COMPARATIVE LIFE CYCLE ASSESSMENT OF A VOID REDUCING ASPHALT MEMBRANE AND OTHER LONGITUDINAL JOINT TREATMENTS

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BACKGROUND

Roads and highways form a sprawling and heavily used infrastructure network with **environmental impacts at all stages of development and use**.

- Motorway **traffic** accounts for a **significant portion** of the greenhouse gases (**GHGs**) and **regulated criteria air pollutants** emitted in association with roadways
- The **construction process** of these roadways and the extraction, manufacture, and transport of the **construction materials** also contribute to the lifetime emissions of roadways
- The **construction** phase of roadways can amount to **ten to twenty percent of all GHG** emissions generated from road traffic across its lifetime

The **transportation and infrastructure construction industries** are under pressure to **improve the sustainability** of roadways, and large-scale initiatives to address on-road emissions are underway.

- These include initiatives around **vehicle electrification** and efficiency and **public transit** availability.
- **Agencies** at the federal, state, and local level are simultaneously working to establish **sustainable best practices** and incorporate **innovative solutions** to reduce GHG and other emissions
- More specifically, recent trends in roadway construction materials serve to **improve life cycle environmental impacts** through improved pavement construction techniques

Roadway asphalt paving projects result in a **longitudinal joint** at the interface between two adjoining hot mix asphalt lifts.

- Due to **lower asphalt density** at the longitudinal joint, air and water **intrusion** result in **weakening** of road performance
- Subsequent trips to **repair** the deteriorated joint are necessary to extend the road's useful life

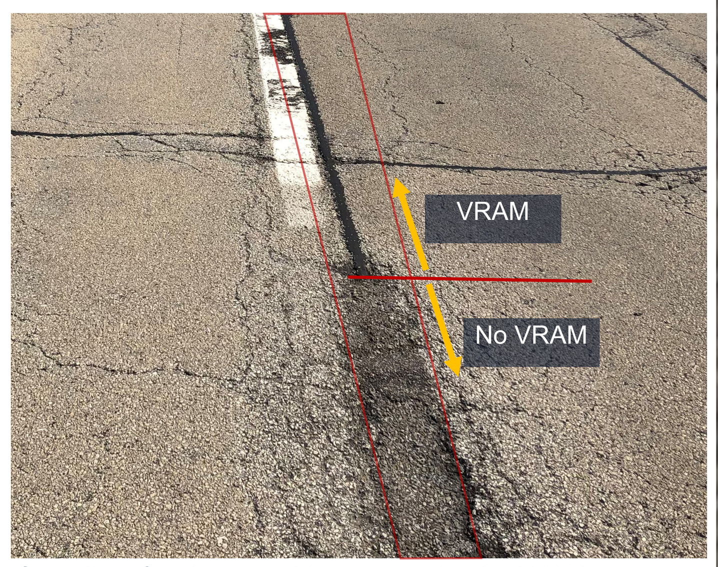
The effects of **climate change** are expected to **exacerbate and accelerate longitudinal joint deterioration** through:

- Increased rainfall
- Extended freeze-thaw periods
- Extreme heat waves and droughts

Several methods have been used to **improve longitudinal joint performance** through **higher density** or **lower permeability** to improve joint durability and longevity.

Four **common methods** are compared in this study:

- Void reducing asphalt membrane (VRAM)
- Infrared (IR) joint heater
- Joint adhesive and sealant
- Pave wide and mill back (PWMB)



Centreline of twelve-year-old pavement showing VRAM treatment

A previous IDOT study compared these treatments on a life cycle cost analysis (LCCA) basis, wherein it was determined that the **benefit of VRAM** relative to the other methods was **three to five time the initial cost**. This study **quantifies the environmental performance** of the longitudinal joint treatment solutions.

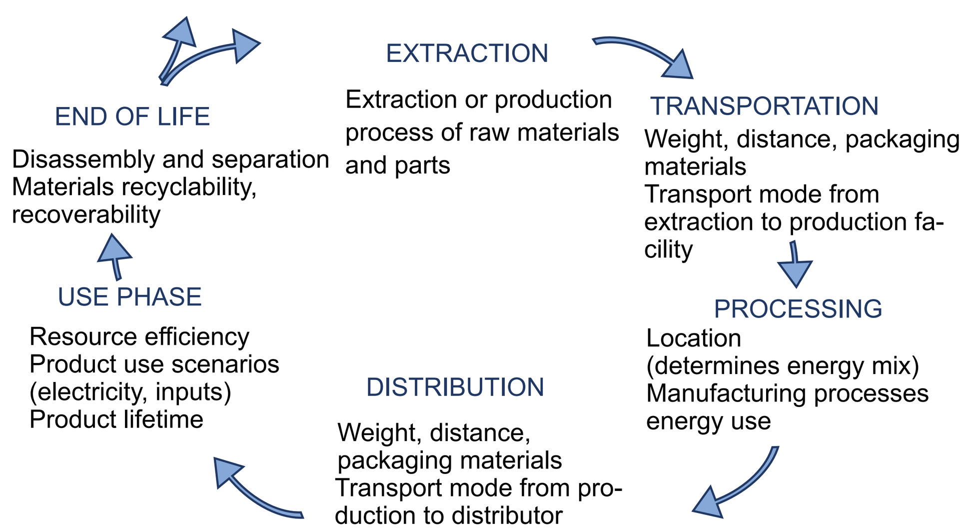
Year - n	A - VRAM	A - No VRAM	Annual Savings	NPV - VRAM	NPV - No VRAM	Net Present Savings
20	$16,744.42	$19,502.75	$2,758.33	$249,116.12	$290,151.64	$41,035.52

Findings from LCCA analysis

QUANTIFYING ENVIRONMENTAL PERFORMANCE: LCAs

Life cycle assessments (**LCAs**) are a **standardised approach** to quantify the **environmental impacts** of a product from cradle-to-grave, including:

- Extraction of the raw materials to create the product
- Upstream and downstream transportation
- Manufacturing energy and materials inputs
- Distribution
- Product use, maintenance, or operation
- End-of-life processing



Benefits of an LCA include:

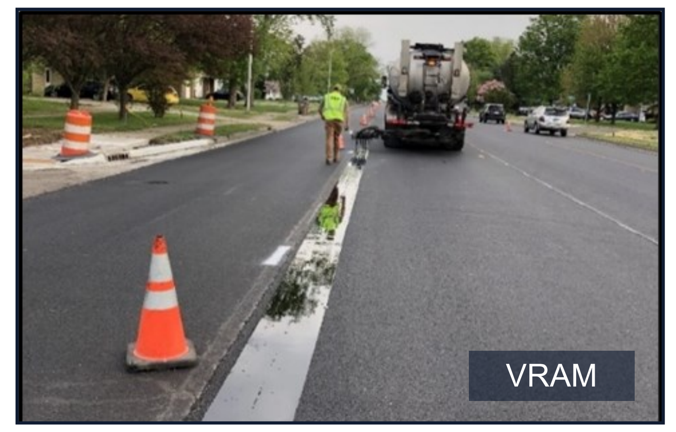
- Method for **standardized comparison** of the environmental impacts for different functional alternatives by capturing the product's life cycle impacts in their entirety
- Can be used with quantification of cost performance by a life cycle cost analysis (**LCCA**) to create a well-rounded assessment of **economic and environmental performance**
- Increased knowledge of a product's environmental performance

Several **variations** of the traditional cradle-to-grave LCA can used when the scope of the analysis differs, such as a **curtailed-boundary life cycle assessment**.

- This follows a similar approach to a traditional cradle-to-grave LCA but allows for **simplification** when looking at **multiple products**.
- Instead of quantifying all life cycle phases in total, phases which are **functionally equivalent can be excluded** from the quantification
- A **comparative curtailed-boundary LCA** can quantify **differences among alternative products** by providing insight into pollutants, energy consumed, waste by-products, and GHG emissions

METHODOLOGY

- This study provides a preliminary assessment of **sustainability performance** of four commonly used **longitudinal joint treatments** with the goal of quantifying the absolute difference in environmental performance between the joint treatments
- A comparative **curtailed-boundary LCA** approach is used to examine sustainability performance across three categories: GHG emissions, criteria air pollutants, and worker safety



Emissions

- **Processes and factors** of each joint treatment were identified from the materials production phase, with the goal of capturing the most relevant sources of GHG and criteria air pollutant emissions
- These include extraction, upstream transportation, and manufacturing, and to the construction phase, including downstream transportation, application, maintenance, and end of life impacts
- All information relating to **fuels, energy, materials, equipment, transportation** was examined, with data sourced from EPA and other state and federal agencies and databases, and vehicle and equipment specifications.

$$GHG\ emissions = \sum GHG_{equipment} + GHG_{vehicles} + GHG_{electricity}$$
$$= \sum Fuel_{equipment} * GWP_{Fuel} + Fuel_{vehicles} * GWP_{Fuel} + Electricity * GWP_{electricity}$$
$$CP\ emissions = \sum CP_{equipment} + CP_{vehicles}$$
$$= \sum Fuel_{equipment} \times CP\ EF_{Fuel} + Fuel_{vehicles} \times CP\ EF_{Fuel}$$

Standard **case parameters** were developed with industry experts, and was defined as a **1 mile-stretch** of interstate road located (**a**) **50 miles away** from the VRAM or joint adhesive manufacturing facility or (**b**) **30 miles away** from the IR heater or PWMB warehousing facility.

Safety

Safety metrics were also calculated for each of the longitudinal joint solutions, based on expected man-hours for each phase of construction work, combined with **BLS and FHWA safety data** and statistics.

RESULTS – SAFETY

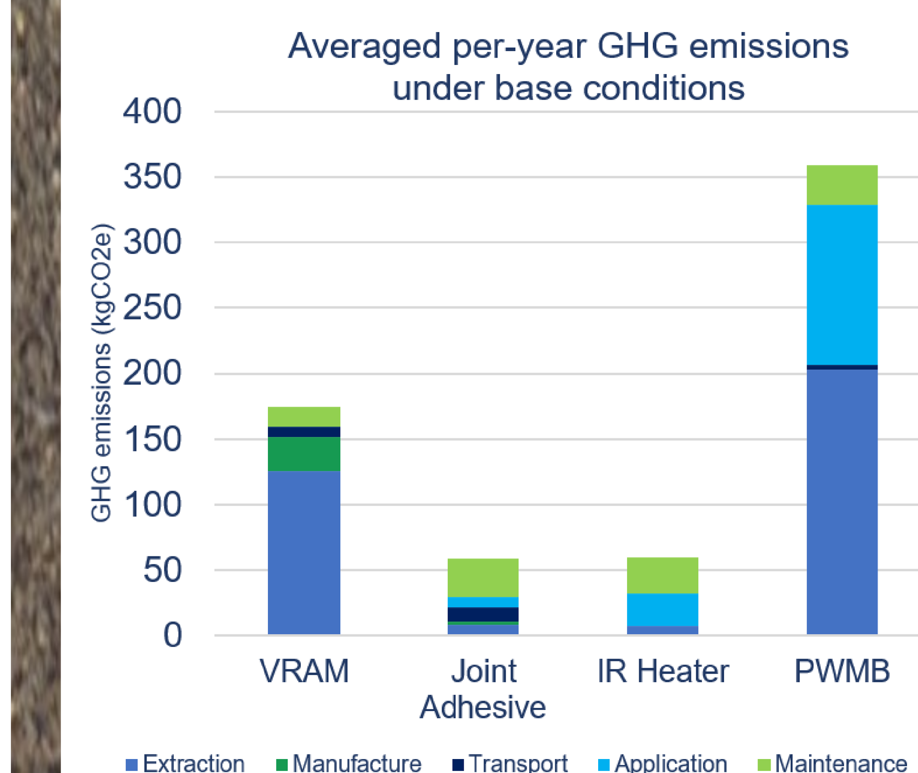
Worker Safety	Injuries per million miles				Fatalities per million miles			
	VRAM	Joint Adhesive	IR Heater	PW/MB	VRAM	Joint Adhesive	IR Heater	PW/MB
Application	21	32	189	284	1	1	6	10
Maintenance Trips	44	837	837	837	1	28	28	28
Total over lifetime	65	868	1,026	1,120	2	29	34	38
Average per year	**4**	**58**	**64**	**75**	**0**	**2**	**2**	**3**

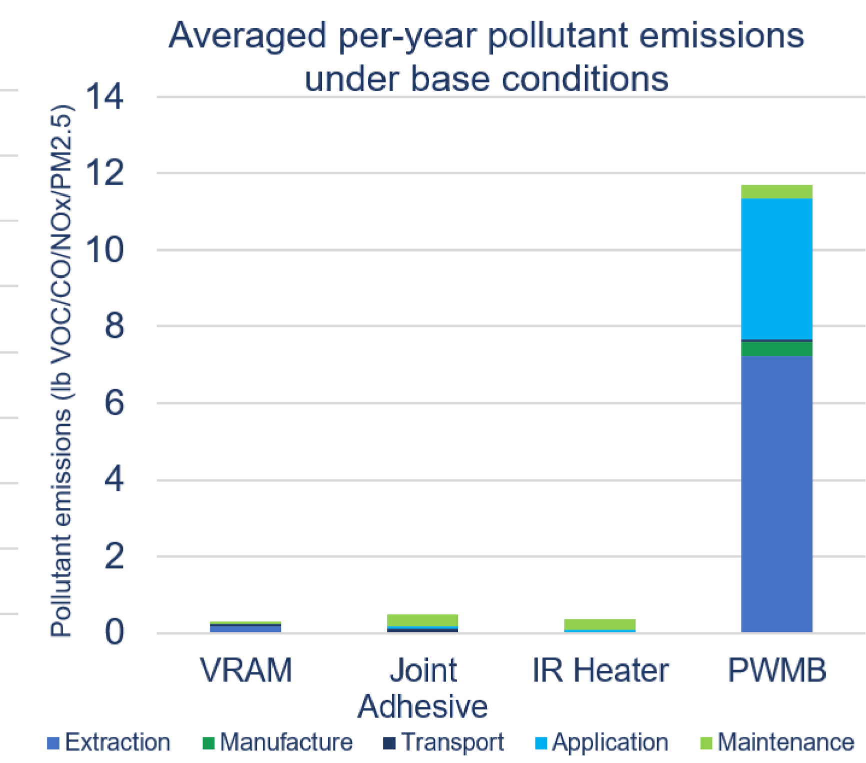
RESULTS – GHG AND AIR QUALITY

Emissions are reported for comparative material production phases and construction phases to highlight potential direct emission reductions at the end-user level, i.e., scope one emissions of the agencies and contractors involved in roadway construction.

Materials-production phases	GHG Emissions (kgCO2e)				Pollutant Emissions (lb VOC/CO/NOx/PM2.5)			
	VRAM	Joint Adhesive	IR Heater	PWMB	VRAM	Joint Adhesive	IR Heater	PWMB
Extraction	2269	126	112	3042	3.06	0.17	0.5	108.36
Manufacture	459	36			3.27e-4	1.82e-5		5.71
Total lifetime materials production emissions	**2728**	**162**	**112**	**3042**	**3.06**	**0.17**	**0.5**	**114.08**
Averaged per-year materials production emissions	**152**	**11**	**7**	**203**	**0.17**	**0.01**	**0.03**	**7.61**

Construction phases	GHG Emissions (kgCO2e)				Pollutant Emissions (lb VOC/CO/NOx/PM2.5)			
	VRAM	Joint Adhesive	IR Heater	PWMB	VRAM	Joint Adhesive	IR Heater	PWMB
Transport	136	160	NA	58	1.38	1.68	NA	0.74
Application	3	119	400	1834	0.03	0.66	0.67	55.67
Maintenance trips	275	444	444	444	0.82	4.84	4.84	4.84
Total lifetime construction phase emissions	**414**	**724**	**844**	**2336**	**2.23**	**7.18**	**5.52**	**61.25**
Averaged per-year construction phase emissions	**23**	**48**	**53**	**156**	**0.12**	**0.48**	**0.34**	**4.08**





CONCLUSIONS

- There is significant potential to **develop transportation infrastructure** in line with the principles of **sustainable development.**
- Sustainability is an increasingly important component of transportation infrastructure, with federal, regional, and state entities having a range of awareness and education programs, all while promoting the use of 'green' or **sustainable roadway products.**
- **Upstream emissions** associated with materials production are outside the carbon accounting of direct emissions, i.e., **scope three** instead of scope one emissions, and thus, as agencies and contractors look to reduce their **scope one** emissions, they will be evaluating methods and materials which will allow for a **reduction in fuel usage**.
- Longitudinal joint solutions that offer the **lowest application-phase emissions**, **reduced maintenance** needs, and **extended road lifetimes**, will result in the **lowest scope one emissions**. In this analysis, VRAM and joint adhesive have the lowest **construction phase** emissions.
- Considered alongside a previous study of joint treatment performance and life cycle cost performance, the inclusion of quantified environmental impacts of these roadway materials can promote informed decision making towards the achievement of greenhouse gas reductions and improved environmental outcomes.

Comparative Life Cycle Assessment of a Void Reducing Asphalt Membrane and Other Longitudinal Joint Treatments

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ABSTRACT

There are significant greenhouse gas and regulated criteria pollutant emissions associated with roadway infrastructure, from both motorway vehicle sources as well as construction materials and processes, and improved materials and construction methods can reduce these emissions. The environmental impacts of four commonly used longitudinal joint treatment solutions including void reducing asphalt membrane (VRAM), joint adhesive, pave wide mill back (PWMB), and infrared joint heater are evaluated. A comparative, curtailed-boundary life cycle assessment approach is employed to estimate differences in greenhouse gas emissions and criteria air pollutants. Emissions are reported for comparative material production phases and construction phases to highlight potential direct emission reductions at the end-user level, i.e., scope one emissions of the agencies and contractors involved in roadway construction. During the roadway lifetime, the average per mile yearly GHG emissions for materials production phases are 152, 11, 7, and 203 kg CO2e/year, and criteria pollutant emissions are 0.17, 0.01, 0.03, and 114.08 kg pollutant/year for VRAM, joint adhesive, IR heater, and PWMB, respectively. For the construction phase, GHG emissions are 23, 48, 53, 158 kg CO2e/year while criteria pollutant emissions 0.12, 0.48, 0.34, and 4.12 kg pollutant/year for VRAM, joint adhesive, IR heater, and PWMB, respectively. Considered alongside a previous study of joint treatment performance and life cycle cost performance, the inclusion of quantified environmental impacts of these roadway materials can promote informed decision making towards the achievements of greenhouse gas reductions.

Keywords: Void reducing asphalt membrane (VRAM), comparative life cycle assessment, joint adhesive, pave wide mill back, infrared joint heater, greenhouse gas

INTRODUCTION

There is a growing need to transform the planning, construction, and management of infrastructure to align with sustainability principles and meet the demands of a changing environment. Upstream raw materials extraction; aggregate, asphalt, concrete, steel, and other production; and construction operations generate significant greenhouse gas emissions across the lifecycle of an infrastructure project.

Climate Change and Climate Change Resiliency

The transportation sector, whose boundaries are defined by the U.S. Environmental Protection Agency's (EPA) to include the direct, end-use emissions from on-road vehicles, rail, aircraft, and marine vessels, contributes a significant portion of U.S. greenhouse gas (GHG) emissions, comprising 27% of total emissions in 2020 (1). With over 65 million kilometers of roadways throughout the United States (2), roads and highways form a sprawling and heavily used infrastructure network with environmental impacts at all stages of development. The environmental impact of U.S. roadways has already been recognized, with estimates that the construction phase of these roads and highways can account for ten to twenty percent of all GHG emissions generated from the lifetime usage of the road by vehicles (3; 4).

The relationship of transportation infrastructure to climate is two-fold. Beyond impacting the climate through GHG emissions during all lifecycle phases, a changing climate is expected to have ramifications on the resiliency of roadway infrastructure. Within the U.S., climate change impacts will vary regionally (5), exerting different pressure on infrastructure across the country. Within the northeast and southeast, extreme precipitation events and hurricanes with associated flooding and mudslides are expected to increase in frequency and severity, leading to damaged and washed-out roadways (6). Throughout midwestern, southern, and western states, extreme heatwaves and persistent droughts will worsen the rate at which buckling, rutting, subsidence, and pavement damage occur (7). Nationally, climate change will lead to a potential shifting and lengthening of freeze-thaw periods, during which roadways are more susceptible to damage (8).

In asphalt pavements, a longitudinal joint occurs at the interface between two separately laid mats of hot mix asphalt pavement and is frequently accompanied by lower asphalt density surrounding the joint. This low-density area allows air and water infiltration into the pavement, accelerating deterioration of the joint and decreasing longevity of the pavement (9). The effects of climate change, including increased rainfall, extended freeze-thaw periods, extreme heat waves and droughts, exacerbates and accelerates joint deterioration (10).

Roadway Construction Stakeholders

The implementation of sustainability principles to infrastructure is a response to internal and external pressures from multiple stakeholders. Within the United States, organizations such as the Federal Highway Administration (FHWA), the National Asphalt Pavement Association (NAPA), and the U.S. Department of Transportation (U.S. DOT), are raising awareness and establishing the importance of sustainability by providing standards and best-practices (11; 12; 13). These groups seek to advance innovation and reduce GHG emissions to increase climate change resiliency and improve community health and quality of life.

State and municipal transportation agencies are more directly involved with the implementation of sustainability. They are actively involved in design, construction, and maintenance of roads, and can explore innovative sustainability solutions to increase the environmental performance of transportation infrastructure.

State DOTs can implement sustainable alternatives that reduce GHG and other air pollutant emissions while providing safety benefits. They can incorporate novel materials and processes that contribute towards the achievement of state-wide emission reduction targets, along with other favorable environmental and social outcomes. State and municipal transportation agencies are in the position to promote increased use of 'green' products by exerting pressure on contractors and suppliers – in the form of sustainable product alternatives, such as warm-mix asphalt or the inclusion of recycled materials such as rubber or recycled asphalt pavements, or in the requirement of environmental impact quantifications such as environmental product declarations (EPDs) or life cycle assessments (LCA).

Currently, many contractors have not incorporated sustainability principles in their operations. While contractors adhere to environmental permit requirements for air emissions, most do not have a sustainability program in place. Many are unaware of the potential benefits from enhanced sustainable practices, or climate impacts from their current operations. Instead, they focus on specification requirements for their projects. Bidding requirements that include EPDs and LCAs are occurring is some states, but nation-wide implementation has not yet occurred. Many contractors have thus far avoided quantifying their sustainability performance; however, some industry leaders are aware of the cost-saving and efficiency-enhancing benefits of implementing sustainability programs, goals, and GHG-reducing measures.

Quantifying Environmental Performance: LCAs and EPDs

Life cycle assessments are an approach to quantify the environmental impacts of a product from cradle-to-grave, including extraction of the raw materials to create the product; upstream and downstream transportation; manufacturing energy and materials inputs; distribution; product use, maintenance, or operation; and the end-of-life processing, as illustrated in **Figure 1**. An LCA provides a standardized comparison of the environmental impacts for different functional alternatives by capturing the product's life cycle impacts in their entirety. An LCA can be used with quantification of cost performance by a life cycle cost analysis (LCCA) to create a well-rounded assessment of economic and environmental performance.

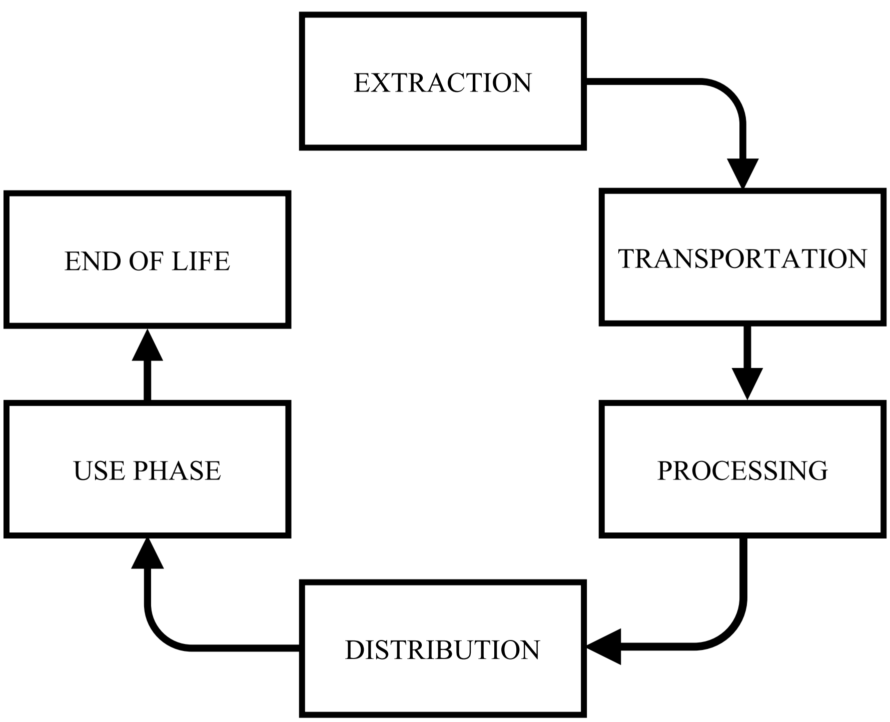

Figure 1 Generalized stages in an LCA

Several variations of the traditional cradle-to-grave LCA are often used when the scope of the analysis differs. One alternative method is a curtailed-boundary life cycle assessment, which follows a similar approach to a traditional cradle-to-grave LCA but allows for simplification when looking at multiple products. Instead of quantifying all life cycle phases in total, phases which are functionally equivalent can be excluded from the quantification, so long as it does not misconstrue the interpretation of the results (14).

A comparative curtailed-boundary LCA can quantify differences among alternative products by providing insight into pollutants, energy consumed, waste by-products, and GHG emissions. Despite differences in scope, both curtailed-boundary LCAs and traditional LCAs can be used to support informed decision-making through the increased knowledge of a product's environmental performance.

SUSTAINABILITY EFFORTS IN PAVEMENTS

Consensus is growing on the need to reduce the sustainability impacts of processes and products used in building pavements. The General Services Administration (GSA) recently issued the document, "Environmentally Preferable Asphalt Standards for all GSA Projects" (15), which states that GSA projects using more than ten cubic yards of hot mix asphalt (HMA) will require an EPD. In addition, the mixture must meet two of four criteria that include recycled material content, reduced temperature, bio-based materials, or improved-energy manufacturing plants.

Some agencies, such as the Port Authority of New York and New Jersey, CalTrans, the Oregon DOT and the Colorado DOT, have implemented "Buy Clean" legislation (16). The Colorado legislation, informally known as "Buy Clean Colorado," was signed into law on 6 July 2021, with goals to reduce emissions by 50 percent by 2030 and 90 percent by 2050 (17). This law (18) aims to track and reduce GHG emissions during the manufacture and transport of products used in public construction projects. Asphalt and asphalt mixtures are among seven material categories affected by the legislation, and on 1 July 2022 the requirement to include EPDs with bids came into effect.

At the same time that agencies are recognizing the environmental impact of transportation projects, the asphalt industry is taking initiatives to decrease its carbon footprint. NAPA recently released their Road Forward campaign (12) and a case for net zero emissions in the asphalt industry by 2050. Some of the proposed tactics include increasing pavement life by using materials that add to pavement longevity, and the use of equipment with reduced GHG emissions.

Trepanier et al. (19) summarized a method to increase pavement life in research performed by the Illinois Department of Transportation (IDOT) using a void reducing asphalt membrane (VRAM) to increase joint life and reduce maintenance needs while increasing the life of the pavement. A VRAM is a high polymer content asphalt binder applied at the location of longitudinal joint prior to the placement of the lifts of HMA. The VRAM material modifies the HMA nine inches on either side of the joint making it more asphalt rich, crack resistant, and impermeable. After testing pavement cores on constructed projects with and without the VRAM material and after those projects had been in place for about 15 years, they concluded that decreased permeability and increased crack resistance of the polymer-modified VRAM material extended the life of the joint three to five years. Life cycle cost analysis (LCCA) determined that the benefit was three to five times the initial cost.

METHODOLOGY

This study provides a preliminary assessment of sustainability performance of four commonly used longitudinal joint treatment treatments based on principles and requirements outlined by ISO 14040:2006 and ISO 14044:2006 (14; 20). A comparative curtailed-boundary LCA approach is used to examine sustainability performance in two categories: GHG emissions and criteria air pollutants. Results are presented for the material production phases and construction phases to highlight the comparative differences.

Selected Longitudinal Joint Treatments

Over the years, several methods have been used to improve longitudinal joint performance. Each method seeks to obtain higher density or lower permeability to improve joint durability and longevity. Four methods examined in this study include VRAM, infrared joint heater, joint adhesive and sealant, and pave wide and mill back, all of which are used in similar market areas. Building on the IDOT study (19) comparing treatments using LCCA, this study evaluates VRAM and three other treatments on an LCA basis.

VRAM Application

VRAM is typically applied with a heavy-duty asphalt distributor that can heat and spray hot polymer-modified asphalt (**Figure 2**). The distributor operates at a temperature up to 320°F, with recirculation to maintain heat uniformity.

The distributor applies the VRAM material as a strip 18 inches wide straddling the centerline of the paving at a typical rate of 1.5 pounds per lineal foot, although the application rate for VRAM depends on asphalt mixture type and thickness. A pickup truck acts as a support vehicle to carry ancillary equipment. An 18-year service life was used, based on the work done by IDOT (19).

Figure 2 Application of VRAM

Infrared joint heater

An infrared joint heater (IR heater) using propane is passed along a cold joint after the application of the first lift, producing a mat temperature of 150°F to 200°F before the second lift is applied to promote bonding of the existing material between the passes (**Figure 3**). The IR heater is typically attached in front of the paver screed about one inch above the pavement. A lifetime of 16 years is assumed in this study for roadways roads using an IR heater along the longitudinal joint.

Figure 3 Infrared Joint Heater

Joint Adhesive and Sealant

Joint adhesive is a polymer-modified asphalt material applied to the face of the first paving pass that promotes bonding between the first and second paving passes. It is usually supplied as 35-pound blocks in cardboard boxes that are melted in a kettle. As the 400-gallon kettle is fed blocks at a rate of one block per minute, a service vehicle pulls the heated kettle while a worker applies the material to the vertical face of the joint with a hand wand (**Figure 4**). A diesel generator heats the material to between 350°F to 400°F.

Joint sealant is an asphalt emulsion often used with joint adhesive, and is applied by a distributor spraying the asphalt emulsion two feet wide over the longitudinal joint after both lanes have been placed (**Figure 5)**. Often, the sealant material is the same asphalt emulsion used for tack coat. The service life of the combined joint adhesive and sprayed joint sealant is 15 years.

Figure 4 Application of joint adhesive

Figure 5 Application of joint sealant

Pave Wide and Mill Back

Pave wide and mill back (PWMB) is a method of joint treatment (**Figure 6**) where the first pass is typically placed three to six inches wider than the lane width. The excess width is then trimmed, which removes lower density material at the edge of the mat, and the excess material is hauled away by dump trucks. The excess material can be trimmed with a cutting wheel when the mat is not completely cooled or with a milling machine after it is cooled to ambient temperature. The analysis in this paper is based on the use of a milling machine removing six inches of material. After cleaning the milled surface, the second paving pass is placed. The expected service life of PWMB is 15 years.

Figure 6 Milling for PWMB

Crack sealing

Crack sealing is a preventive treatment for filling the cracks to prevent water intrusion into the pavement layer. The equipment for crack sealing is the same equipment used for joint adhesive as shown in **Figure 4. Figure 7** shows a crack along a longitudinal joint being filled. Before filling, the joint is routed, then cleaned with compressed air using a hand wand operated by a worker on the ground. Heated asphalt crack sealant is applied using a hand wand to fill the joint. On an interstate highway as modeled in this analysis, both the routing and cleaning operation and the crack filling kettle have separate trucks.

Each selected longitudinal joint treatment has a different expected maintenance schedule. For VRAM, crack sealing is expected to occur every three years, with 100 ft/mile being sealed at year three, and 200 ft/mile being re-sealed at each of years six, nine, twelve, and fifteen. The pavement is rehabilitated at year eighteen.

For both joint adhesive and PWMB, crack sealing activities were modelled with 25, 50, 75, and 100 percent of total longitudinal joint length being re-sealed at years three, six, nine, and twelve, respectively. The pavement is rehabilitated at year fifteen. For IR heater the initial crack sealing is delayed to year four, followed by sealing at a three-year interval. Twenty-five, 50, 75, and 100 percent of the total longitudinal joint length is re-sealed at year four, seven, ten, and thirteen. Pavement rehabilitation occurs at year sixteen.

Figure 7 Crack filling on a longitudinal joint

ANALYSIS METHODS

A comparative curtailed-boundary LCA was conducted to quantify the impact differences of the selected longitudinal joint treatments. The goal of this study was not to quantify the full life cycle impacts of each joint treatment, nor to analyze the percentage differences in environmental performance, but rather, to quantify the absolute differences in environmental performance between joint treatments. Thus, a comparative curtailed-boundary LCA was chosen as the approach to assess the selected joint treatments against one another. The boundaries of this LCA exclude all factors common between each joint treatment from quantification, focusing instead on aspects where they differ.

Processes and factors of each joint treatment were identified related to the materials production phase, including extraction, upstream transportation, and manufacturing, and to the construction phase, including downstream transportation, application, maintenance, and end of life impacts, with the goal of capturing the most relevant sources of GHG and criteria air pollutant emissions. All information relating to fuels, energy, materials, equipment, transportation was examined.

Data sources

Information used to build this comparative LCA model came from a variety of sources. GHG emissions factors were sourced from EPA reports, including GHG inventories (21) and waste reduction model documentation (22). Air quality emission calculations were made using U.S. EPA, NC DEQ (24), FHWA (25), and ecoinvent data (23; 24; 25; 26).

Vehicle and equipment specifications, such as fuel efficiencies and power capacities, were gathered from original manufacturers when available, with averages from the US Department of Energy used as proxy when such information was unavailable (27). Additional data was gathered from various sources as needed, including from personnel working in the various markets where the selected joint treatments are used.

In addition, primary manufacturing data was obtained from the manufacturer of a VRAM product. Data was allocated on a production basis between the VRAM product and other products manufactured at the facility to determine fuel and electricity consumption, and was normalized to a standard unit of measure.

Due to a lack of primary manufacturing data, and with the difference in composition between VRAM and joint adhesive products being deemed de minimus for the purpose of this analysis, joint adhesive extraction and manufacturing phase emissions calculations were performed using VRAM primary data as a proxy and calculated in relation to the volume of VRAM used, i.e., $1/18^{th}$. When needed, secondary data in the form of emission factors were used, incorporating the appropriate scope for the life cycle stage.

Evaluation of Materials Production Phase and Construction Process Phase Emissions

Greenhouse Gas Emissions

Calculation of GHG emissions is split between materials production emissions, including material extraction and manufacturing, and construction phase emissions, including all vehicles, generators, heaters, and other construction and maintenance equipment. Emissions of carbon dioxide equivalents were calculated for the identified sources based on base-conditions for the model.

$$GHG\ emissions = \sum GHG_{equipment} + GHG_{vehicles} + GHG_{electricity}$$

$$= \sum Fuel_{equipment} * \ GWP_{Fuel} + Fuel_{vehicles} * GWP_{Fuel} + Electricity * \ GWP_{electricity}$$

Air Quality

Comparative impacts from emissions of traditional, regulated compounds were quantified. Although hundreds of compounds are codified under 40 CFR and regulated by the U.S. EPA, states, and Indian Tribal Governments, this assessment quantified emissions of particulate matter (PM), volatile organic compounds

(VOC), carbon monoxide (CO), and nitrogen oxides (NOx) for each joint treatment. This group of four compounds make up the largest percentage of regulated emissions occurring from fuel combustion and roadway project activities as widely documented in public domain emission factors (28).

VRAM manufacturing emissions were calculated using primary activity data, and remaining project level emissions were calculated using traditional air quality methodology, applying published emission factors to the equipment type, equipment quantity, duration used, and fuel type for the 1-mile baseline project model.

$$CP\ emissions = \sum CP_{equipment} + CP_{vehicles}$$

$$= \sum Fuel_{equipment} \times\ CP\ EF_{Fuel} + Fuel_{vehicles} \times CP\ EF_{Fuel}$$

The total for all four compounds were summed for a total pound pollutant/activity air quality impact metric.

$$^{kg\ Poll}/_{Proj} = CP_{VOC} + CP_{NOx} + CP_{CO} + CP_{PM2.5}$$

Assumptions

Several key assumptions were made while developing the comparative LCA model. Standard case parameters were established using information provided by industry experts familiar with the selected joint treatments and typical use scenarios, and thus the base case was defined as a 1 mile-stretch of paved road that is situated (a) 50 miles away from the VRAM or joint adhesive manufacturing facility or (b) 30 miles away from the IR heater or PWMB warehousing facility. The analysis is based on interstate conditions and the associated standard practices and approaches.

The quantification of joint sealant material production emissions was excluded from analysis, as emissions contributions were deemed de minimus. For PWMB, the width of pavement being milled off is assumed to be 6" and atmospheric pollutant impacts for HMA extraction was calculated using the asphalt binder extraction emission factor as a proxy with an additional 10% to account for aggregate extraction. Other reasonable assumptions and estimations had to be made in some cases to accommodate for unavailable data, such as not accounting for varying fuel efficiency between normal driving speeds compared to construction phase driving speeds.

RESULTS

The primary life cycle stages were identified to summarize the selected joint treatments' sustainability impact differences across materials production and construction phases. Material production includes extraction, upstream transportation, and manufacturing emissions; construction phase emissions include downstream transportation, application, maintenance, and end of life.

Identification of Life Cycle Stages

Details of the life cycle stages for the selected joint treatments were outlined and compared. All required materials and processes used in the extraction, transportation, manufacture, use phase and end of life were detailed, and are summarized in **Table 1**. For the comparative analysis, the factors that remain consistent among the treatment options are identified to be excluded from analysis, represented in **Table 1** as the italicized factors, while the factors that differ between the treatment options remain for analysis.

TABLE 1 Details of the life cycle stages for the selected joint treatments with identified differences to be analyzed.

		Description	VRAM	Joint Adhesive (JA)	IR Heater	PWMB
Materials Production	Extraction & Processing	*Extraction of all raw materials used during road paving and/or joint treatment*	(*HMA products*) + Additional asphalt binder production	(*HMA products*) + Additional asphalt binder production	(*HMA products*) + Propane production	(*HMA products*) + 6" additional HMA production
	Transportation (upstream)	*Movement of materials from point of extraction to production facility*	*Differences at this stage are built into the upstream emission factors selected for the materials associated with each joint treatment. Upstream emission factors were selected for upstream transportation within the system boundary.*			
	Manufacturing	*Manufacturing processes and inputs to create joint treatment materials*	*(HMA products)* + VRAM manufacture (electricity consumption, heat)	*(HMA products)* + JA manufacture (electricity consumption, heat)	*(HMA products)*	*(HMA products)* + HMA manufacture (electricity consumption, heat)
Construction Process	Transportation (downstream)	*Movement of materials from production facility to job site*	*(HMA transport)* + Distributor spray truck, pick-up truck	*(HMA transport)* + Asphalt emulsion distributor, pick-up truck	*(HMA transport)*	*(HMA transport)* + Dump trucks (additional waste)
	Use	*Application of HMA and joint treatment; lifetime maintenance*	*(Traditional HMA)* + VRAM application + Maintenance	*(Traditional HMA)* + JA application + Maintenance	*(Traditional HMA allows for pass of IR Heater)* + Maintenance	*(Traditional HMA)* + Application and milling of additional 6" HMA + Maintenance
	End of Life	*Management of materials at road end of life.*	*Standard road rehabilitation and waste management*			
	Factors italicized in parentheses represent the factors that are consistent among the four treatments and are excluded from quantification					

Furthermore, results are specified for material production emissions, which includes the extraction, processing of raw materials, and final manufacture of the joint treatment product, and construction phase emissions, which include the downstream transportation, construction, maintenance, and end of life.

A model was constructed based on the identified factors and results are reported for the assumed base case conditions reported above. For practicality, the breakdown of the life cycle into industry nomenclature, rather than the nomenclature of traditional life cycle stages, was chosen to aid in comprehension. Specifically, the use phase stage is split into application and maintenance.

Materials Production Emissions

Greenhouse Gas Emissions

The GHGs associated with the production of the materials used for each longitudinal joint solution were quantified across the identified life cycle stages and are summarized in **Table 2**.

For VRAM, extraction phase emissions, which includes the extraction and processing of an asphalt binder-like product, are 2269 kg CO2e, while joint adhesive emissions, calculated at a $1/18^{th}$ rate based on proportional usage volume to VRAM, are 126 kg CO2e. Manufacturing phase emissions, which include fuel and electricity used in the production of the VRAM and joint adhesive product are 459 kg CO2e for VRAM, and 36 kg CO2e, which are again calculated at a $1/18^{th}$ proportional rate to VRAM.

For IR heater, an emission factor was selected for the propane that included all upstream emissions, i.e., extraction, processing, and manufacturing, and are thus reported as a single value of 112 kg CO2e. Emission factors selected for HMA included the same upstream boundaries so upstream extraction, processing, and manufacturing emissions for PWMB are 3042 kg CO2e.

Based on the pavement lives used for each treatment, the averaged per-year materials production emissions are 152 kg CO2e/yr for VRAM; 11 kg CO2e/yr for joint adhesive; 7 kg CO2e/yr for IR heater; and 203 kg CO2e/yr for PWMB.

Air Quality Emissions

Similar to the GHGs summarized in **Table 2**, criteria pollutants were quantified associated with the production of the materials used for each joint treatment across the identified life cycle stages.

Following the same system boundaries outlined above, criteria pollutants for the extraction and manufacture of VRAM are 3.06 and 3.3e-4 kg, respectively, and 0.17 and 1.8e-5 kg, respectively for the joint adhesive. For the IR heater, an emission factor with the same upstream boundary as above was selected and thus emissions are reported as a single value of 0.50 kg. There are 108.36 kg of pollutants associated with HMA extraction for PWMB, and PWMB manufacturing emissions are 5.71 kg of pollutants.

Averaged per-year materials production emissions are 0.17 kg pollutant/yr for VRAM; 0.01 kg pollutant/yr for joint adhesive; 0.03 kg pollutant/yr for IR heater; and 7.61 kg pollutant/yr for PWMB.

TABLE 2 Emissions associated with the materials production phases of the selected longitudinal joint treatments per base conditions

	GHG Emissions (kgCO2e)				Pollutant Emissions (kg VOC/CO/NOx/PM2.5)			
	VRAM	Joint Adhesive	IR Heater	PWMB	VRAM	Joint Adhesive	IR Heater	PWMB
Extraction	2269	126	112	3042	3.06	0.17	0.5	108.36
Manufacture	459	36			3.27e-4	1.82e-5		5.71

Total lifetime materials production emissions	**2728**	**162**	**112**	**3042**	**3.06**	**0.17**	**0.5**	**114.08**
Averaged per-year materials production emissions	**152**	**11**	**7**	**203**	**0.17**	**0.01**	**0.03**	**7.61**

Construction Process Emissions

Greenhouse Gas Emissions

GHGs arising from the construction and maintenance process were quantified and results are summarized in **Table 3**.

Downstream transportation, which includes a 50-mile travel distance between the manufacturing facility and the job site, is 136 kg CO2e for VRAM and 160 kg CO2e for joint adhesive, while the application phase emissions for VRAM are 3 kg CO2e, and 119 kg CO2e for joint adhesive. Emissions from maintenance trips for VRAM and joint adhesive, whose maintenance schedules are outlined above, are 275 kg CO2e and 444 kg CO2e, respectively.

For PWMB, the transportation phase emissions are 58 kg CO2e. For IR heater, as no additional transportation vehicles are necessary, there are no transportation phase emissions. Application phase emissions for IR heater are 400 kg CO2e, while they are 1834 kg CO2e for PWMB. Maintenance phase emissions are 444 kg CO2e for both IR heater and PWMB.

Averaged per-year construction phase emissions are 23 kg CO2e/yr for VRAM; 48 kg CO2e/yr for joint adhesive; 53 kg CO2e/yr for IR heater; and 156 kg CO2e/yr for PWMB.

Adding the materials production emissions to the construction and maintenance emissions the total lifetime GHG emissions are 3142 kg CO2e for VRAM; 885 kg CO2e for joint adhesive; 956 kg CO2e for IR heater; and 5379 kg CO2e for PWMB. Using the expected life for each longitudinal joint treatment, the averaged per year emissions are 175 kg CO2e/yr for VRAM; 59 kg CO2e/yr for joint adhesive; 60 kg CO2e/yr for IR heater; and 359 kg CO2e/yr for PWMB.

Air Quality Emissions

In addition to GHG emissions, **Table 3** also presents a summary of the air pollutant emission impacts for the construction and maintenance phases, with the same baseline assumptions.

Downstream transportation from the manufacturing facility is 1.38 kg pollutant for VRAM and 1.68 kg pollutant for joint adhesive. Application phase emissions for VRAM are 0.03 kg pollutant, and 0.66 kg pollutant for joint adhesive. Maintenance phase pollutant emissions for VRAM and joint adhesive are 0.82 and 4.84 kg, respectively.

PWMB emits 0.74 kg pollutant at the extraction phase, while there is no additional transport associated with the IR heater. Application phase emissions are 0.67 kg pollutant for the IR heater and 55.67 kg pollutant for PWMB. Maintenance phase emissions as outlined above, are 4.84 kg pollutant for both the IR heater and PWMB.

Averaged per-year pollutant emissions for the construction and maintenance phase are 0.12 kg/yr for VRAM; 0.48 kg/yr for joint adhesive; 0.34 kg/yr for IR heater; and 4.08 kg/yr for PWMB.

Adding material production pollutants to the construction and maintenance phase pollutants, the total lifetime emissions are 5.29 kg pollutant for VRAM; 7.35 kg pollutant for joint adhesive; 6.02 kg pollutant for IR heater; and 175.33 kg pollutant for PWMB. Considering the lifetime for each longitudinal joint treatment, the averaged per year emissions are 0.29 kg pollutant/yr for VRAM; 0.49 kg pollutant/yr for joint adhesive; 0.38 kg pollutant/yr for IR heater; and 11.69 kg pollutant/yr for PWMB.

TABLE 3 Emissions associated with the construction and maintenance phases of the selected longitudinal joint treatments per base conditions

	GHG Emissions (kgCO2e)				Pollutant Emissions (kg VOC/CO/NOx/PM2.5)			
	VRAM	Joint Adhesive	IR Heater	PWMB	VRAM	Joint Adhesive	IR Heater	PWMB
Transport	136	160	NA	58	1.38	1.68	NA	0.74
Application	3	119	400	1834	0.03	0.66	0.67	55.67
Maintenance trips	275	444	444	444	0.82	4.84	4.84	4.84
Total lifetime construction phase emissions	**414**	**724**	**844**	**2336**	**2.23**	**7.18**	**5.52**	**61.25**
Averaged per-year construction phase emissions	**23**	**48**	**53**	**156**	**0.12**	**0.48**	**0.34**	**4.08**

DISCUSSION

A comparative curtailed-boundary LCA provides a reasonable measure by which to quantify comparative GHG and air pollutant emissions and can form the basis of sustainability and environmental performance assessment. However, the usefulness of a comparative approach is limited to situations where equivalent products or measures exist in the same functional context as is the case for the longitudinal joint treatments examined herein. As comparative differences comprise the only quantified stages, emissions results can only be interpreted within the context of the original selected products, and broader statements making comparisons to other products outside the scope of this assessment cannot be made. The addition or removal of products from the assessment would necessitate a re-evaluation of comparative life cycle differences.

The separation of results into materials production phases and construction phases is done to highlight the differences that would be seen by the end user, i.e., the first-hand differences that could be achieved by contractors using these different joint treatment options. The upstream emissions associated with materials production are outside the carbon accounting of direct emissions, i.e., scope three instead of scope one emissions, and thus, as agencies and contractors look to reduce their scope one emissions, they will be evaluating methods and materials which will allow for a reduction in fuel usage. In this case, longitudinal joint solutions that offer the lowest application-phase emissions, reduced maintenance needs, and extended road lifetimes, will simultaneously offer a reduction in fuel usage, and thus scope 1 emissions.

In addition, the separation of materials production emissions from construction phase emissions allows for inferences to be made on the perceived carbon efficiency of treatment options between materials of similar composition, for example, VRAM and joint adhesive. The application of VRAM uses eighteen times more material volumetrically than joint adhesive, and thus materials production-phase emissions are eighteen times higher for VRAM. Despite this higher comparative materials usage, VRAM's application phase and reduced maintenance needs, combined with joint longevity improvements, reduces the per-year emissions differences over the lifetimes of the two products.

The analysis in this paper focused on the singular component of the life cycle of a longitudinal joint. Within a roadway system, other products and processes produce emissions which were not quantified in this study, including grading, base layers, and asphalt mixture not associated with treatments for longitudinal joint stability, i.e., PWMB. The results of this analysis represent the comparative differences among different joint treatments, and the inclusion of these additional factors, among others, would expand the bounds of this comparative LCA for longitudinal joint treatment solutions into a comparative LCA of complete asphalt pavement roadways.

Furthermore, initial pavement deterioration often begins at longitudinal joints but is not the only consideration for maintenance. Potholes, rutting, and other forms of cracking all impact roadway integrity and may dictate different maintenance or rehabilitation schedules.

The comparative LCA in this study aimed to quantify the direct life cycle emissions of the selected joint treatment solutions. Secondary emissions, such as vehicle delay and speed changes from road construction and maintenance, were not accounted for. Extended periods of vehicle idling, as active driving lanes are restricted, reduced speed limits and altered traffic flows have the potential to contribute significant secondary GHGs and air pollutants.

Longitudinal joint treatments that require the fewest disruptions to normal traffic flow, such as quick and non-disruptive applications techniques and reduced maintenance needs, would be expected to have lower secondary emissions. In this case, VRAM, with reduced maintenance needs and non-disruptive application, would be expected to have considerably lower secondary emissions from idling compared to other joint treatment solutions. Similarly, other large scale sustainability impacts, such as the social and health impacts of reduced congestion due to construction, safety benefits arising from fewer man-hours required during construction and maintenance, or economic losses, were not quantified.

As a continuation from an LCA, there is potential benefit to examining the environmental sustainability impacts of these various measures through the lens of an EPD. An EPD is a disclosure tool based on LCA processes and principles, seeking to quantify and communicate all environmental impacts, including GHG emissions, ozone impacts, water source acidification or eutrophication, in a manner designed to facilitate the benchmarking of functionally similar products. EPDs are frequently likened to nutrition labels, where information is standardized and easily digestible, and can promote informed decision making.

Product LCAs or EPDs are already being employed by entities at the state and regional level with increasing frequency to aid in the quantification of environmental impacts of construction projects, with EPDs being mandated for some products in some cases. By selecting roadway products that have quantified their environmental and sustainability impacts, organizations can maintain a competitive edge while staying ahead of regulation that would limit the use of non-quantified products.

CONCLUSIONS

There is significant potential to develop transportation infrastructure in line with the principles of sustainable development. Sustainability is an increasingly important component of transportation infrastructure, with federal, regional, and state entities having a range of awareness and education programs, all while promoting the use of 'green' or sustainable roadway products.

One location where there is potential for increasing sustainability is the selection of the longitudinal joint treatment. Treatment options exist that can provide extended roadway longevity and construction efficiency improvements. Considered alongside previous work that examined performance and LCCA of various longitudinal joint treatments, an assessment of sustainability performance was performed through a comparative, curtailed boundary LCA.

VRAM and joint adhesive were found to emit an average of 152 and 11 kg CO2e per year of service life at the materials production phase, while IR heater and PWMB materials production emit an average of 7 and 203 kg CO2e per year of service life. During construction phases, VRAM and joint adhesive emit an average of 23 and 48 kg CO2e per year of service life, while IR heater and PWMB emit an average 53 and 156 kg CO2e per year of service life. For the four criteria pollutants quantified, VRAM and joint adhesive emit an averaged 0.17 and 0.01 kg pollutant per year of service life at the materials production phase, while IR heater and PWMB materials production emit an averaged 0.03 and 7.61 kg pollutant per year of service life. During construction phases, VRAM and joint adhesive emit an average of 0.12 and 0.48 kg pollutant per year of service life, while IR heater and PWMB emit an average of 0.35 and 4.08 kg pollutant per year of service

With tools such as LCAs and EPDs allowing for translatable and meaningful comparison of the environmental performance of functionally similar products, it becomes easier for contractors and managers of infrastructure projects to identify areas of improvement and can promote industry-wide shifts towards more sustainable products. These tools, combined with LCCA, give designers and policy makers the ability to make more informed decisions.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Kelleher and Thomas; data collection: Kelleher and Yoder; analysis and interpretation of results: Kelleher and Yoder; draft manuscript preparation: Kelleher, Thomas, and Huber. All authors reviewed the results and approved the final version of the manuscript.

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