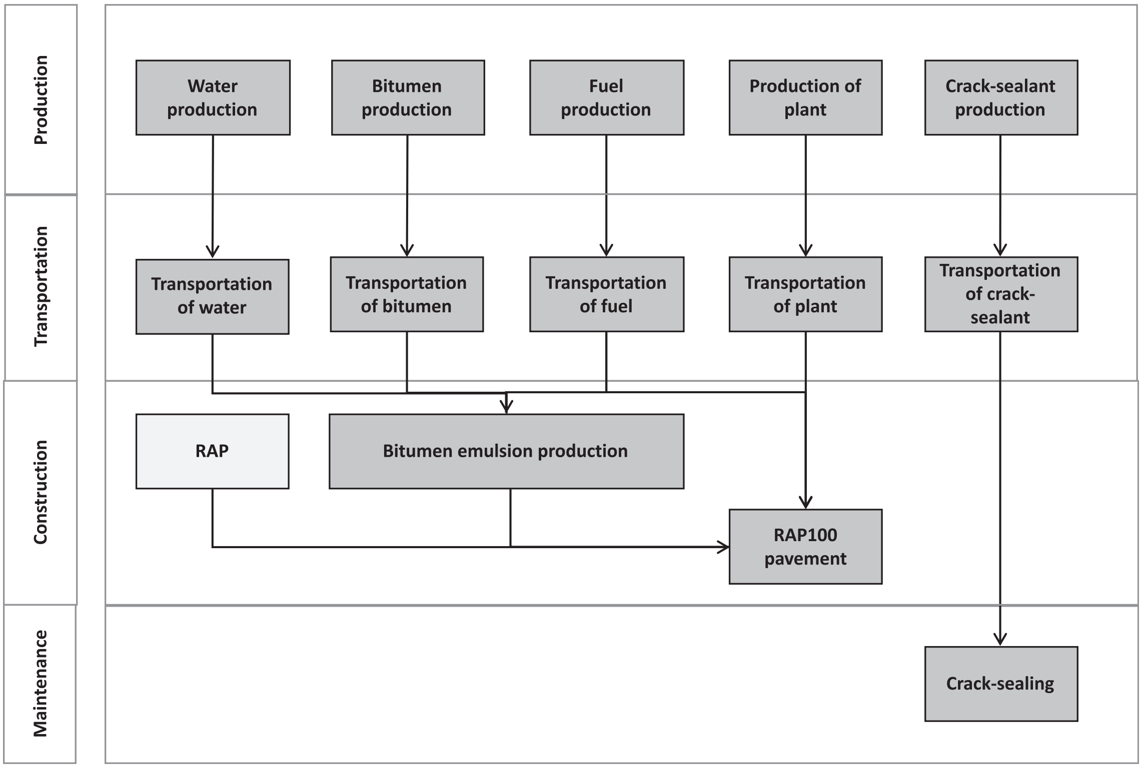

Fig. 2. Diagram of life cycle stages and processes considered in the RAP100 product system. No impacts are associated with RAP.

2.2.3. 50 % RAP with bitumen emulsion

In the RAP50 scenario the pavement is rehabilitated using FDR with a RAP portion from the milled pavement. The surface material is milled to 250 mm, reaching a depth 15 mm below the 235 mm of existing HMA pavement. A portion of the milled material is reclaimed for in-situ recycling as RAP following the same procedure as with CIR; crushing, sorting, and mixing with bitumen emulsion. The aggregate mix is composed of 50 % HMA and 50 % RAP and bitumen emulsion mix. The HMA is sourced from the same materials and processes as described in the MF scenario. The remaining spoil is graded into the road shoulder (no spoil is removed). A 50 mm wearing course of HMA is overlaid. Assuming FDR has a structural layer coefficient of 0.38, the RAP50 pavement has a structural number 6.9 (Miller Group, 2021).

In the RAP50 scenario, the pavement mix is composed of 50 % CIR mix and 50 % HMA. Like the RAP100 scenario, the CIR mix is made up of bitumen, water and emulsifier in the ratios shown in Table 5. These are combined in-situ using equipment trucked in 313

Table 5
Specifications of materials for RAP50.

Flow	Unit	Quantity/lane-km
Milled pavement	T	2269
RAP50 mix (input)	T	2269
RAP mix (input)	T	1134
RAP	T	1054
Bitumen emulsion	T	23
Water	T	57
HMA (input)	T	1134
Spoil (unused RAP, output)	T	1214
HMA wearing course (input)	T	454

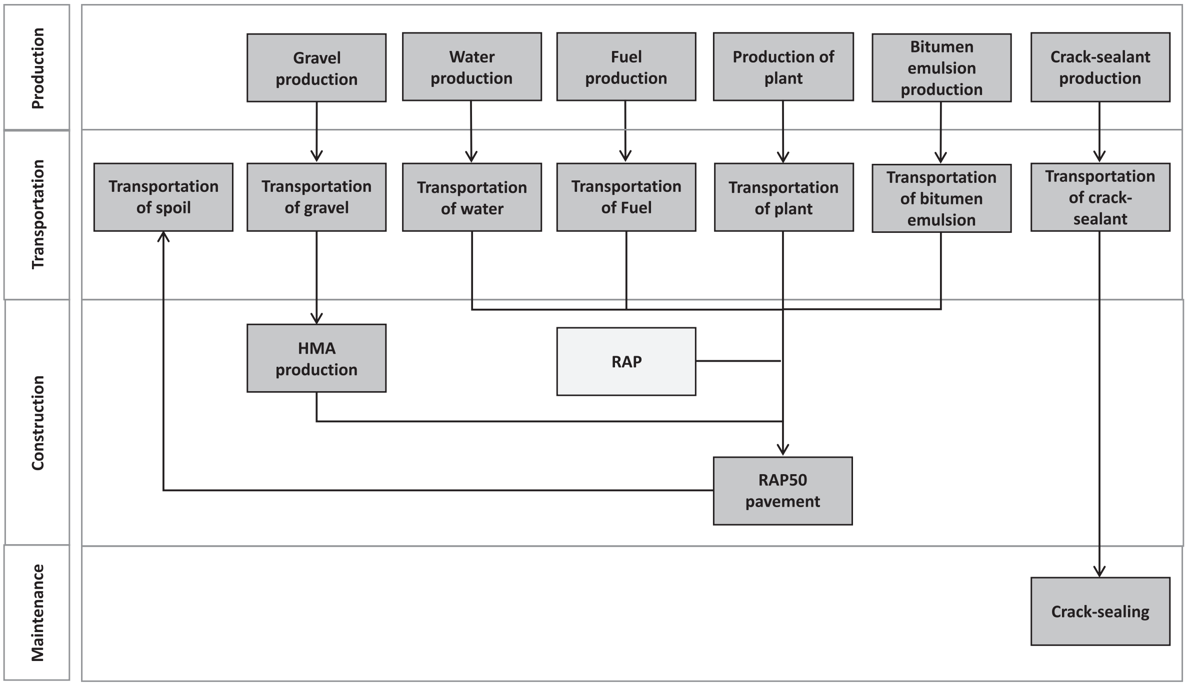

Fig. 3. Diagram of life cycle stages and processes considered in the RAP50 product system. No impacts are associated with RAP.

km from Aurora, as in the RAP100 scenario. The constituents and their quantities are shown in Table 5, which are calculated from NRCan (2005) and personal communications with Miller Group (2021).

In the RAP100 and RAP50 scenarios, on-site equipment, which totals 172 tonnes bare weight, is trucked 313 km from Aurora, Toronto. The full list of CIR and FDR machinery is listed in the Supplementary Table 1. It is assumed the FDR on-site equipment in the RAP50 scenario uses the same fuels rate as in the RAP100 scenario (i.e., 187 L per hour, 10 m per minute). However, FDR is done in two steps, thus doubling the diesel use compared to the RAP100 scenario to 624 L per lane-km. These processes are shown in Fig. 3.

Each scenario has a unique set of transport journeys to supply the input materials and remove spoil. Fuels are supplied by Waddick Fuels in Chatham. HMA materials are supplied by Aaroc, Johnston, Norfolk, and Lafarge, which are all stored at the intermediate Huron site. Heavy machinery for HMA production and water are also supplied by Huron. Bitumen is supplied by McAsphalt. Specialty CIR and FDR plants are supplied by Miller. These locations are illustrated in Fig. 4, while the transportation distances and tonnages are available in Supplementary Table 2.

2.3. Time horizons

The analysis is performed over a 30-year period – the estimated service life of the rehabilitated RAP50 pavement. The number of cycles each scenario undergoes is proportioned to one cycle of the RAP50 pavement. The relative cycles reflect the slightly higher structural numbers of the RAP100 and RAP50 compared to the MF scenario. The MF pavement has an estimated service life of 7 years and the RAP100 pavement 15 years (Miller Group, 2021). As such, the Mill & Fill rehabilitation is repeated four times, and the RAP100 is repeated twice. The RAP50 rehabilitation lasts 30 years but it requires a near wearing course at year 20 to carry the road until 30 years when it will be fully reconstructed. Maintenance activities are interspersed between rehabilitation cycles. The timeline of this is shown in Fig. 5.

2.4. Impact categories

The life cycle impact assessment was performed for all impact categories in the ReCiPe method. We focused on global warming potential (GWP100; kg CO_2-eq), fossil depletion potential (FDP; kg oil-eq.), metal depletion potential (MDP; kg FE-eq), and water depletion potential (WDP; m^3), and results for the remaining categories are reported in Supplementary Table 3. GWP100 is an indicator

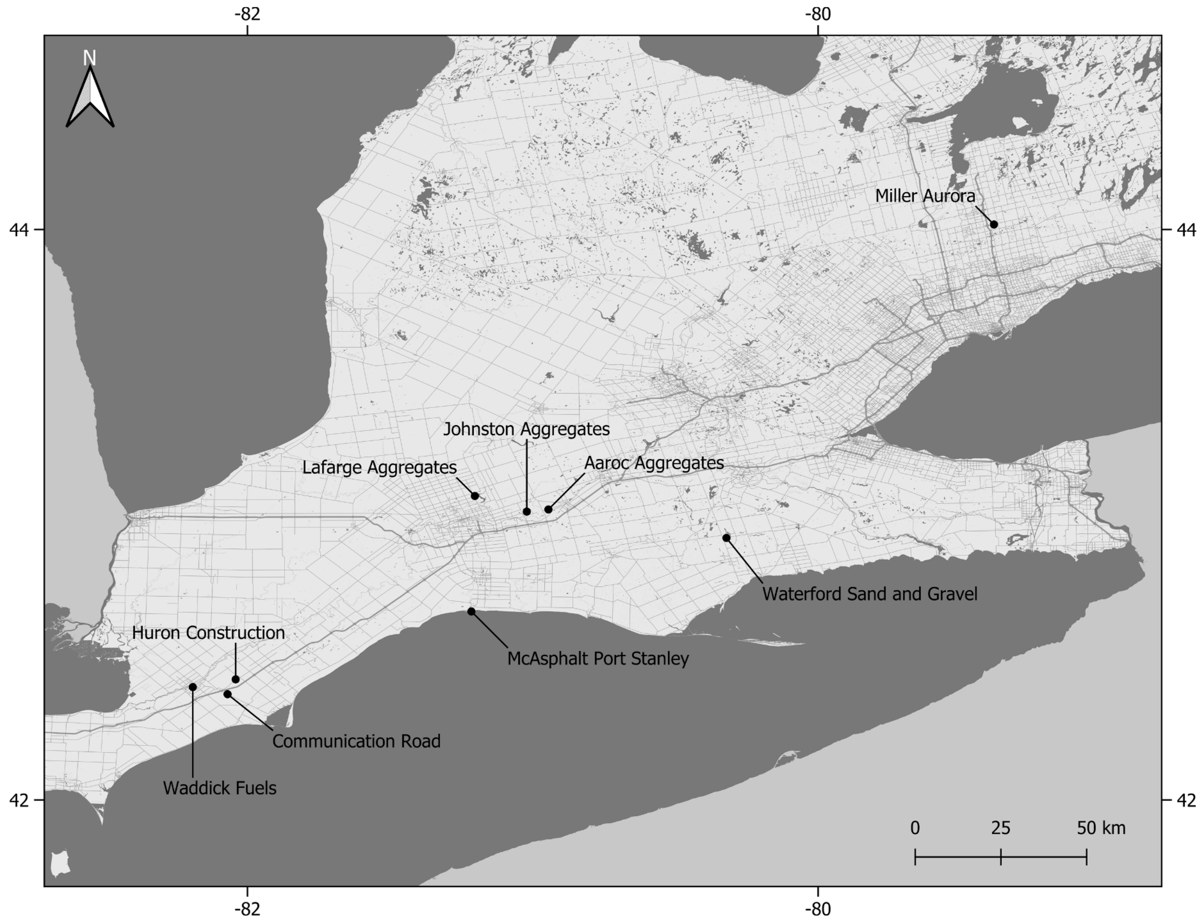

Fig. 4. Map showing construction site (Communication Road) and locations of material and plant suppliers in Ontario, Canada.

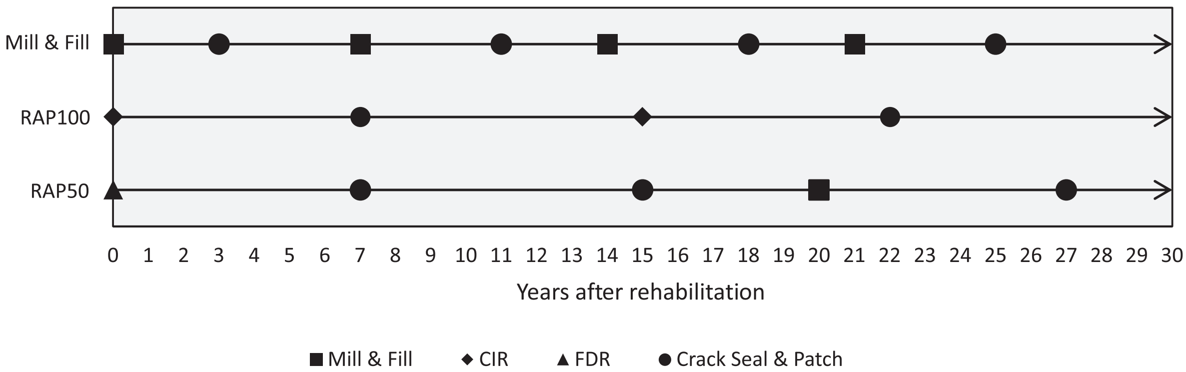

Fig. 5. Rehabilitation schedule for each scenario over 30 years.

of the impacts of activities on climate change measured over a 100-year time horizon. FDP, MDP and WDP are indicators of resource use, which is relevant to understand the trade-offs between scenarios that re-use resources while requiring additional inputs of others. These impact categories are selected on the premise that transport of heavy construction materials using fossil fuels will play a role in greenhouse gas emissions. On the other hand, the comparison of scenarios using varying quantities of water and bitumen in a low-lying rural location poses risks to water and fossil resource scarcity.

2.5. Model framework

The model calculations were performed using *openLCA* 1.10.3 (https://openlca.org) and the ecoinvent 3.4 cut-off database (Wernet et al., 2016). We used economic allocation and the ReCiPe Midpoint (hierarchist) impact assessment method (Huijbregts et al., 2016).

2.6. Sensitivity analysis

Sensitivity analysis was performed on transportation distances and type of HMA plant. Firstly, as materials and machinery are transported from a variety of locations for the RAP100 and RAP50 scenarios, transportation is an LCA stage that we think could be improved. These rehabilitation methods are still maturing meaning the logistics are far from their potential scale. Therefore, comparing the more common MF to the less common RAP100 and RAP 50 scenarios does not take into account the likely improvements to RAP-scenario logistics as those methods scale in time. The sensitivity allows us to gauge the importance of that likely improvement. This sensitivity analysis was performed by modelling each of the three scenarios with the minimum transportation distance, assumed on the basis that substitutable HMA materials are in the base case sourced from a range of locations. Specifically, the HMA aggregates travel between 116 km and 183 km depending on the supplier location. Setting all aggregate transportation distances to 116 km serves as a reasonable minimum distance, and sensitivity of environmental impacts to this alternative distance will important information on the benefits of logistical supply chain choices. Meanwhile, for the RAP100 and RAP50 scenarios, the distance travelled by the CIR/FDR plants are set to 11 kms – the distance travelled by the HMA plant. In this way, we provide a hypothetical analysis for RAP100 and RAP50 if ever these methods become commonplace.

Secondly, the portable HMA plant was compared to a stationary HMA plant located at Huron. The consequences of this include changes in energy inputs from diesel and heavy fuel oil to natural gas, liquid petroleum gas, and electricity. This also means the HMA plant is not transported to the construction site, nor are the fuels it needs to operate.

3. Results

The impacts are assessed in three life cycle stages: production (including cradle-to-factory gate of resources), transportation, and construction (including maintenance activities) of the pavement. The following results were obtained for different impact categories. All results are reported per functional unit (one lane-km over a 30-year estimated service life). Environmental impacts vary across the three scenarios. RAP100 yields the lowest GWP, FDP and MDP, while the MF scenario has the lowest WDP. RAP50 fares worst for all impact categories. Table 6 provides a detailed breakdown of these four impact categories across life cycle stages. Full result tables for all eighteen impact categories can be found in the Supplementary Table 3.

Production is the life cycle stage which plays the largest role in all scenarios. That is unsurprising due to the large amounts of diesel, bitumen, and gravel used in all scenarios, as well as water in the RAP100 and RAP50 scenarios. Transportation plays a large role, especially towards climate change impacts. Construction plays a larger role in the impacts of climate change for the RAP50 scenario due to the combustion of diesel by the HMA plant for mixing with RAP, whereas in both MF and RAP100 scenarios HMA is using only as a surface course. Construction also generates a larger portion of impacts to water depletion in RAP100 and RAP50 scenarios due to the demand for water in both CIR and FDR processes. The other processes involved in the construction stage are largely the flow of reused materials (RAP), which transfers little in the way of material depletion due to construction. Maintenance generates relative low impacts in all scenarios as the maintenance processes only include impacts associated with crack-sealant production and laying. In general, environmental impacts are strongly associated with the production of input resources (materials and energy), and as such the difference between the scenarios is that RAP100 is superior due to its lighter demand on virgin materials. This holds true for climate change, fossil and metal depletion, but not for water depletion. This is because the higher demand for water in the CIR construction process used for the RAP100 scenario outweighs savings in water depletion during production of avoided virgin resources. Fig. 6 highlights these comparative trade-offs between absolute impacts at different life cycle stages and scenarios for each of the four impact categories.

Looking at specific processes in the MF scenario shows that the production impacts are dominated by bitumen manufacturing. Production of bitumen accounts for 49 % of climate change impacts, while the production of gravel and sand only account for 3 %. In the MF construction stage, 27 % of climate impacts are generated by the portable HMA plant burning diesel operating at Communication Road, and upstream production of diesel accounts for 5 % of the climate change impacts. 13 % of climate change impacts are associated with transportation of materials, spoil, diesel, heavy machinery, between source locations around Ontario, the Huron Construction storage pit and to the construction site at Communication Road. The remaining impacts are due to the production of lubrication and water.

Depletion of resources in the MF scenario has a similar profile to that of climate change. The majority (71 %) of fossil depletion is associated with upstream bitumen production, while 19 % of fossil depletion occurs in the production of diesel. 66 % of metal depletion occurs in the production of bitumen and 21 % in production of gravel, while a further 4 % is due to diesel production, and 9 % for

Table 6

Selected environmental impact results for one lane-km pavement for each scenario given in absolute impacts and impacts per tonne of materials over 30-year service life.

Impact category	Unit	Mill & Fill (MF)					100 % RAP with bitumen emulsion (RAP100)					50 % RAP with bitumen emulsion (RAP50)				
		Production	Transportation	Construction	Maintenance	Total	Production	Transportation	Construction	Maintenance	Total	Production	Transportation	Construction	Maintenance	Total
Climate change (GWP100)	t CO_2-Eq	149	23	6	7	184	108	37	2	3	151	153	35	34	5	227
Fossil depletion (FDP)	t oil-Eq	106	9	0	6	121	85	14	0	3	102	134	14	0	5	153
Metal depletion (MDP)	t Fe-Eq	6	1	0	0	7	5	1	0	0	6	8	1	0	0	9
Water depletion (WDP)	m^3	278	20	0	24	322	263	34	149	12	458	374	31	72	18	495

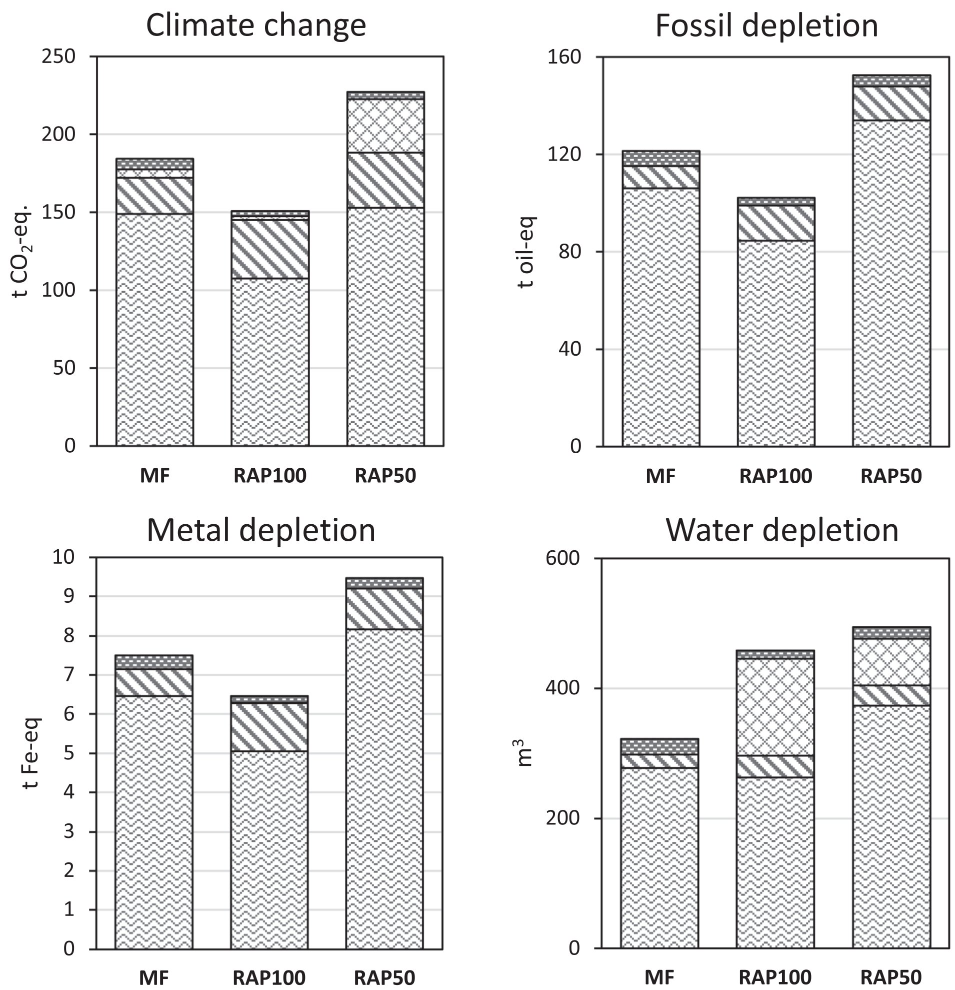

Fig. 6. Comparison of environmental impacts under each scenario associated with production (including resource extraction), transportation, construction, and maintenance life cycle stages.

transportation. Very little water depletion occurs in the MF scenario and that which does is largely associated with upstream production processes. 73 % of water depletion occurs in the production of bitumen, followed by 11 % in production of gravel.

In the RAP100 scenario, the production of bitumen contributes 52 % of the climate change impacts. Nearly half of this is due to bitumen emulsion used in the RAP mixture, while a small majority is associated with bitumen used in the HMA surface courses. This illustrates the consequences of needing high quantities of bitumen emulsion in the CIR mix. Transportation generates 25 % of climate change impacts – much more than in the M&F scenario, due to the long movements of heavy CIR machinery. 16 % of climate change impacts are generated by the portable HMA plant burning diesel operating at the construction site to lay the HMA wearing course. This shows the large role that adding a wearing course plays in the environmental performance of CIR rehabilitation. The largest contribution to fossil depletion is the production of bitumen (73 %, the majority of which is for HMA surface courses), followed by transportation (14 %). Metal depletion is again dominated by the production of bitumen (66 %), followed by transportation (19 %) then production of gravel (12 %). Water depletion is also dominated by production of bitumen (45 %). This is followed by supply of water (38 %), then transportation (7 %).

The climate change impact of RAP50 is 50 % more than that of RAP100. The largest impact in the RAP50 scenario came from the production of bitumen (51 %). This is made up of 23 % from bitumen production for HMA in the RAP mix, 7 % from bitumen emulsion in the RAP mix, 18 % from HMA wearing course, and 2 % for crack sealant used in maintenance. Climate impacts of bitumen production is followed by diesel combustion for running the HMA plant (24 %) and transportation (16 %).

73 % of RAP50 fossil depletion is associated with bitumen production (as in RAP100). The largest portions of the bitumen fossil depletion impacts are associated with HMA production used in the RAP mix (33 %), and with HMA production for the wearing course (26 %). Production of diesel accounts for 17 % of fossil depletion. Meanwhile, bitumen production also accounts for 67 % of metal depletion in the RAP50 scenario (c.f. 66 % in RAP100). Production of gravel and sand accounts for 18 % of metal depletion, due to the

higher volume of virgin HMA materials required in the FDR process (c.f. 12 % in RAP100).

Water use generates 17 % of water depletion in RAP50 (c.f. 38 % in RAP100 and 1 % in MF). However, bitumen production is again the largest source of water depletion (61 %). Production of gravel used in HMA in the RAP50 scenario contributes 8 % to water depletion, while only contributing 4 % to water depletion in the RAP100 scenario due to the lower virgin gravel demand. These higher impacts for all four categories are due to the RAP50 requiring a larger volume of HMA; not only the same 454 tonnes of HMA wearing course in the initial rehabilitation, but an additional 1134 tonnes HMA in the 50 % RAP mix in subbase, then 454 tonnes again in the subsequent wearing course rehabilitation cycle (c.f. Table 5).

Sensitivity analysis of transportation distances shows fewer tonne-kilometers travelled for HMA materials in all scenarios. However, the main benefits pertained to the reduced transportation distance for the CIR/FDR plant. Overall, there were 13 %, 66 %, and 36 % fewer tonne-kms for MF, RAP100 and RAP50 respectively. Translating these haulage changes to environmental impacts resulted in 2 % lower climate change impacts in the MF scenario, compared to 14 % and 6 % lower climate change impacts in the RAP100 and RAP50 scenarios. Fossil, metal, and water depletion improved to lesser extents, showing less sensitivity to haulage distances. Sensitivity analysis on the type of HMA plant showed both decreases and increases to impacts. The substitution of gas and electricity for as plant fuel reduced climate change and fossil depletion impacts, but increased water depletion by a much higher proportion. The changes in results for both sensitivity analyses for each scenario are shown in Fig. 7.

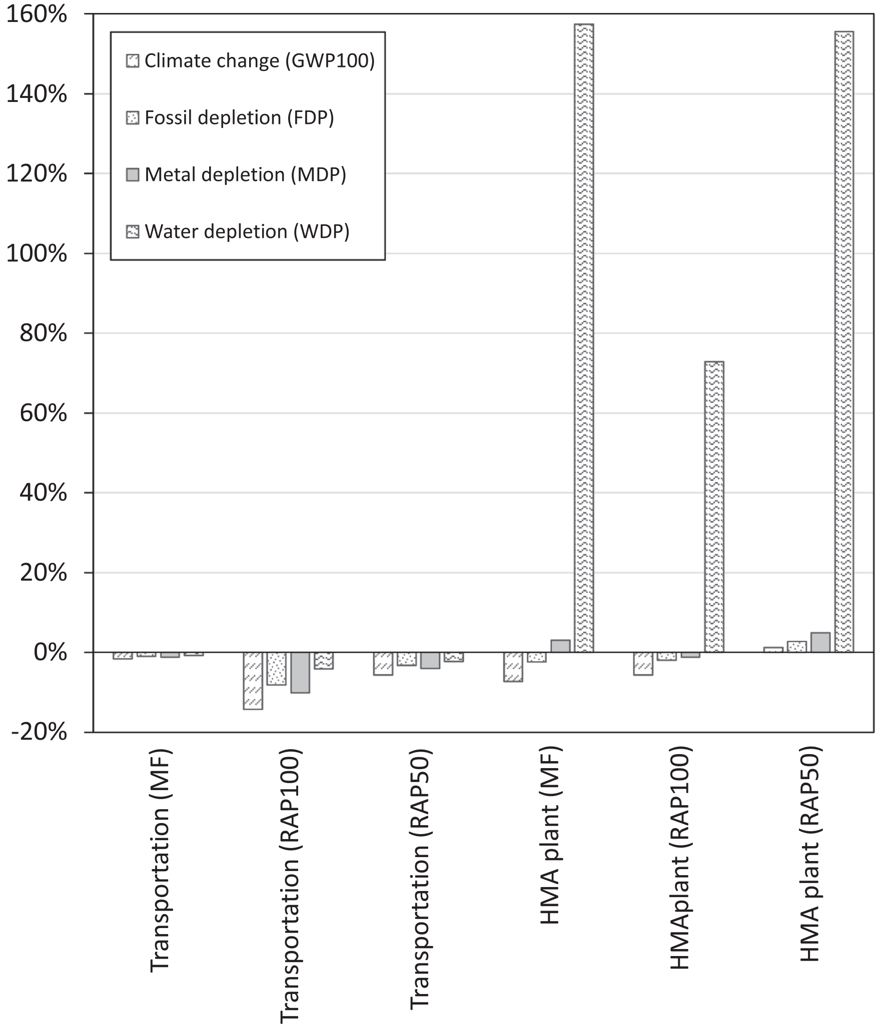

Fig. 7. Sensitivity of impacts due to transportation and HMA plant changes.

4. Discussion

4.1. Reducing impacts

Impacts associated with the RAP scenarios could be decreased if transport distances were reduced. Currently the materials travel great distances from Aurora, and with large masses these contribute sizeable impacts. Our sensitivity analysis shows that reduced distances in the transportation life cycle stage could lower impacts in the transportation stage by 66 % in the RAP100 scenario, contributing to a 14 % GWP decrease overall in the RAP100 scenario. On the other hand, swapping the portable HMA plant to a stationary plant has mixed, but generally poor outcomes. Savings in transportation of the HMA plant and its fuels to the construction site save on climate and fossil impacts, but gives mixed results for metal depletion. Most importantly, the substitution of fuels increases the water depletion impacts by much larger proportions than any other savings. This is mostly a consequence of hydroelectric electricity generation in the Canadian electricity mix. Overall, the sensitivity analyses suggest decreasing transport distances improves environmental performance, especially for RAP100 which is already less environmentally intensive for three out of four categories, indicating this method is preferable in the longer term as it becomes more mainstream. However, the largest portion of impacts is in the production stages for all scenarios (especially bitumen production), meaning efforts should focus on improving other processes in the upstream production systems.

The choice of functional unit in this study was made based on industry data. The RAP50 scenario using FDR is expected to require major rehabilitation at 30 years. As such, the comparison between rehabilitation methods was scaled to this 30-year period. This approach works for comparing the environmental impacts of substitutable rehabilitation methods such as MF, RAP100, and RAP50. However, as the performance of the three methods differ, so to do the number of maintenance cycles differ over the 30-year period, making it difficult to explain which rehabilitation method performs best on a "per cycle" basis.

By reorganizing the results into rehabilitation cycles, we can demonstrate the relative contribution of subsequent maintenance on environmental impacts over the 30-year service life. The MF scenario is simply-four cycles interspersed with four crack-filling maintenance cycles. Therefore, 25 % of the total environmental impacts are associated with one cycle of MF. Similarly, RAP100 is two cycles of CIR interspersed with two crack-filling cycles. Therefore, a single cycle of CIR and its crack-filling accounts for 50 % of the RAP100 impacts. However, the RAP50 scenario is more complicated as it is a mixed scenario between FDR and MF (c.f. Fig. 5). Excluding the maintenance activities of the MF and its associated crack-filling, the FDR portion of the scenario accounts for 80 % of GWP, FDP, and MDP; and 84 % of WDP.

By comparing the non-maintenance portion of the rehabilitation schedules in each scenario, we can begin to understand the potential for improved service life in reducing the environmental impacts of the two RAP approaches. As these processes cover different time periods, we compare them on a per year basis. One cycle of MF has a service life of seven years; one cycle of RAP100 has a service life of 15 years; and on cycle of RAP50 has a service life of 20 years. The per annum comparisons are shown in Fig. 8.

Fig. 8 shows that in spite of the longer estimated service life of a single FDR cycle, the per annum impacts are higher for all categories than both the MF and CIR. This confirms that CIR is an environmentally superior method for GWP, FDP, and MDP. Moreover, it shows the WDP of FDR is less competitive with CIR than shown in Table 6 and Fig. 6, making RAP100 a clear second-best for WDP.

Two striking lessons have emerged from this analysis: the environmental performance of RAP50 is hindered due to their need for a HMA wearing course, which negates most of their anticipated benefits of pavement recycling. Secondly, the high water demand for bitumen emulsion in both RAP100 and RAP50 results in a contest between climate and water impacts. RAP100 achieves the lowest GWP score over the 30-year service life while having a poor WDP score. Local judgments will pervade in the selection between methods: water-scarce environments may select MF for future road rehabilitation, while locations where water availability is not an

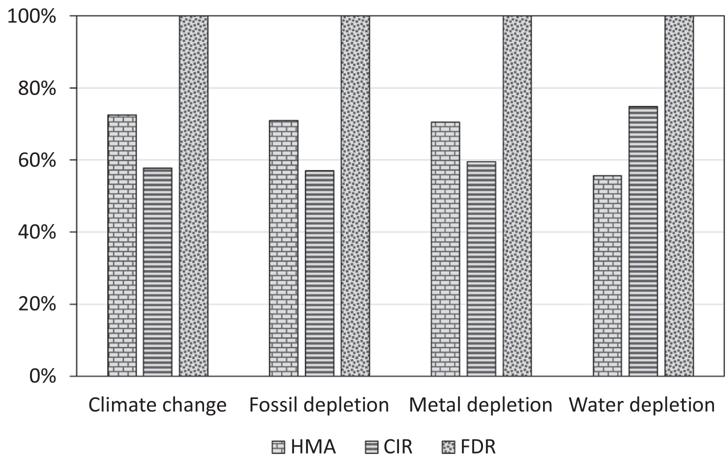

Fig. 8. Comparison of a single rehabilitation cycle per annum for each scenario scale to the highest impact in each impact category.

issue may prefer to reduce the carbon footprint of roading projects by choosing RAP100 rehabilitation.

Findings such as this reveal the complexity of environmental impacts in engineering projects. There is no clear best solution, but these results do provide clarity for approaching specific challenges, be they climate or water-related. In the case of southern Ontario, water is abundant (McKitrick, 2018) while high GHG profiles in the region (T. Elliot & Levasseur, 2022) suggest that RAP100 would be a more suitable environmental choice. Meanwhile, in the case of RAP100, there is an opportunity to look at ways to decrease water consumption.

4.2. Regional comparisons

Many studies have estimated the life cycle environmental impacts of road pavements in different regions. For example, J. Harvey, Saboori, Dauvergne, Steyn, and Jullien (2014) compared environmental impacts (including GWP) of HMA-based pavements in USA (California), China, France, and South Africa and assessed their sensitivity to different energy sources for 5 kms of two-lane roads with 3.6 m width over a 20-year time horizon. Their work is most comparable to the MF scenario as none of the cases considered by J. Harvey et al. (2014) include variable RAP constituent or CIR, although they do allude this important consideration. In terms of system boundary, their study assumed a more generalized transportation phase. Aggregate and asphalt were sourced 20 kms and 100 kms from the construction site respectively. Like our study, the mobile mixing plant was located at the construction site.

The pavement designs used by J. Harvey et al. (2014) were converted based on approximate equivalent performance and traffic characteristics. The California case, whose pavement design consists of two layers, is most similar to our MF scenario in Ontario: 460 mm base layer of aggregate overlaid with 150 mm asphalt concrete. However, the maintenance schedule is more like the French case, for which surface treatment or resurfacing is expected every 8 to 10 years (c.f. Fig. 5), which may be a reflection of the similar weather conditions between Ontario and France. Their results varied greatly between France (which had the lowest GWP due to electricity generated by nuclear reactors) to China (highest GWP due to high coal-use in electricity generation and fuel oil used in asphalt mixing). By converting their functional unit to a 1 lane-km, 30-year time horizon we can compare those results to our own for the GWP impact category, shown in Fig. 9.

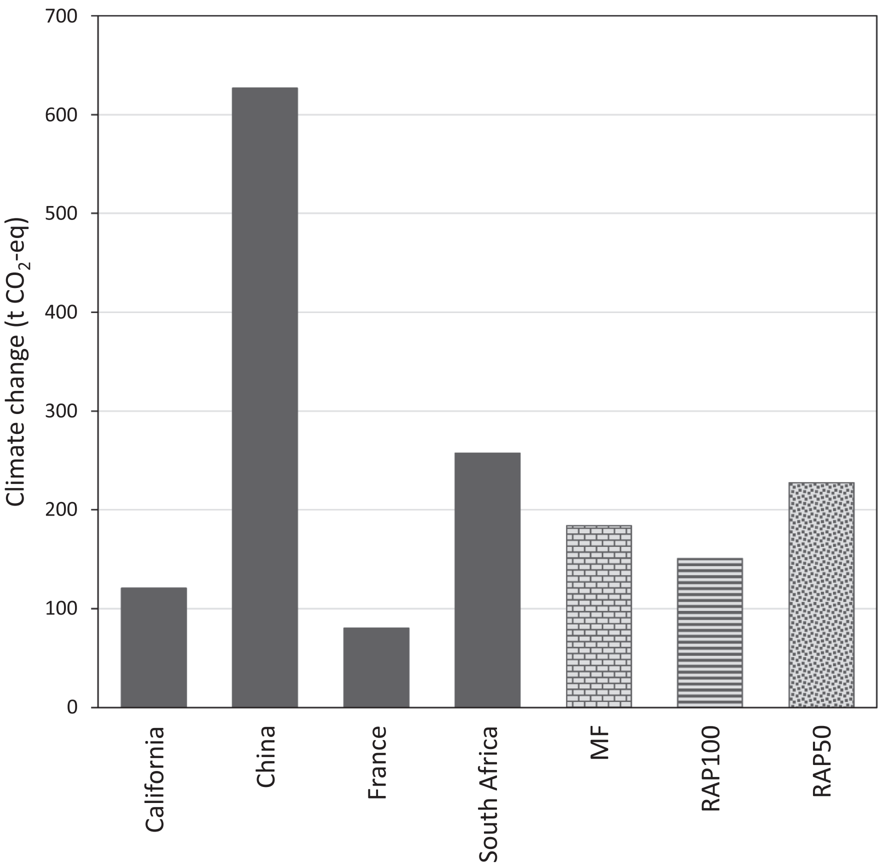

Fig. 9. GWP of MF, RAP100, and RAP50 compared to four regions assessed by J. Harvey et al. (2014).

Importantly for the validation of our results, the work of J. Harvey et al. (2014) illustrates the variation of results between regions, which is far greater than the variation between our three scenarios. Our RAP100 scenario has a similar GWP to that of the California scenario, while all our scenarios fare better than the South Africa and China cases.

The case study of Communication Road has low electricity demand due to the mobile machinery used by the Miller Group, which allows for in situ production of HMA, for example (Miller Group, 2021). A conclusion from the work of J. Harvey et al. (2014) suggests our approach would show different results for rehabilitations done in different regions of Canada, where low-carbon electricity is more available and more readily utilized, such as in the neighbouring province of Québec (T. Elliot & Levasseur, 2022).

The Italian study of Giani et al. (2015) assessed the environmental impacts of constructing three pavement designs with variable portions of RAP in the surface, course, binder layer, and base layer. All 18 ReCiPe Midpoint (H) impact categories had lower burdens as RAP content increased. They found the best option to be the one with highest portions of RAP in all three pavement layers: 10 % and 20 % RAP with HMA in the surface and binder layers, and 30 % RAP with *warm* mix asphalt in the base layer. This option was then paired with two rehabilitation scenarios to meet a 30-year service life: cold in-*plant* recycling or cold in-*place* recycling (i.e., CIR). considered a 30-year life with either cold in-*plant* recycling or CIP. The difference being variation in fuel types used and transportation. They found 35 % of water depletion occurred in the extraction and production of bitumen, leading to overall 15 % lower water depletion when higher portions of recycled material replaced the need for virgin bitumen, in spite of the use of recycled materials demanding more water in the construction phase. We did not find this, which is largely due to the pavement design we used which required virgin bitumen *and* water in the CIR process, and our crack-sealing maintenance for all scenarios being based on virgin bitumen and thus incurring water depletion.

We are able to compare GWP of our CIR results with those of Giani et al. (2015) more thoroughly than other impact categories. Their results show 1183 tonnes CO_2-eq, or around 297 tonnes CO_2-eq per lane-km equivalizing approximately to the functional unit we used (dividing their results by four gives an approximation of our 1 lane-km functional unit, although this is an oversimplification given the absence of pavement design criteria). This, however, includes initial base-layer burdens, which were out of our system boundary. Removing the road building activities which amounted to 650 tonnes CO_2-eq, or around 163 tonnes CO_2-eq per lane-km, gives 134 tonnes CO_2-eq. Our results show higher GWP for all three scenarios: 184 tonnes CO_2-eq (MF), 144 tonnes CO_2-eq (RAP100), and 227 tonnes CO_2-eq (RAP50) per lane-km over 30 years. While our results are comparatively high, this is attributed to higher material tonnages needed to meet local conditions. For example, weather conditions (high seasonal temperature range) and traffic loads have a strong influence on pavement design in Canada, and therefore the material demands.

On a material mass basis, scenarios assessed by Giani et al. (2015) to build roads convert to between 52 and 60.2 kg CO_2-eq per tonne, similar to 57 kg CO_2-eq per tonne from Miliutenko, Björklund, and Carlsson (2013) and 45 kg CO_2-eq per tonne from Hammond and Jones (2008). Meanwhile, we found pavement rehabilitation to have a wider variation between our scenarios. The MF scenario performs worst on a per tonne basis (101 kg CO_2-eq per tonne), while the RAP100 generates 44 kg CO_2-eq per tonne and RAP50 71 kg CO_2-eq per tonne over the 30-year estimated service life. This highlights the superior environmental performance associated with material efficiency of the two in-place recycling approaches, despite the potentially higher impacts during construction, while the variation with Giani et al. (2015) reaffirms the caution needed when comparing road pavement rehabilitation over different pavement designs as pointed out by a number of earlier articles (c.f. AzariJafari et al., 2016).

4.3. Assumptions and limitations

This LCA does not report all the environmental impact categories, but we selected those categories that were deemed most relevant for the interpretation of trade-offs, and most likely to be considered in road rehabilitation decision-making.

Data sources ranged from stakeholder meetings with local industry to establish the case study (Miller Group, 2021), while missing data were gathered from more general Canadian (and sometimes broadly North American) academic and gray literature, especially NRCan (2005). The range of data quality and publication dates between sources is a main limitation, principally because road rehabilitation technology and methods have changed in the last two decades. For example, at the time of publication of some data sources, FDR and CIR were marginal technologies with presumably less efficient supply chains and implementation methods. Moreover, these technologies are still not mainstream and will likely become more widespread, leading to hopefully shorter transportation distances and refined construction methods with lower environmental burdens. Therefore, results communicated here should be considered a first step towards revealing environmental trade-offs between MF, and recycling using CIR and FDR.

5. Conclusions

This paper quantified and compared the environmental impacts of three road rehabilitation scenarios in Ontario, Canada, using life cycle assessment. The assessment was calculated for one lane-km of road over a 30-year estimated service life. Large volumes of virgin materials are required to produce Hot Mix Asphalt, the basis of the Mill & Fill (MF) scenario. MF also has a seven-year rehabilitation cycle, meaning the procedure must be repeated four times during the 30-year service life. Reclaimed Asphalt Pavement (RAP) can be used to substitute aggregates and bitumen in HMA or in cold recycling mixes where other materials like water and bitumen emulsion are required. The RAP100 scenario deploys Cold In-place Recycling (CIR) technology using RAP and bitumen emulsion finished with a HMA wearing course, and has a 15-year rehabilitation cycle, meaning it must be repeated only twice during the 30-year estimated service life. The RAP50 scenario deploys Full-Depth Reclamation (FDR) technology using a mixture of 50 % RAP with bitumen emulsion and the remaining material is HMA. RAP50 still requires a further HMA wearing course. Moreover, after its 20-year use period it must be rehabilitated by a MF cycle to reach the 30-year estimated service life, meaning it has a high demand for HMA throughout its life cycle. While the materials and processes used to make HMA are relatively environmentally intensive compared to the use of RAP, the dependence on supplementary HMA in the RAP50 scenario, and the demand for water and bitumen in RAP100, highlighted trade-offs between impacts and life cycle stages across the three scenarios. We considered four impact categories, and found RAP100 to give the lowest global warming potential (GWP), making it the least burdensome for climate change, as well as performing best for fossil (FDP) and metal depletion (MDP). However, the demand for water used to make bitumen emulsion in both RAP scenarios rendered them poor for water depletion (WDP).

We also considered hotspots in the life cycle of each scenario. Production of bitumen contributes the higher portion of all impacts in every scenario. WDP was significantly higher in the RAP100 scenario due to the higher direct use of water in bitumen emulsion production, although still marginally better than RAP50. The MF scenario only requires water for the bitumen emulsion used in crack-filling maintenance, and due to the lower demand had around two-thirds of the WDP impact compared to the RAP100 scenario, countering the assumption that higher use of RAP will result in overall improved environmental performance.

Sensitivity analysis showed improvements could be made by reducing transportation distances, especially in the RAP100 scenario. However, other stages of the life cycles may have more room for improvement, namely in the upstream production of bitumen. Meanwhile, switching to a stationary HMA plant showed varying sensitivity, including some improvements and some increased burdens to water depletion. There is room for further research into sensitivity of results to production and construction processes, among other parameters, which are likely to decrease as RAP technology becomes more mainstream in road pavement rehabilitation projects.

While the results highlight the complexity of comparing conventional and emerging pavement recycling methods, we can conclude that RAP100 is a superior approach if climate change and material scarcity are the main environmental criterion. In water-rich regions of Canada such as Ontario, water depletion is likely to be less relevant for decision-makers selecting their preferred road rehabilitation method. In other (e.g., water-scarce) regions, however, or as environmental objectives shift, these priorities are likely to differ.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2023.103720.

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