Paving the Path to Net-Zero: A Life Cycle Assessment of Asphalt Pavement Construction Projects in Washington State

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Abstract

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With the US setting a goal of reaching net-zero carbon emissions by 2050, industries must act towards progressing towards this goal. The National Asphalt Pavement Association has stepped up to this challenge by setting an industry goal of halting climate change by achieving net-zero carbon emissions by 2050 during asphalt production and construction. This study examines four Washington State Department of Transportation (WSDOT) asphalt case studies from the 2023 paving season. It analyzes the carbon emissions from the material production through the construction phase (life cycle stages A1-A5). Environmental Product Declarations (EPD) and construction data were collected from contractors to cover upstream asphalt mixture production (A1-A3) and construction (A4-A5) impacts. Life cycle assessments were completed on the openLCA software using project data to quantify the environmental impacts. With a functional unit per short ton of asphalt and based on trends in the life cycle assessments (LCA), material production obtained from the mix design EPD had the most significant impact. Material production (A1-A3) of the four projects fell between 65-80% of the project's total global warming potential (GWP), followed by transportation (A4) at 10-20% and construction activities (A5) at 8-13%. Material production has such a significant impact on the total GWP that obtaining the mix design's EPD can provide a good understanding of a project's total carbon emissions through the construction stage. Reducing the carbon emissions associated with the asphalt paving industry is essential in meeting net-zero carbon emissions goals. This study provides a glimpse into the state of carbon emissions of the asphalt paving industry in Washington State.

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1 INTRODUCTION

Addressing the climate crisis will be one of the biggest challenges faced by today's generation. It will require dedication and lots of innovation to stop and reverse the harmful effects of human-induced warming. Impacts from climate change are noticeable across the globe through the increased weather and climate extremes (e.g., heatwaves, heavy precipitation, droughts, and tropical cyclones). The Intergovernmental Panel on Climate Change (IPCC) is a United Nations body that assesses the science related to climate change and reports on the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation. The most recent IPCC report emphasized the need to limit warming to 1.5 °C to avoid severe climate impacts (Calvin et al. 2023). The IPCC's Working Group One emphasized this need; "From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality." (IPCC 2021).

In 2021, the White House released their long-term strategy and pathways to net-zero, which committed to net-zero greenhouse gas (GHG) emissions by 2050 in response to the information presented in the IPCC report. Additionally, the National Asphalt Pavement Association (NAPA) created the Climate Stewardship Task Force, which is comprised of NAPA members, state asphalt pavement associations, and academia, to develop sustainability and resilience objectives for the industry. NAPA has joined other industries by setting an industry goal to "Achieve net zero carbon emissions during asphalt production and construction by 2050." (National Asphalt Pavement Association n.d.).

What does net-zero have to do with asphalt pavement construction? Roads and highways are crucial element within transportation infrastructure. In the U.S., there are over 4 million miles of public roadways, with 93% paved with asphalt pavement. In 2021, the transportation sector accounted for 29% of total greenhouse gas (GHG) emissions in the United States (U.S. EPA 2023). At 29%, the transportation sector held the largest share of GHG emissions by economic sector.

Most reported GHG emissions come from vehicular use. However, the construction of roadways through new transportation infrastructure, road reconfigurations, and maintenance and rehabilitation are also significantly associated with GHG emissions (Sharifi et al. 2021). In 2019, the International Energy Agency (IEA) reported that of the GHG emissions reported for the transportation sector, 74% of them were from road traffic and construction processes ("International Energy Agency" 2019). Current research investigates technological shifts in road traffic emissions (vehicles driven on the road) by replacing fossil fuels with electricity or hydrogen and changing the manual drive to platooning and autonomous vehicles.

While the construction portion of the transportation infrastructure's total emissions is relatively small, to reach net zero the entire industry will need to contribute to the mission. The transportation industry emits approximately 1.88 $MTCO_2eq$, roughly only 0.13 $MTCO_2eq$ is due to road construction. Understanding asphalt pavement's embodied carbon is necessary to fully understand the impact of transportation infrastructure. Embodied carbon (EC) is defined as the “greenhouse gas emissions generated during the extraction, production, transportation, placement, repair and disposal processes for all materials used to build and maintain roadways.” (Ashtiani et al. 2024a). Life cycle assessments (LCA), the most agreed upon EC accounting method, are typically used to analyze the EC of asphalt pavements. Legislation such as the Bipartisan Infrastructure Deal (BIL) and Inflation Reduction Act (IRA) have accelerated consideration of EC in roadway infrastructure. The BIL authorized funding for projects that reduced transportation-related carbon emissions. The IRA allocates funding for using low-embodied carbon construction materials and products. This study, which looks at four asphalt paving projects across Washington State, utilizes LCA methodology to calculate the project's EC of the asphalt pavement.

1.1 Research Question

Washington State law (RCW 70A.45.020) mandates limits on GHG emissions and sets reduction targets for 2020, 2030, 2040, and 2050. Due to this type of legislation, Washington State Department of Transportation (WSDOT) will likely be called upon to measure and reduce the carbon footprint generated by the infrastructure they build and operate. Environmental Product Declarations (EPD) and similar accounting tools are used to credibly inventory carbon. Integrating these tools into WSDOT's standard procurement and specifications will be the next crucial step in decarbonizing transportation infrastructure to meet the 2050 net-zero goal set by NAPA and the White House.

The specific research question presented for this thesis is:

> *“What are the GHG emissions associated with materials production, transport to the jobsite, and construction operations for asphalt pavement in Washington State?”*

To answer this question, this thesis quantifies the carbon emissions from material acquisition, the hot mix asphalt’s (HMA) embodied carbon, material transfer from plant to site, and all on-site construction operations completed for four WSDOT paving project case studies from the 2023 paving season. Based on data from these case studies, this thesis will offer insight into the asphalt pavement’s embodied carbon of the four WSDOT paving case studies. Additionally, this thesis will address further details associated with trends identified in data and construction activities and the methods used in LCA calculation from ongoing project data.

The outcome of this thesis will be to provide in-depth insight on the four projects presented using their primary data. From here, general conclusions will be drawn based on the outcomes of the LCA calculations that can be compared to existing carbon emission knowledge for asphalt pavements. Additionally, an understanding of asphalt pavement’s embodied carbon and its origin will be aggregated from the final environmental impact results.

1.2 Federal Highway Administration Climate Challenge

On April 22nd, 2022, the Federal Highway Administration (FHWA) announced many planned actions in response to the additional funding the BIL provided and to celebrate Earth Day. Programs, such as the Climate Challenge, will work towards lowering emissions generated by the transportation sector and assist communities in investing in clean transportation projects. The goal set forth by the Climate

Challenge is: “State department of transportations (DOT) or other public sector stakeholders explore the use of LCA and EPDs as a standard practice to inform pavement material and design selection for enhancing sustainable pavement practices and quantify the emissions and impacts of those practices.” Any state DOTs that wanted to participate in the FHWA’s Climate Challenge had to apply for funding.

In October 2022, the WSDOT applied to the Climate Challenge. In the proposal, WSDOT focuses on the integrated use of EPDs and LCA tools to achieve the DOT’s carbon emissions goals. Additionally, Washington has laws that limit GHG emissions and will require a reduction in statewide emissions to be net zero by 2050. Working towards this goal, this study is separated into three stages: training, data and metrics, and implementation. This thesis focuses on the data and metric stage of the overarching proposal submitted to the FHWA. Researchers at the University of Washington (UW) and the Carbon Leadership Forum (CLF) completed the data acquisition and analysis presented in this work for WSDOT.

1.3 Project Overview/Data Collection

The objective of WSDOT’s Climate Challenge work is to establish GHG emissions performance metrics based on project data collected on DOT work (roadway maintenance, rehabilitation, and new construction) to quantify the impact of transportation infrastructure on the state’s total GHG emissions.

Data for this initial observational study was gathered from four different WSDOT asphalt paving projects dispersed across Washington State to gather a geographical variety of data. Each project’s primary contract focus is paving operations, without much other auxiliary work. Data collected from each project included EPDs for the HMA mix and specific construction data (e.g., fuel consumption, engine sizes, trucking/transportation distances, etc.).

2 BACKGROUND

2.1 Life Cycle Assessment (LCA) Overview

LCA is an accounting process used to determine and quantify the environmental impacts of a specified product, system of products, or processes. LCAs are the primary accounting process used in this thesis to quantify the Global Warming Potential (GWP) in kg of CO_2 of the four asphalt paving case studies analyzed. Generally, LCAs are split into three different stages, which will be outlined in further detail in the General LCA Framework section and Figure 2, production (i.e., extractional upstream production, transport to factory, manufacturing), construction (i.e., transport to site, installation), use (i.e., use, maintenance, repair, replacement, refurbishment), and end-of-life (i.e., deconstruction/demolition, transport to waste processing or disposal, waste processing, disposal of waste). This thesis utilizes the production and construction stages to determine the associated GHG emissions of the asphalt paving projects. The FHWA provides a description of LCAs:

> *"LCA is a technique that can be used for analyzing and quantifying the environmental impact of a product, system, or process. LCA provides a comprehensive approach to evaluating the total environmental burden of a product or process by examining all of the inputs and outputs over the life cycle, from raw material production to end of life. This systematic approach identifies where relevant impacts occur and where the most significant improvements can be made while identifying potential trade-offs. The process and rules for conducting an LCA are generally defined by the International Organization for Standardization (ISO) in its 14040 family of standards (ISO 2006)."* (Harvey et al. 2016a).

In the next section, a brief history of LCAs in the US, from conception to present day will be covered.

2.1.1 The Overview of LCAs

The history of LCAs in the US outlined in this section is mainly taken from an LCA report put out by the Scientific Applications International Corporation (SAIC) and the *Life Cycle Assessment: Theory and Practice* textbook published in 2018 (Bjørn et al. 2017; (SAIC) 2006). The origins of LCAs date back to the 1960s, when concerns arose over limited access to raw materials and energy sources. These concerns sparked collaboration between universities and industry to create an accounting tool that quantifies energy use, future resource supplies, and use for a project. The first LCA, then known as Resource and Environmental Profile Analysis (REPA) or Ecobalances, was completed in 1969 when The Coca-Cola Company completed their first LCA that compared different types of beverage containers that the standardization of methods, which influenced current methodology, was formed. Early REPAs studies were created primarily for a company's internal use and focused on establishing a standard methodology that focused on cataloging the energy and resource use, emissions and generation of solid waste, and environmental impacts of the associated product systems.

2.1.2 LCA Standards

Transitioning to the name life cycle assessment became standard practice in the 1990s. Concerns over the inappropriate use of LCAs in the 1990s to make broad marketing claims were prevalent, leading to the pressure for a standardized LCA methodology. The International Organization for Standardization (ISO) is a non-governmental worldwide federation that works to prepare international standards for 170 national standards bodies. Their goal is to bring together experts in their respective fields to share knowledge and collaborate in a way that supports innovation and presents solutions to global challenges. The ISO released one of the leading frameworks used to conduct LCAs worldwide and includes requirements and guidelines that should be adhered to during the analysis of LCAs. In 2006, the ISO released its latest version of standards for LCAs. In their publication 14044, they described LCAs as follows, "LCA addresses the environmental aspects and potential environmental impacts (e.g., use of resources and environmental consequences of releases) throughout a production's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave)."

2.1.3 General LCA Framework

The general LCA framework consists of the following four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Figure 1 shows the phases of an LCA framework as outlined in the ISO 14040 standard. Below Figure 1 are the corresponding definitions and explanations of the concepts outlined.

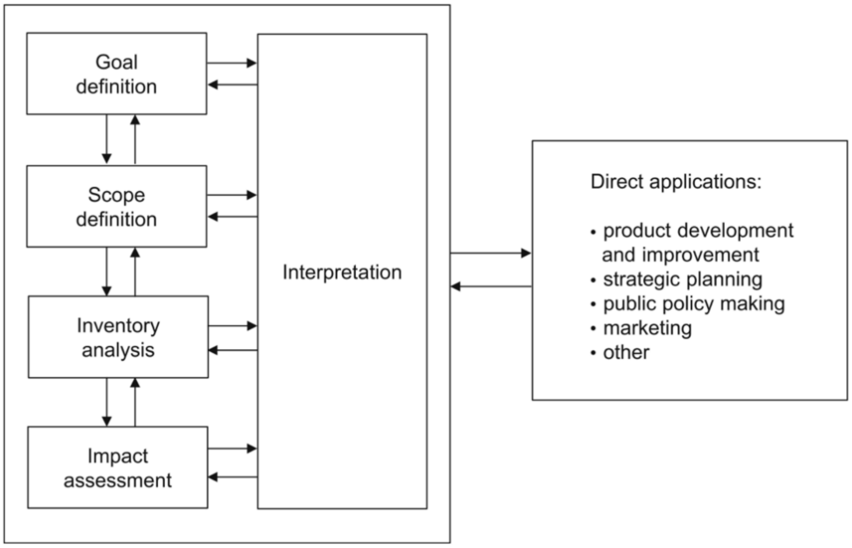


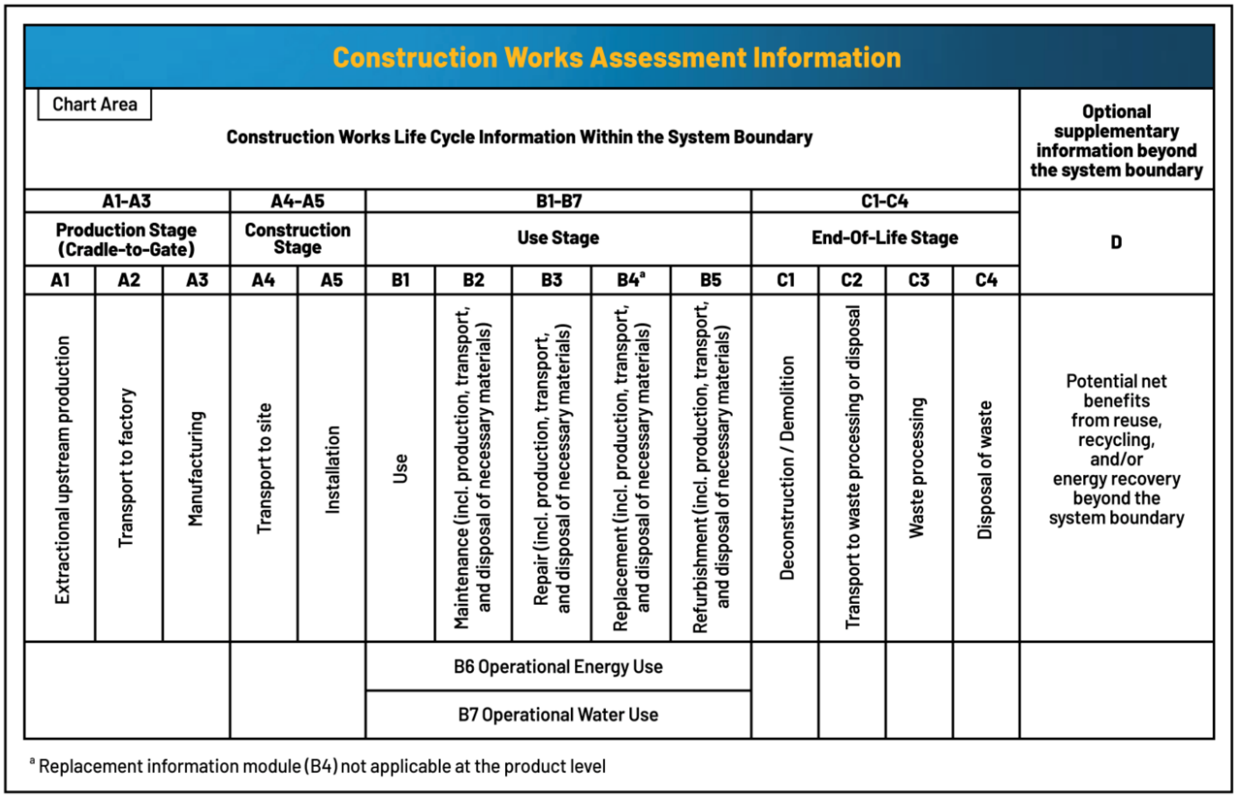
Figure 1 - Framework of an LCA modified from ISO 14040 Standard (Hauschild 2017)

- Goal and Scope: should be set by the primary organization performing the LCA.
    - Primary organizations: determine the approach to assess impacts, make decisions, and define the system analysis boundary (Harvey et al. 2016b).
    - Functional units: function and performance of the subject of the product or process being studied (Weiland and Muench 2010).
- Inventory Analysis: where environmental flows for the study are identified and quantified to be used in the model of the process being analyzed.

- Impact Assessment: tools are used to quantify the environmental and human health impacts of the model process created in the inventory analysis phase (Harvey et al. 2016b).
    - Characterization Factors: translates assigned emissions and LCI results into impact indicators.
        - TRACI (tool for the reduction and assessment of chemical and other environmental impacts)
        - CML (center for environmental studies at the University of Leiden, the Netherlands)
    - Uncertainty of the LCA should also be considered in this phase due to the inherent variability in data, input values, and imprecisions of the model
        - Uncertainty in areas such as a functional unit, the analysis period, system boundary assumptions, the impact assessment, and the sources of data should be considered and added into the LCA environmental impact calculations.
- Interpretation: is connected to every other piece of the framework as results and the data collected are being analyzed in this stage.

The first three phases of the framework typically work in a linear pattern that builds on each other. However, it is important to remember that at each stage, interpretations are made and considered throughout the duration of completing an LCA.

Figure 2 shows a detailed visual representation of standardized life cycle stages defined by ISO 21930 for construction products (Shacat et al. 2024). When identifying the scope of a LCA, identifying which life cycle stages fall within system boundaries is a key step in establishing boundaries for the models. In Figure 2, stages (i.e., production, construction, use, and end-of-life) identify different points in a product's life cycle and can be used to describe a specific duration of time. Additionally, each step within a stage has a corresponding module identifier (i.e., A1, A2, A3, etc.). Module identifiers and labels refer to different parts of a product's life cycle. For example, if a project considers the entire life cycle of a product, it could refer to it as "cradle to grave" or "stages A-C." (Figure 3). This terminology is commonly used when describing which portions of a life cycle an LCA calculates.



Construction Works Assessment Information

Chart Area

Construction Works Life Cycle Information Within the System Boundary															Optional supplementary information beyond the system boundary
A1-A3			A4-A5		B1-B7					C1-C4					
Production Stage (Cradle-to-Gate)			Construction Stage		Use Stage					End-Of-Life Stage					D
A1	A2	A3	A4	A5	B1	B2	B3	B4[a]	B5	C1	C2	C3	C4		
Extractional upstream production	Transport to factory	Manufacturing	Transport to site	Installation	Use	Maintenance (incl. production, transport, and disposal of necessary materials)	Repair (incl. production, transport, and disposal of necessary materials)	Replacement (incl. production, transport, and disposal of necessary materials)	Refurbishment (incl. production, transport, and disposal of necessary materials)	Deconstruction / Demolition	Transport to waste processing or disposal	Waste processing	Disposal of waste		Potential net benefits from reuse, recycling, and/or energy recovery beyond the system boundary
					B6 Operational Energy Use										
					B7 Operational Water Use										

[a] Replacement information module (B4) not applicable at the product level

Figure 2 - Pavement Life Cycle Stages (Shacat et al. 2024)

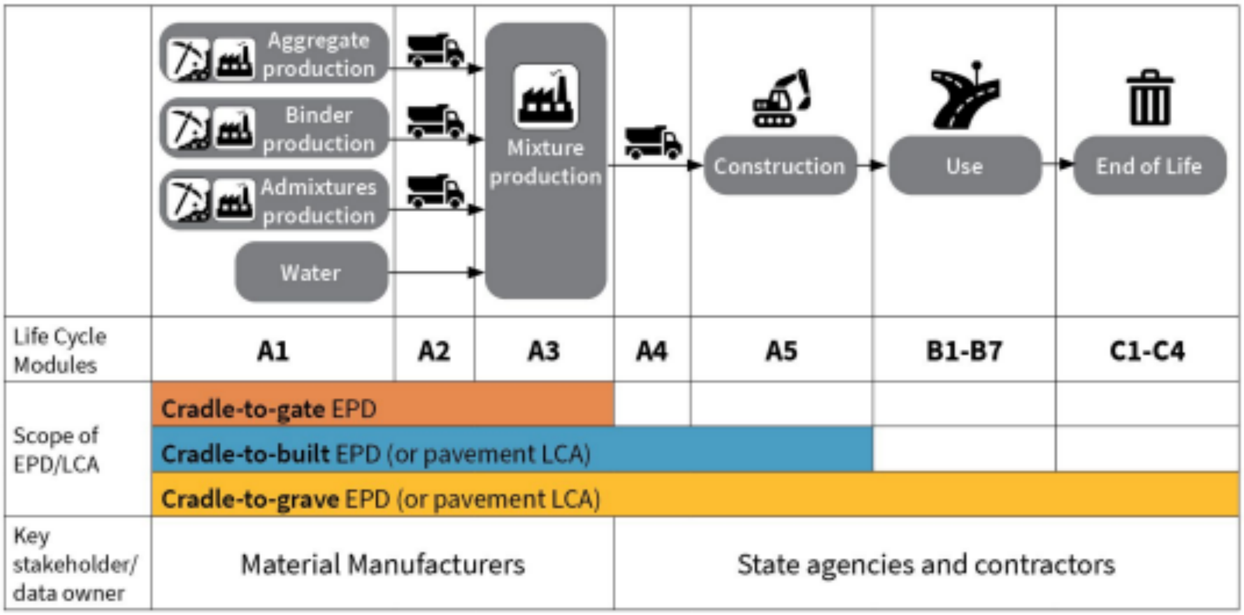


Figure 3 - Life cycle stages included in EPDs or pavement LCA with different scope, based on EN 15804 (Ashtiani et al. 2024b)

2.2 Environmental Product Declaration (EPD) Overview

EPDs are reports that quantify and communicate the environmental impacts associated with manufacturing construction materials that manufacturers have verified and developed (Shacat et al. 2024). EPDs can be used to quantify various environmental impacts for a given product (e.g., acidification potential, eutrophication potential, global warming potential, etc.). However, most studies focused on GWP. The following section will provide a brief overview of EPDs, their origins, and product category rules (PCR) that inform EPDs.

2.2.1 PCR Overview

As defined by the ISO, PCRs are specific rules, requirements, and guidelines for developing an EPD for a product group. PCRs are established by interested parties within the industry group, who then come to a consensus on how their products should be measured. Typically, they specify life cycle stages to include (scope), the functional or declared unit, system boundaries, criteria for including or excluding items, data quality requirements, inventory analysis required data, allocation of inputs/outputs, and the impact assessment (parameters used) (Frydendal et al. 2017; National Asphalt Pavement Association 2022a). PCRs generally promote consistency between the EPDs generated for similar products to enable transparency and comparability (Frydendal et al. 2017).

2.2.2 EPD Overview

In 1999, EPDs were introduced by ISO 14021 and 14024 as part of environmental labels and declarations. Since then, ISO 14025, an updated version, was released in 2006. The ISO specified three different environmental declarations that can be made. EPDs are a type 3 environmental declaration under ISO 14025. Therefore, EPDs need to be verified by a third party, report various environmental impacts that reflect a supply chain, and calculated using predefined rules known as product category rules (PCR) using LCA methodology (Rangelov et al. 2021a).

In recent years, PCRs and EPDs have been developed by various industries (e.g., food, chemical, building industries, etc.) since they are effective ways to communicate product-specific environmental performances from LCAs that are easily comprehensible to audiences, with or without LCA backgrounds (Rangelov et al. 2021a). Two primary EPDs are utilized: industry-wide and product-specific. Industry-wide EPDs use generalized data for products across many manufacturers and report the average product's environmental impacts. Product-specific EPDs are LCAs done on a singular product from a specific manufacturer and do not consider data that is not explicit to that product. In addition, product-specific EPDs can compare materials used for similar applications. Therefore, as stated in ISO 14025, EPDs can be used to assist purchasers in making an educated decision on the product by considering its environmental performance.

2.2.2.1 EPD Example

In this section, an example of the key pages of an asphalt EPD document (procured from Emerald EcoLabel) is broken down with descriptions in Figure 4, Figure 5, Figure 6, and Figure 7. All EPD graphics shown in the figures below are only representative of the asphalt EPDs procured from Emerald EcoLabel that were used in this study.

Emerald ECO LABEL

An Environmental Product Declaration (EPD) for Asphalt Mixtures

Company Information

Central Washington Asphalt is an asphalt mixture producer.

Rocky Reach, a stationary asphalt plant at
27 Rams Lane Wenatchee, WA 98801 USA

CENTRAL WASHINGTON ASPHALT

Product Description

This EPD reports the potential environmental impacts and additional environmental information for an asphalt mixture, which falls under the United Nations Standard Products and Services Code 30111509. Asphalt mixtures are typically incorporated as part of the structure of a roadway, parking lot, driveway, airfield, bike lane, pedestrian path, railroad track bed, or recreational surface.

Mix Name: HMA2023-021
Specification Entity: WSDOT
Specification: HMA CLASS 3/8"
Gradation Type: dense
Mix Design Method: superpave
Nominal Maximum Aggregate Size: 0.375 inches
Performance Grade of Asphalt Binder: PG 76-28
Customer [Project/Contract] Number: hMA2023-021

This mix producer categorizes this product as a Hot Mix Asphalt (HMA) asphalt mixture. This asphalt mixture was produced within a temperature range of 166 to 171°C (331.0 to 340.0°F). Energy and environmental impacts are based on a plant's average performance over a 12-month period and are not adjusted for mix-specific production temperatures.

Environmental Product Declaration NAPA VERIFIED

This declaration is an EPD in accordance with ISO 14025:2006[1] and ISO 21930:2017[2]. The PCR is *Product Category Rules for Asphalt Mixtures*[3,4]. This EPD transparently describes the potential environmental impacts associated with the identified life cycle stages of the described product.

Declaration Number: 253.746.2546 v3 **Software Version:** 2.0.1
Date of Issue: Oct. 10, 2023 **Period of Validity:** March 31, 2027

This EPD is valid for asphalt mixtures produced at the location indicated on this page. Data used to inform this EPD reflect plant operations from a 12-month period beginning on Jan. 1, 2022.

This EPD can be found at https://asphaltepd.org/epd/d/mYUPBE/
LCA performed by: Ben Ciavola, PhD

Who was this EPD for?
Central Washington Asphalt

Product Description
A description of the product that the EPD is for

Which PCR informed the EPD?
International Standards Organization ISO 14025:2006 and ISO 21930:2017

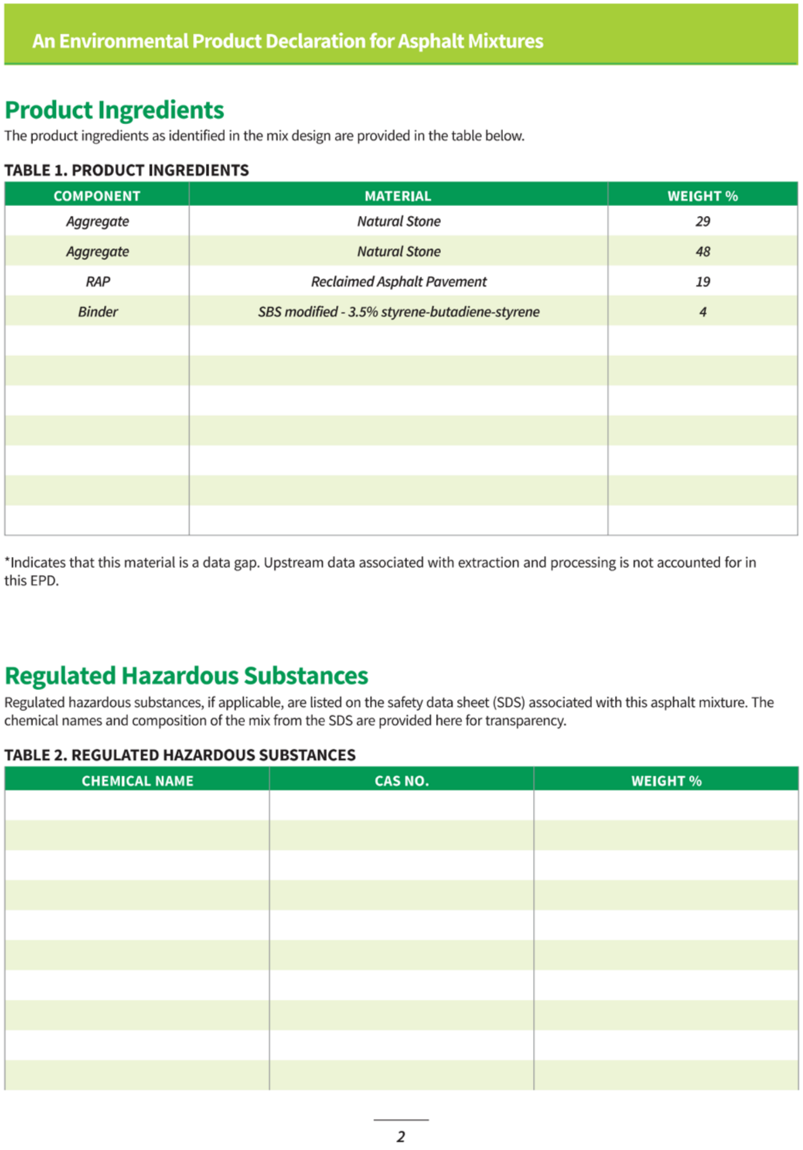
Period of Validity
EPDs are typically valid for 5 years

Who did the EPD?
WAP Sustainability Consulting

Figure 4 - EPD Breakdown (Project and Mix Design Information, EPD Verifier, Relevant Dates)

Product Ingredients

A list of materials included in the product being analyzed with their inclusion in weight %



An Environmental Product Declaration for Asphalt Mixtures

Product Ingredients

The product ingredients as identified in the mix design are provided in the table below.

TABLE 1. PRODUCT INGREDIENTS

COMPONENT	MATERIAL	WEIGHT %
Aggregate	*Natural Stone*	*29*
Aggregate	*Natural Stone*	*48*
RAP	*Reclaimed Asphalt Pavement*	*19*
Binder	*SBS modified - 3.5% styrene-butadiene-styrene*	*4*

*Indicates that this material is a data gap. Upstream data associated with extraction and processing is not accounted for in this EPD.

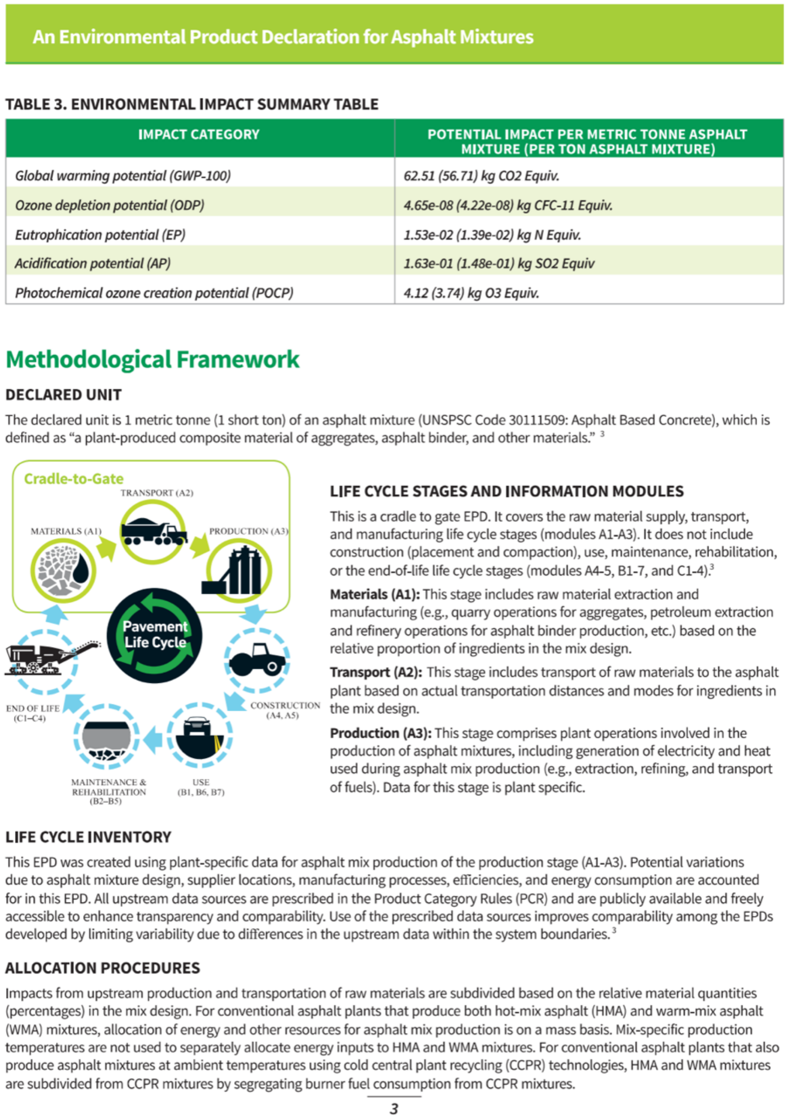
Regulated Hazardous Substances

Regulated hazardous substances, if applicable, are listed on the safety data sheet (SDS) associated with this asphalt mixture. The chemical names and composition of the mix from the SDS are provided here for transparency.

TABLE 2. REGULATED HAZARDOUS SUBSTANCES

CHEMICAL NAME	CAS NO.	WEIGHT %

Figure 5 - EPD Breakdown (Product Ingredients)



An Environmental Product Declaration for Asphalt Mixtures

TABLE 3. ENVIRONMENTAL IMPACT SUMMARY TABLE

IMPACT CATEGORY	POTENTIAL IMPACT PER METRIC TONNE ASPHALT MIXTURE (PER TON ASPHALT MIXTURE)
Global warming potential (GWP-100)	*62.51 (56.71) kg CO2 Equiv.*
Ozone depletion potential (ODP)	*4.65e-08 (4.22e-08) kg CFC-11 Equiv.*
Eutrophication potential (EP)	*1.53e-02 (1.39e-02) kg N Equiv.*
Acidification potential (AP)	*1.63e-01 (1.48e-01) kg SO2 Equiv*
Photochemical ozone creation potential (POCP)	*4.12 (3.74) kg O3 Equiv.*

Methodological Framework

DECLARED UNIT

The declared unit is 1 metric tonne (1 short ton) of an asphalt mixture (UNSPSC Code 30111509: Asphalt Based Concrete), which is defined as "a plant-produced composite material of aggregates, asphalt binder, and other materials." [3]

LIFE CYCLE STAGES AND INFORMATION MODULES

This is a cradle to gate EPD. It covers the raw material supply, transport, and manufacturing life cycle stages (modules A1-A3). It does not include construction (placement and compaction), use, maintenance, rehabilitation, or the end-of-life life cycle stages (modules A4-5, B1-7, and C1-4).[3]

Materials (A1): This stage includes raw material extraction and manufacturing (e.g., quarry operations for aggregates, petroleum extraction and refinery operations for asphalt binder production, etc.) based on the relative proportion of ingredients in the mix design.

Transport (A2): This stage includes transport of raw materials to the asphalt plant based on actual transportation distances and modes for ingredients in the mix design.

Production (A3): This stage comprises plant operations involved in the production of asphalt mixtures, including generation of electricity and heat used during asphalt mix production (e.g., extraction, refining, and transport of fuels). Data for this stage is plant specific.

LIFE CYCLE INVENTORY

This EPD was created using plant-specific data for asphalt mix production of the production stage (A1-A3). Potential variations due to asphalt mixture design, supplier locations, manufacturing processes, efficiencies, and energy consumption are accounted for in this EPD. All upstream data sources are prescribed in the Product Category Rules (PCR) and are publicly available and freely accessible to enhance transparency and comparability. Use of the prescribed data sources improves comparability among the EPDs developed by limiting variability due to differences in the upstream data within the system boundaries.[3]

ALLOCATION PROCEDURES

Impacts from upstream production and transportation of raw materials are subdivided based on the relative material quantities (percentages) in the mix design. For conventional asphalt plants that produce both hot-mix asphalt (HMA) and warm-mix asphalt (WMA) mixtures, allocation of energy and other resources for asphalt mix production is on a mass basis. Mix-specific production temperatures are not used to separately allocate energy inputs to HMA and WMA mixtures. For conventional asphalt plants that also produce asphalt mixtures at ambient temperatures using cold central plant recycling (CCPR) technologies, HMA and WMA mixtures are subdivided from CCPR mixtures by segregating burner fuel consumption from CCPR mixtures.

3

Product Summary

The product's calculated environmental impact per functional unit

LCA Framework

A description of each stage that is being analyzed in the EPD

Which PCR informed the EPD?

International Standards Organization ISO 14025:2006 and ISO 21930:2017

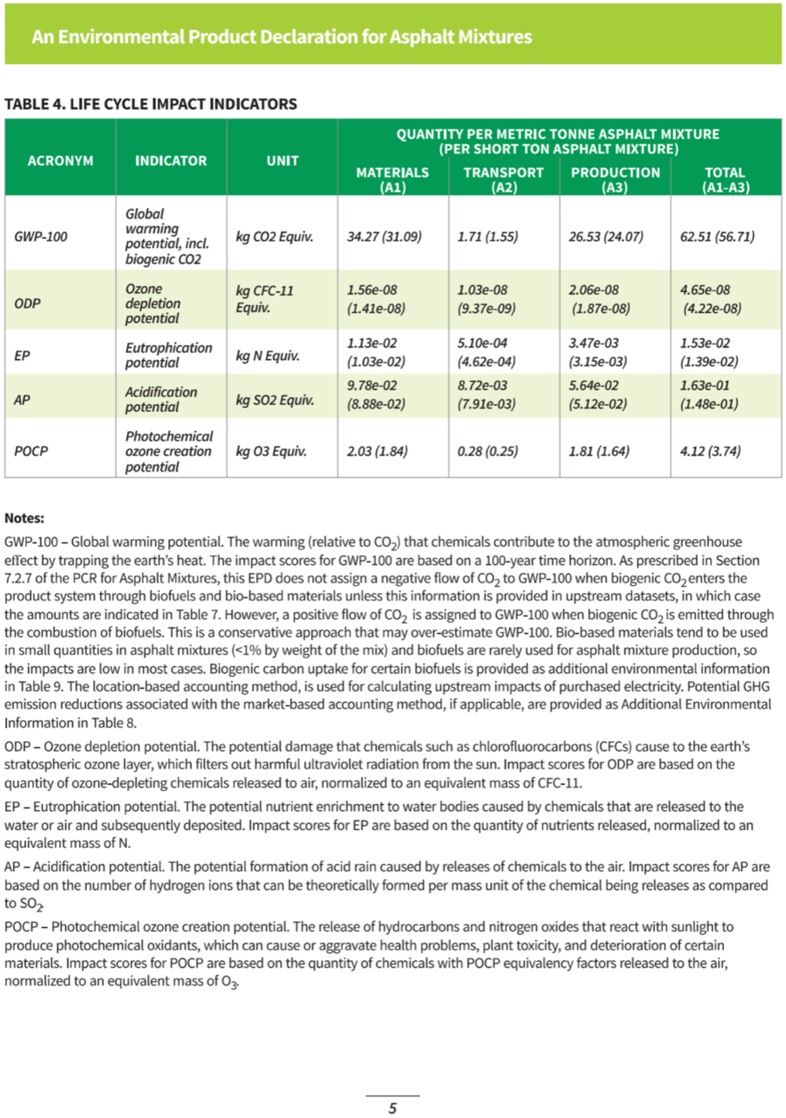
Declared Unit

This EPD is describing the emissions associated with **1 metric tonne (or 1 short ton) of asphalt mixture**. Used for normalization.

Figure 6 - EPD Breakdown (Environmental Impact, LCA Framework, Declared Unit, Referenced PCR)

Project Summary

The product’s calculated environmental impact per functional unit separated out by contribution per life cycle stage



An Environmental Product Declaration for Asphalt Mixtures

TABLE 4. LIFE CYCLE IMPACT INDICATORS

ACRONYM	INDICATOR	UNIT	QUANTITY PER METRIC TONNE ASPHALT MIXTURE (PER SHORT TON ASPHALT MIXTURE)			
			MATERIALS (A1)	TRANSPORT (A2)	PRODUCTION (A3)	TOTAL (A1-A3)
GWP-100	*Global warming potential, incl. biogenic CO2*	*kg CO2 Equiv.*	*34.27 (31.09)*	*1.71 (1.55)*	*26.53 (24.07)*	*62.51 (56.71)*
ODP	*Ozone depletion potential*	*kg CFC-11 Equiv.*	*1.56e-08 (1.41e-08)*	*1.03e-08 (9.37e-09)*	*2.06e-08 (1.87e-08)*	*4.65e-08 (4.22e-08)*
EP	*Eutrophication potential*	*kg N Equiv.*	*1.13e-02 (1.03e-02)*	*5.10e-04 (4.62e-04)*	*3.47e-03 (3.15e-03)*	*1.53e-02 (1.39e-02)*
AP	*Acidification potential*	*kg SO2 Equiv.*	*9.78e-02 (8.88e-02)*	*8.72e-03 (7.91e-03)*	*5.64e-02 (5.12e-02)*	*1.63e-01 (1.48e-01)*
POCP	*Photochemical ozone creation potential*	*kg O3 Equiv.*	*2.03 (1.84)*	*0.28 (0.25)*	*1.81 (1.64)*	*4.12 (3.74)*

Notes:

GWP-100 – Global warming potential. The warming (relative to CO_2) that chemicals contribute to the atmospheric greenhouse effect by trapping the earth’s heat. The impact scores for GWP-100 are based on a 100-year time horizon. As prescribed in Section 7.2.7 of the PCR for Asphalt Mixtures, this EPD does not assign a negative flow of CO_2 to GWP-100 when biogenic CO_2 enters the product system through biofuels and bio-based materials unless this information is provided in upstream datasets, in which case the amounts are indicated in Table 7. However, a positive flow of CO_2 is assigned to GWP-100 when biogenic CO_2 is emitted through the combustion of biofuels. This is a conservative approach that may over-estimate GWP-100. Bio-based materials tend to be used in small quantities in asphalt mixtures (<1% by weight of the mix) and biofuels are rarely used for asphalt mixture production, so the impacts are low in most cases. Biogenic carbon uptake for certain biofuels is provided as additional environmental information in Table 9. The location-based accounting method, is used for calculating upstream impacts of purchased electricity. Potential GHG emission reductions associated with the market-based accounting method, if applicable, are provided as Additional Environmental Information in Table 8.

ODP – Ozone depletion potential. The potential damage that chemicals such as chlorofluorocarbons (CFCs) cause to the earth’s stratospheric ozone layer, which filters out harmful ultraviolet radiation from the sun. Impact scores for ODP are based on the quantity of ozone-depleting chemicals released to air, normalized to an equivalent mass of CFC-11.

EP – Eutrophication potential. The potential nutrient enrichment to water bodies caused by chemicals that are released to the water or air and subsequently deposited. Impact scores for EP are based on the quantity of nutrients released, normalized to an equivalent mass of N.

AP – Acidification potential. The potential formation of acid rain caused by releases of chemicals to the air. Impact scores for AP are based on the number of hydrogen ions that can be theoretically formed per mass unit of the chemical being releases as compared to SO_2

POCP – Photochemical ozone creation potential. The release of hydrocarbons and nitrogen oxides that react with sunlight to produce photochemical oxidants, which can cause or aggravate health problems, plant toxicity, and deterioration of certain materials. Impact scores for POCP are based on the quantity of chemicals with POCP equivalency factors released to the air, normalized to an equivalent mass of O_3.

5

Figure 7 - EPD Breakdown (Project Summary)

2.3 LCAs in Pavement Construction

LCAs in pavement construction have varied over the years from study to study, covering numerous variations of the life cycle stages. This thesis analyzes the material production through construction/installation stages A1-A5. LCA usage in the pavement field is still growing, with only a few agencies applying them consistently. Within the pavement agencies that utilize LCAs, the most common uses are aiding material or pavement structural design selection, evaluation of the potential impact of policy or specification, LCA tool development, scenario evaluation for network-level decisions and strategies for preservation, maintenance, and rehabilitation, and material EPD development for pavement application (Harvey et al. 2016a). Many previous studies have aimed to compare asphalt and concrete pavements. This thesis focuses solely on asphalt pavement case studies as they are within the same industry and thus would use the same background data, allowing for a fairer comparison between projects.

2.3.1 Overview of LCAs in Pavement Construction

One of the first noted LCAs in pavement construction was in 1996 when Häkkinen and Mäkelä completed one of the first studies that looked at asphalt and concrete pavements in Finland (Häkkinen and Mäkelä 1996). In the years that followed, studies looked at different metrics such as emergy (a summation method for life-cycle energy consumption accounting for quality and source of error), exergy (a derivative of energy that describes the distance a product is from thermos equilibrium), impact of industrial by-products (e.g. coal ash, crushed concrete waste, blast furnace slag, etc.), hot and cold production techniques, and material required for urban collector road versus highway routes, to name a few (Santero et al. 2010a). Many early studies attempted to look at the differences in LCA analysis between asphalt and concrete pavements. Numerous studies in pavement literature had conflicting conclusions and recommendations on whether asphalt or concrete pavement was better with a lower environmental impact. (Ashtiani 2022; Barbieri et al. 2021a; Häkkinen and Mäkelä 1996; Horvath and Hendrickson 1998; Stripple 2001; Zapata and Gambatese 2005). However, studies that looked specifically at the use of recycled materials in place of virgin materials found that utilizing these materials has reduced emissions and thus reduced the environmental impact. (Santero et al. 2010b).

Inconsistencies and issues (e.g., differing functional units, system boundaries, industry data availability, life cycle inventory (LCI) and impact results, the overall utility of LCAs) make it hard to use LCA results for comparison across industries or geographical areas (Barbieri et al. 2021b; Hoxha et al. 2021; Santero et al. 2010b). Another conclusion drawn from the literature on pavement construction was that the acquisition of data and methods used were not always transparent, making these studies hard to replicate (Hoxha et al. 2021). Lastly, it was notable that many LCA studies did not explicitly mention their use of the data collected and analyzed from the projects to complete an LCA. Since the 1990s, when LCAs were introduced to the pavement construction industries, more funding has been funneled into the area (like the FHWA Climate Challenge grant funding this work) to quantify the carbon emissions the design, construction, and maintenance of pavements.

2.4 EPDs and PCRs in Pavement Construction

Typically, projects utilize product-specific EPDs for HMA mix designs. Today, Emerald Eco-Label calculates the asphalt pavement industry product-specific EPDs. EPDs on Emerald Eco-Label cover stages A1-A3 or cradle-to-gate (Senseney 2023). "It's common for EPDs for materials to only include the cradle-to-gate stages, since the environmental impacts in subsequent life cycle stages depend on factors outside the control of the manufacturer" (Shacat et al. 2024). The EPDs used in this study were created and are available on Emerald Eco-Label.

The PCR committee NAPA created is comprised of stakeholders in industry, academia, and governmental agencies (National Asphalt Pavement Association 2022a). Additionally, NAPA develops and maintains the PCRs for asphalt mixtures produced in North America and is a subcategory under ISO 21930 (National Asphalt Pavement Association 2022b; Shacat et al. 2024). PCRs created by this stakeholder group are used as a standard to inform the EPDs developed by the asphalt industry to keep EPDs consistent.

2.5 Overview of EPDs in Pavement Construction

In 2022, NAPA released the second version of the *Product Category Rules for Asphalt Mixtures*. This report establishes principles, specifications, and requirements as a PCR for asphalt mixtures sold in the U.S. that produce facility-specific and industry-averaged EPDs (National Asphalt Pavement Association 2022c). Asphalt EPDs are strictly cradle-to-gate, meaning they are within Modules A1: Raw Material Supply, A2: Transport, and A3: Manufacturing (Figure 2) (National Asphalt Pavement Association 2022c; Rangelov et al. 2021b). Module A1 considers the material acquisition of aggregate, asphalt binder, and other materials within the mixture. Module A2 considers transporting materials such as RAP from the storage facility to the plant. Module A3: Manufacturing includes the production of the asphalt mixture at the plant following the material acquisition and transport until the mixture is transferred to a truck that will deliver it to the customer.

EPDs have been slowly entering the transportation and roadway construction industry. In the U.S., a handful of EPD legislation is making its way into state-level legislation. In California and Oregon, EPDs have been required for select building materials and concrete for city construction projects (Rangelov et al. 2021a). The states intend to use the collected EPDs to create an environmental impact benchmark that outlines limitations for specific project materials. These instances are geared towards building EPDs and not roadway construction. However, in 2023, Colorado passed "The Buy Clean Colorado Act," which requires contractors to submit EPDs for asphalt and asphalt mixtures, cement and concrete mixtures, and steel that is installed on all Colorado Department of Transportation (CDOT) projects (Senseney 2023). Ultimately, the goal of this bill is to encourage construction product manufacturers to reduce their overall emissions and specify greener construction materials. Related to CDOT's benchmarking goal, NAPA recently published a benchmarking study related to EPD results of asphalt pavements that could be used to inform these decisions (Miller et al. 2024).

2.6 Pavement LCA Calculation Software

Other primary tools and calculation software utilized to calculate LCAs include the FHWA's LCA Pave tool, Athena, and Simapro. The LCA Pave tool is a Microsoft® Excel® spreadsheet created by the FHWA to assess the impact of materials, construction processes, and the related transportation activities for various pavement design projects (i.e., new construction, reconstruction, rehabilitation, and maintenance and preservation) (Meijer et al. 2021). The Athena Pavement LCA was created with the support of the Cement Association of Canada and Athena Institute members. Users can develop environmental LCAs for their specific roadway design by selecting from the over 150 existing roadway designs in the database or by creating a custom roadway design (Athena Pavement LCA 2002). SimaPro was created in 1990 as an LCA accounting tool that is easy to understand and use when assessing the measurability of sustainability data (PRé Sustainability 1990). Like openLCA, SimaPro can be used for more applications than just roadway pavement.

2.7 LCA Terminology

OpenLCA put together accessible tutorial videos on YouTube, that explain the basics of the program (openLCA 2021).

Table 1 outlines common LCA terminology.

2.7.1 OpenLCA

OpenLCA is a tool used for LCA calculations. Within openLCA, input variables such as mass, distance, volume, etc., influence the overall environmental impact of the product or material analyzed. Calculations conducted in openLCA use specified datasets such as the US Life Cycle Inventory (USLCI), ecoinvent, and the FHWA Repository to provide upstream data to inform environmental impact calculations.

Table 1 lists common LCA terminology used through this thesis.

Table 1 - Common LCA Terminology

Term	Description
Background Data	Where all the flow properties (i.e. mass, volume, length, etc.), unit groups (i.e. currency, gram, etc.), actors (provided data & can edit), sources of data (literature data was obtained from), and locations (countries processes have been made) will be found.
Indicators and Parameters	Where the impact assessment methods, social indicators, global parameters, and data quality systems are located.
Global Parameter	Parameters that stay consistent and can be used throughout calculations.
Data Quality Systems	Used to assess the quality of data; like an uncertainty analysis.
Flow	Basis of processes. Can be used in pre-created or new processes.
Process	Production or modification of products and materials. Based on an initial flow (pre-made or new) that holds background information on the specified product or material.
Input Flow	Quantified product, material, or energy flow that enters a unit process.
Output Flow	Quantified product, material, or energy flow that leaves a unit process.
Provider	This is the correlating process linked to the flow in the input/outputs tab or a process.
Product System	A collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.
Unit Process	The smallest element is considered in the life cycle inventory analysis for which input and output data are quantified.
Project	Allows comparison between product systems and can change specific parameters in the comparison.
Functional Unit	A functional description of the product or system that is being studied. Defines the quantity of the material/system and the key performance aspects that define is function over its lifetime (Ashtiani et al. 2024b).
Declared Unit	Can be used in place of a functional unit if the function requirement and application are uncertain or undefined (Ashtiani et al. 2024b).

2.8 Functional Unit

Typically, functional units used within roadway construction are a unit of length (lane-miles or lane-kilometers), area (square foot or square meter), or volume (cubic meter or cubic yard) (Zokaei Ashtiani 2022). Ultimately, the functional units are utilized to normalize the data results. This normalization helps to make relative comparisons between similar projects with the same function unit easier. EPD results are reported in per short ton of asphalt for specific mix designs. Bid tabulations also specify asphalt pavement quantities in units of short tons. Therefore, a functional unit of “per short ton of asphalt pavement” is compatible with EPD and bid tabulation quantities. All LCA results in this thesis will report results per ton of asphalt pavement placed on the respective project.

3 METHODS

This section discusses the methodology and decision making that was taken throughout the course of this thesis. Starting with Project Selection, decisions regarding how projects were selected, and visits were conducted are stated. Then, the Data Collection process is described and shows each project's metadata. The Data Analysis section describes how data was organized, what data gaps occurred, and any rules of thumb or proxy data that was used. LCA Modeling and specifically openLCA Modeling is outlined based on the methods described in the data analysis. From the data obtained, the Data Quality Analysis of the GWP for each case study was modeled in openLCA.

3.1 Project Selection

The goal when selecting projects was to analyze a variety of asphalt mixtures and construction procedures across the state. These projects would provide a broad understanding of the types of asphalt paving projects taking place in the state of Washington. For projects that were selected to participate in this Climate Challenge study, WSDOT issued a change order and provided $10,000 in funds to the contractors to cover EPD generation and additional work that would take place to accommodate the additional data collection.

The Washington Asphalt Pavement Association (WAPA), a stakeholder in the project, selected the four asphalt paving projects from different cities and counties across Washington, as shown in Figure 8. The four projects chosen were pavement preservation projects (PI) with minimal construction activities outside direct paving activities. These projects were selected to gain an understanding of pavement preservation projects across Western, Central, and Eastern Washington all completed by different primary contractors. Additionally, WAPA also provided EPD generation support to contractors and helped facilitate meetings between project and research teams throughout of this study. This thesis will refer to each case study by their project contract number.

Once the four projects were selected, initial contact was made with each of the four contractors and WSDOT project teams to introduce the UW research team. Following the initial introduction, virtual meetings were set up to provide background on the research that would be conducted, introduce the FHWA's Climate Challenge, and let them know what data would be requested regarding the asphalt pavement mix and construction activities. These meetings were also used to gather initial information from project teams, such as scope and paving timeline.

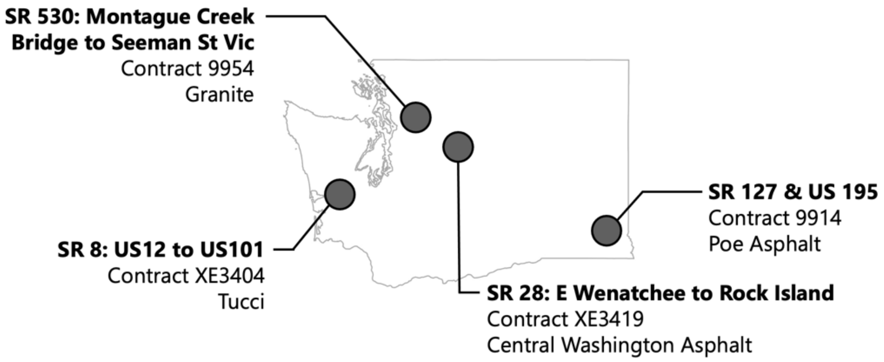


Figure 8 - Project Location and Identification

3.1.1 Site and Project Visits

Once project teams established a paving timeline, site visits were scheduled as a way for researchers to meet the project teams and observe paving on site. Over 400 photos of the project sites and equipment utilized were taken as documentation during site visits. During site visits, researchers gained further insight into the project and an understanding of planned and day-to-day activities. Notes and pictures from site visits, regarding the project site and equipment utilized, were taken using HeadLight's Fieldbook. Headlight's Fieldbook is a software used to generate construction daily reports that details a project in real-time to ensure project quality and accountability. This software was used as the primary note taking software during site visits and documented observations through notes, images, videos, weather, and timing data.

3.2 Data Collection

The data collection process began after initial meetings and site visits were completed. The goal throughout data collection was to collect general project information, all information needed to complete the openLCA model, and any additional information that can be used in future LCA efforts. Data requests were sent out to contractors and owner representatives. General project documents, such as plans and specifications, were gathered from the WSDOT FTP site. The WSDOT FTP website shares electronic plans for current and previous WSDOT projects. Projects are organized by project number and name, updated by WSDOT engineers and contractors, and made available for external organizations. All other general information, material, construction, and trucking information regarding the project was obtained through the contractors. The EPDs collected for each case study are publicly available on the Emerald Eco-Label website. Each contractor completed the EPD for their specific plants, some with assistance from WAPA. However, no assistance was provided by the research team to contractors for EPD generation.

Each contractor had a different way of collecting the data requested. Therefore, a mix of spreadsheets and PDF records was provided with the requested information. Additionally, throughout the data collection process, email was used as the main method of communication between researchers and project contacts for meeting requests, site visits, and data collection requests. In some cases, phone calls were conducted between researchers and contractors to specify the types of data requested and answer any additional questions.

Table 10 lists the documents requested, their origins, the form they were received in, and how they were utilized. All documents listed in Table 10 provided the necessary information to inform input data utilized in LCA calculations. Additional material sheets for line items, such as guardrails, guideposts, pavement markings, etc., were requested from contractors as supplemental information (Table 11). Table 11 illustrates the additional information that was initially requested from WSDOT Project Engineers and the Primary Contractors that was not used in final calculations. The documents in Table 11 were not utilized mainly due to either the data being outside of the project's scope or the data being too granular for the chosen calculation method. While this information was not specifically used in this study, it is presented here to accurately represent all information initially requested and so that further research could be conducted to expand this LCA.

3.2.1 9914 SR 127 and US 195 Meta Data

Poe Asphalt Paving Inc constructed the HMA pavement rehabilitation of both SR 127 and US 195 shown in Figure 9 and Figure 10. Located in Whitman County and the city of Dusty, a defining characteristic of this project was that it encompassed parts of both SR 127 and US 195 under the same contract.

3.2.1.1 9914 Project Description

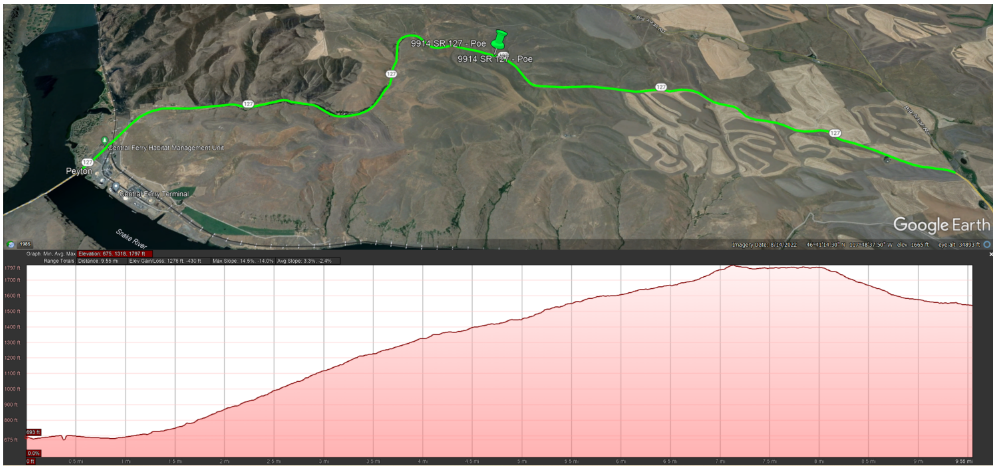


Figure 9 - 9914 SR 127 Project Route and Elevation Profile

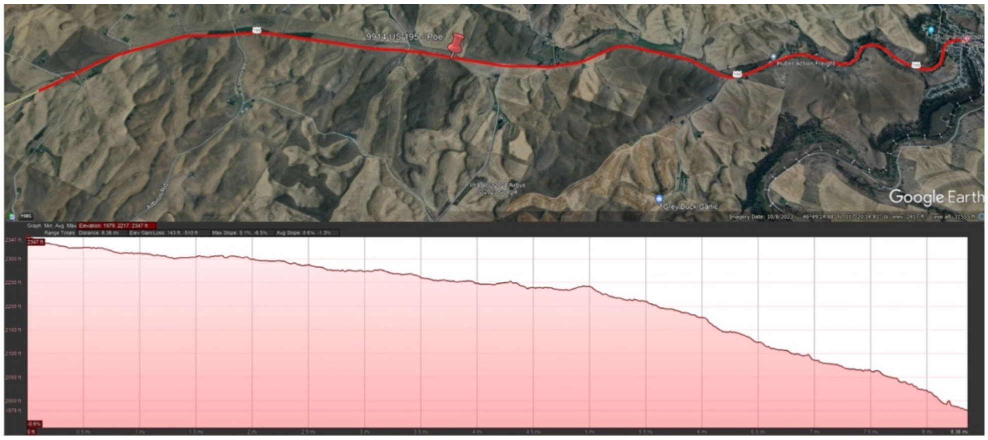


Figure 10 - 9914 US 195 Project Route and Elevation Profile

Road work on this project was located in a primarily rural setting along a two-lane highway. Figure 11 and Figure 12 shows the condition of the pavement prior to the pavement activities that took place. A site visit was conducted on Friday, September 22nd, 2023.

Figure 11 - 9914 SR 127 Pre-Project Roadway View

Figure 12 - 9914 US 195 Pre-Project Roadway View

Table 2 highlights general project information, details regarding pavement construction and design, and the asphalt plant for WSDOT Contract 9914's project. The mix design used for this project consisted of 20% RAP which was under the WSDOT specified threshold for RAP inclusion (WSDOT 2024).

Table 2 - WSDOT Contract 9914 Meta Data

SR 127 and US 195	
GENERAL PROJECT DETAILS	
Contract Number	9914
Contractor Name	Poe Asphalt Paving Inc
Primary Pavement Type	Hot Mix Asphalt
Project Type	Mill and Fill with Crack Sealing
State	Washington
City	Dusty
County	Whitman
Location 1 Mile Post	SR 127 10.00 to 19.45
Location 2 Mile Post	US 195 29.09 to 37.55
Estimated Bid Price	$6,131,860.75
Final Contract Price	$5,877,042.57
Pavement Activities	Planning Bituminous Pavement, Crack Sealing, Pavement Repair, Paving with HMA, Bridge Deck Repair, and Erosion/Water Pollution Control
PAVEMENT CONSTRUCTION DETAILS	
Predominant Lane Configuration	2
Project Area (ft^2)	64,092,072
Project Length (mi)	17.91
Elevation Gain (ft)	1419
Number of Paving Days	20
Paving Dates	8/15/2023 to 10/5/2023
Thickness of Layer (ft)	0.15/0.25
MIX DESIGN DETAILS	
Total HMA Quantity (short tons)	33118.25
Tack Coat (short tons)	56.1
HMA GWP A1-A3 (kg CO_2e per short ton)	58.43
RAP %	20%
HMA Class	3/8"
Traffic Level (Million ESALs)	1.1 (SR 127) and 2.8 (US 195)
ASPHALT PLANT DETAILS	
Name	Pullman Plant
Location	Pullman, WA
TRUCKING DETAILS	
HMA Average One-Way Distance (mi)	31.47
Tack Coat Estimated Travel Distance (mi)	161.5
Truck Type Used	Dump Truck - End/Super
Average Number of Trucks Running (Daily)	22
Average Truck Capacity (short ton)	25
Double Cycling	Yes

3.2.1.2 9914 Typical Paving Operations

Work on US 195 was completed first and took place during the night from 6 pm to 6 am. Work on SR 127 was started after the completion of the US 195 section and took place during the day from 6 am to 6 pm. During the paving process, two rollers were used for compaction: a breakdown and finishing roller. Additionally, the milling on this project needed to be done in two separate passes instead of just one pass. Aside from the HMA overlay paving that this project completed, the contractor also crack sealed the old pavement within the project area. Table 3 outlines the equipment used on the project. A comparison of all equipment types and models can be seen in Appendix F: Equipment Summary List.

3.2.1.3 9914 Equipment Used on the Project

Table 3 - 9914 Equipment Descriptor

Contract 9914: SR 127 and US 195	
Equipment Type	**Model**
Backhoe	*not used in project*
Grader	*not used in project*
Loader	Cat IT-24F, Cat 980M, Cat 972M, Cat 950G, JD 844 Loader, JD 310sj, Cat 259d Skid-Steer Loader
Milling Machine	Wirtgen W210i
MTV	Weiler Transfer
Paver	Vogele 8ft Paver, Weiler p3858, Vogele 10ft Paver
Roller	Dynapac Cc1200, Dynapac Dd1300 Roller, Dynapac Cc-1200, IR DD110 Roller, Caterpillar CB54 Roller, Volvo DD105 OS Roller, Volvo PT240/PF, Volvo DD120 Roller, Dynapac Roller
Sweeper	Broce Broom
Tack Truck	KW Etnyre Distr
Water Truck	Sterling Water Tr, Peterbilt Water Tk

The figures below are the equipment observed on-site during the site visit conducted.

Figure 13 - 9914 Paver

Figure 14 - 9914 MTV

Figure 15 – 9914 Dump Truck

Figure 16 - 9914 Roller

3.2.2 9954 SR 530 Montague Creek Bridge to Seeman St Vic

Granite Construction Company undertook this HMA paving project along State Route 530 in Washington State. The project route spanned from Darrington to Arlington along the path shown in Figure 17.

3.2.2.1 9954 Project Description

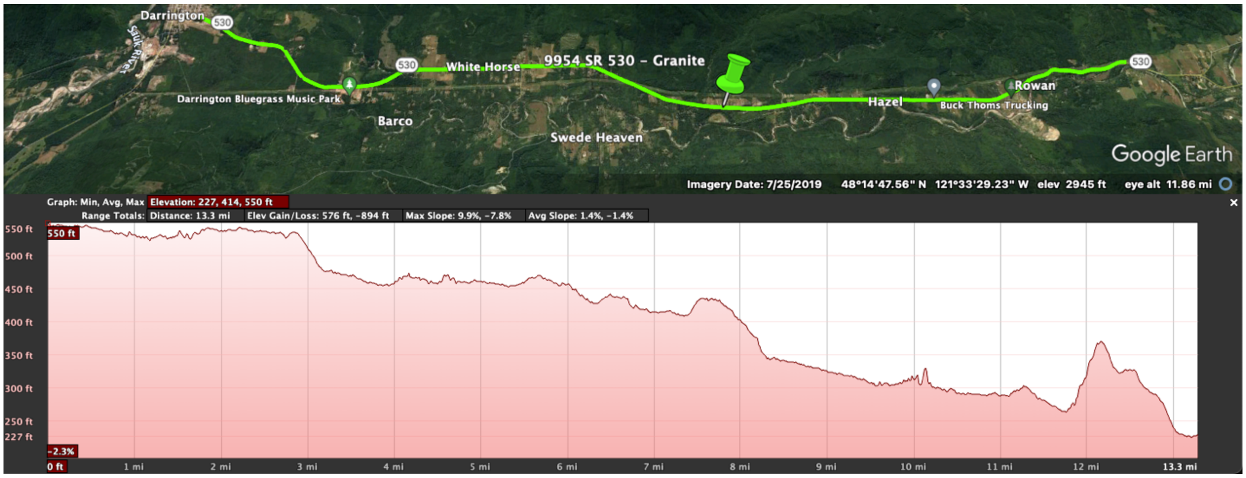


Figure 17 - 9954 Project Route and Elevation Profile

Pavement rehabilitation work on this project took place in a primarily rural setting along a two-lane highway. Figure 18 shows the condition of the pavement prior to the pavement activities that took place. A site visit was conducted on Thursday, June 15th, 2023.

Figure 18 – 9954 Pre-Project Roadway View

Table 4 highlights general project information, details regarding pavement construction and design, and the asphalt plant for WSDOT Contract 9954's project.

Table 4 - WSDOT Contract 9954 Project Information

SR 530, Montague Creek Bridge to Seeman St Vic Paving	
GENERAL PROJECT DETAILS	
Contract Number	9954
Contractor Name	Granite Construction Company
Primary Pavement Type	Hot Mix Asphalt
Project Type	Mill and Fill
State	Washington
City	Arlington
County	Snohomish
Location 1 Mile Post	SR 530 35.37 to 48.65
Estimated Bid Price	\$5,629,676.50
Final Contract Price	\$6,385,005.81
Pavement Activities	Pavement Repair, HMA Paving, Bridge Deck Repair, Waterproof Membrane Application, Temporary Erosion Control, Pavement Marking, Temporary Traffic Control
PAVEMENT CONSTRUCTION DETAILS	
Predominant Lane Configuration	2
Project Area (ft^2)	1,682,841.6
Project Length (mi)	13.28
Elevation Gain (ft)	323
Number of Paving Days	25
Paving Dates	6/14/2023 to 7/28/2023
Thickness of Layer (ft)	0.15
MIX DESIGN DETAILS	
Total HMA Quantity (short tons)	24451.96
Tack Coat (short tons)	29.29
HMA GWP A1-A3 (kg CO_2 eq per short ton)	41.44
RAP %	39%
HMA Class	1/2"
Traffic Level (Million ESALs)	2.5 to 5
ASPHALT PLANT DETAILS	
Name	Smith Island
Location	Everett, WA
TRUCKING DETAILS	
HMA Average One-Way Distance (mi)	35
Tack Coat Estimated Travel Distance (mi)	99.2
Truck Type Used	Dump Truck - End/Super
Average Number of Trucks Running (Daily)	22
Average Truck Capacity (short ton)	32
Double Cycling	No

One particularly distinctive aspect of this project was Granite Construction's use of 39% RAP. This mix design exceeded the threshold set by WSDOT which allows for up to 20% RAP by total weight of HMA without needing to meet any additional requirements to prove the mix design's durability (WSDOT 2024).

3.2.2.2 9954 Typical Paving Operations

Paving and grinding operations occurred during daylight hours between 6 am and 6 pm. For this specific project, grinding or milling of the existing roadways was the main objective on specific workdays. Therefore, the paving of the overlays occurred on separate days, with no planned overlap between grinding and paving activities. On the day of the site visit, HMA paving was the objective of the day as milling of the planned section was done previously. A tack truck laid down the tack and was then followed by the paver and rollers. There was a total of three rollers on site, two compaction rollers with vibration/oscillation capabilities, and one finishing roller. Two rollers were mainly used to meet a compaction of 93-95%. However, the third roller was used when necessary to achieve the desired compaction. Table 5 describes the equipment used during the project. A comparison of all equipment types and models can be seen in Appendix F: Equipment Summary List.

3.2.2.3 9954 Equipment Used on the Project

Table 5 - 9954 Equipment Descriptor

Contract 9954: SR 530, Montague Creek Bridge to Seeman St Vic Paving	
Equipment Type	**Model**
Backhoe	Cat 420E Backhoe 4x4 E Stick
Grader	*not used in project*
Loader	Cat 299D2 Compact Track Loader
Milling Machine	*not specified*
MTV	Roadtec SB-2500C Shuttle Buggy
Paver	Cat AP1055F Asphalt Paver
Roller	Cat CB24BCompactor, Cat CB224E DE,V Roller, Cat CB64 Asphalt Compactor-Versa Vibe, Cat CB66B Asphalt Compactor-5 Amplitude, Hamm HD+90IVO Compactor, I-R DD138HF DD,V Asphalt Roller
Sweeper	*not used in project*
Tack Truck	Petrb 335 2000GL Oil Dist
Water Truck	Intl 2AX Water

The figures below are the equipment observed on-site during the site visit conducted.

Figure 19 - 9954 Paver

Figure 20 - 9954 MTV

Figure 21 - 9954 Dump Truck

Figure 22 - 9954 Roller

3.2.3 XE3404 SR 8 US 12 to US101

Tucci and Sons undertook the SR 8, US 12 to US 101 HMA pavement project in Washington State. This project was located in Grays Harbor County in McCleary Washington shown in Figure 23.

3.2.3.1 XE3404 Project Description

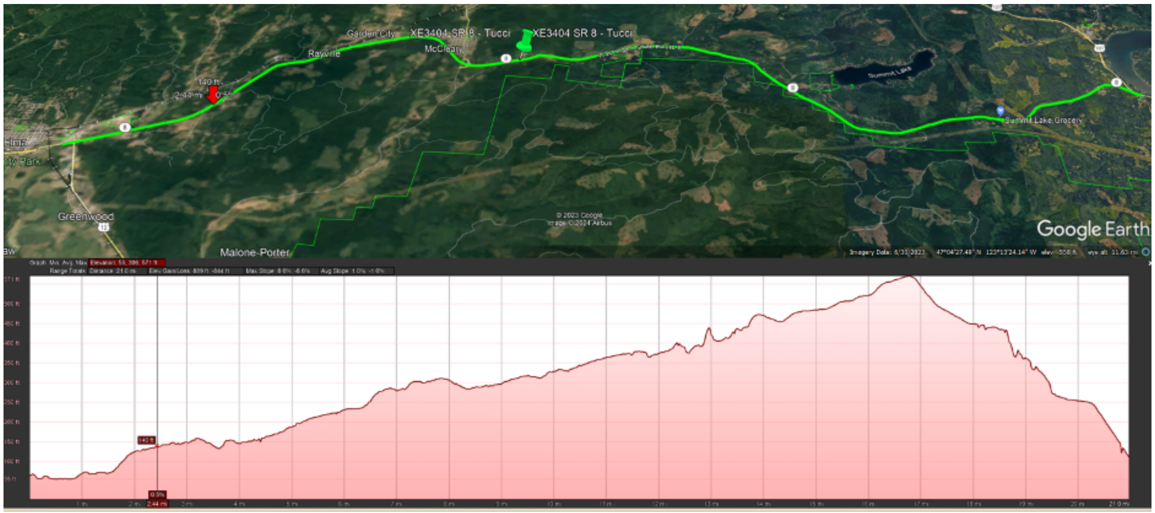


Figure 23 – XE3404 Project Route and Elevation Profile

Pavement repair and rehabilitation took place along SR 8 that has two lanes going in both east and westbound, separated by a median. Figure 24 shows the condition of the pavement prior to the pavement activities that took place. A site visit was conducted on Tuesday, June 27th, 2023.

Figure 24 – XE3404 Pre-Project Roadway View

Table 6 highlights general project information, details regarding pavement construction and design, and the asphalt plant for WSDOT Contract XE3404's project. The mix design used for this project consisted of 18% RAP which was under the WSDOT specified threshold for RAP inclusion (WSDOT 2024).

Table 6 - WSDOT Contract XE3404 Meta Data

SR 8 US12 to US101	
GENERAL PROJECT DETAILS	
Contract Number	XE3404
Contractor Name	Tucci & Sons Inc
Primary Pavement Type	Hot Mix Asphalt
Project Type	Mill and Fill
State	Washington
City	McCleary
County	Grays Harbor
Location 1 Mile Post	SR 8 0.00 to 20.63
Location 2 Mile Post	SR 108 0.00 to 0.50
Estimated Bid Price	$5,287,685.15
Final Contract Price	$5,410,085.93
Pavement Activities	Pavement Repair, Planning of Bituminous Pavements, HMA Sawcut and Seal, Pavement Marking, Traffic Control
PAVEMENT CONSTRUCTION DETAILS	
Predominant Lane Configuration	2
Project Area (ft^2)	1,911,571.2
Project Length (mi)	21.13
Elevation Gain (ft)	889
Number of Paving Days	22
Paving Dates	6/12/2023 to 7/19/2023
Thickness of Layer (ft)	0.15
MIX DESIGN DETAILS	
Total HMA Quantity (short tons)	28851.93
Tack Coat (short tons)	47.76
HMA GWP A1-A3 (kg CO_2eq per short ton)	49.53
RAP %	18%
HMA Class	1/2"
Traffic Level (Million ESALs)	SR 8 (4.5), SR 108 (1.7)
ASPHALT PLANT DETAILS	
Name	McChord Plant
Location	Lakewood, WA
TRUCKING DETAILS	
HMA Average One-Way Distance (mi)	40
Tack Coat Estimated Travel Distance (mi)	130.35
Truck Type Used	Dump Truck - End
Average Number of Trucks Running (Daily)	20
Average Truck Capacity (short ton)	25
Double Cycling	Yes

3.2.3.2 XE3404 Typical Paving Operations

Paving and grinding operations occurred during the night between 6 pm and 6 am. For this specific project, grinding and milling of the existing roadways was completed during the same shift. The work schedule that Tucci & Sons utilized consisted of milling starting the night by grinding off the top layer of the pavement surface. A paver would then begin about an hour and a half after the milling began to cover up the milled roadway. This way, all portions of the roadway that was milled were covered by the end of the night shift leaving no exposed roads. Having milling and paving done in the same night also allowed double-cycling of the haul trucks. A unique aspect about this project was that there were delamination failures which led to the contractors having to mill down an extra 200th of a foot to fix the issue. Table 7 describes the equipment used on the project. A comparison of all equipment types and models can be seen in Appendix F: Equipment Summary List

3.2.3.3 XE3404 Equipment Used

Table 7 – XE3404 Equipment Descriptor

Contract XE3404: SR 8 US12 to US101	
Equipment Type	**Model**
Backhoe	*not used in project*
Grader	*not used in project*
Loader	*not used in project*
Milling Machine	Wirtgen W100fi, Wirtgen Cold Milling Machine W 1200 F
MTV	Weiler E2850 Transfer Machine
Paver	Cat 1055E 10Ft Paver
Roller	Cat CB68B Pave Roller, Dynapac pneumatic roller, Cat CB64 Pave Roller
Sweeper	Elgin Broom Bear Mechanical Sweeper, Elgin Regenerative Air Vacuum Sweeper
Tack Truck	Petrb 335 2000gl Oil Distributer
Water Truck	*not used in project*

The figures below are the equipment observed on-site during the site visit conducted.

Figure 25 - XE3404 Paver

Figure 26 - XE3404 MTV

Figure 27 – XE3404 Dump Truck

Figure 28 - XE3404 Roller

3.2.4 XE3419 SR 23 E Wenatchee to Rock Island Project Description

Central Washington Asphalt was the prime contractor on the E Wenatchee to Rock Island project along SR 28 shown in Figure 29. This project was located in Douglas County in Rock Island, Washington.

3.2.4.1 XE3419 Project Description

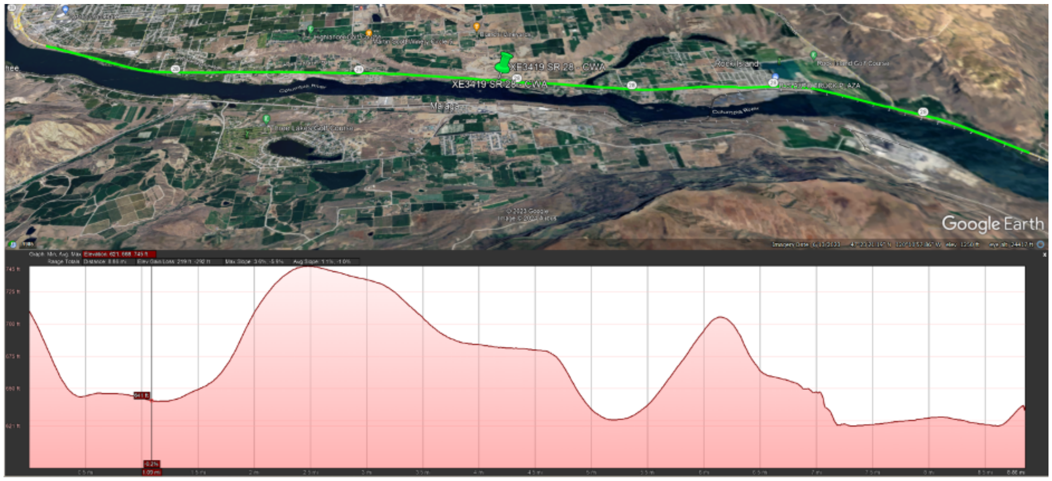


Figure 29 - XE3419 Project Route and Elevation Profile

Pavement rehabilitation work on this project took place in a primarily rural setting along a two-lane highway. Figure 30 shows the condition of the pavement prior to the pavement activities that took place. A site visit was conducted on Monday, August 21st, 2023

Figure 30 – XE3419 Pre-Project Roadway View

Table 8 highlights general project information, details regarding pavement construction and design, and the asphalt plant for WSDOT Contract XE3419’s project. The mix design used for this project consisted of 20% RAP which was under the WSDOT specified threshold for RAP inclusion (WSDOT 2024).

Table 8 - WSDOT Contract XE3419 Project Information

SR 28 E Wenatchee to Rock Island	
GENERAL PROJECT DETAILS	
Contract Number	XE3419
Contractor Name	Central Washington Asphalt
Primary Pavement Type	Hot Mix Asphalt
Project Type	Mill and Fill with Crack Sealing
State	Washington
City	Rock Island
County	Douglas
Location 1 Mile Post	SR 28 0.11B to 1.64B and 1.02 TO 10.21
Estimated Bid Price	$6,015,000.00
Final Contract Price	$5,773,469.14
Pavement Activities	Clearing and Grubbing, Pavement Repair, Planning Bituminous Pavement, HMA Sawcut and Seal, Joint Adhesive for Bituminous Pavement, and Shoulder Fixing
PAVEMENT CONSTRUCTION DETAILS	
Predominant Lane Configuration	3
Project Area (ft^2)	1,421,758.8
Project Length (mi)	10.54
Elevation Gain (ft)	219
Number of Paving Days	35
Paving Dates	7/18/2023 to 10/12/2023
Thickness of Layer (ft)	0.15
MIX DESIGN DETAILS	
Total HMA Quantity (short tons)	33462.67
Tack Coat (short tons)	50.5
HMA GWP A1-A3 (kg CO_2 eq per short ton)	56.71
RAP %	19%
HMA Class	3/8"
Traffic Level (Million ESALs)	5
ASPHALT PLANT DETAILS	
Name	Rocky Reach
Location	Wenatchee, WA
TRUCKING DETAILS	
HMA Average One-Way Distance (mi)	18.1
Tack Coat Estimated Travel Distance (mi)	130.35
Truck Type Used	Dump Truck - Belly
Average Number of Trucks Running (Daily)	15
Average Truck Capacity (short ton)	30
Double Cycling	Yes

3.2.4.2 XE3419 Typical Paving Operations

Paving and grinding operations occurred during the night between 7 pm and 6 am. This project utilized belly dump trucks to transport their material. The contractor also double cycled their haul trucks by reusing the belly dump trucks that bring HMA to site to haul grindings back to their plant. Aside from the HMA overlay paving that this project completed, the contractor also completed crack sealing within the project area. Table 9 describes the equipment used on the project. A comparison of all equipment types and models can be seen in Appendix F: Equipment Summary List.

3.2.4.3 XE3419 Equipment Used on the Project

Table 9 - XE3419 Equipment Descriptor

Contract XE3419: SR 23 E Wenatchee to Rock Island	
Equipment Type	**Model**
Backhoe	Case 580 Super N, Case 580SN, Case 580CFN
Grader	Cat 120H Motor Grader
Loader	*not used in project*
Milling Machine	*not specified*
MTV	Lincoln 660AXL, Roadtech 2B02500E Shuttle Buggy, Kol Cal
Paver	Vogele S2000 Paver, Vogele Super 2000-3i, Roadtech RP195, Vogele S1700 Paver
Roller	Cat 4 Roller, Volvo DD 120 Roller, Volvo DD140 Roller
Sweeper	Broce Broom RC350, Broce Broom RCT350, Broce Highway Sweeper Broom
Tack Truck	*not specified*
Water Truck	*not used in project*

The figures below are the equipment observed on-site during the site visit conducted.

Figure 31 – XE3419 Paver

Figure 32 - XE3419 MTV

Figure 33 - XE3419 Dump Truck

Figure 34 - XE3419 Roller

Table 10 - Requested Project Data

Document Name	Origin	Form Received In	Data Desired	How it was Utilized
Bid Tabulation	WSDOT/Contractor	PDF	Estimated material quantities	Identify largest pay item contributions to the project
Plans	WSDOT FTP Site	PDF	Paving plans, roadway section designs	Background on roadway design of mill and fill areas vs pavement repair & contribute to project meta data
Specifications	WSDOT FTP Site	PDF	Description of work, Project Length	Understand the project's scope of work and total length & contribute to project meta data
Mix Deign	Contractor	PDF	Asphalt binder content, HMA material quantities	Description and quantities of asphalt binder and RAP & tack coat details
EPD	Emerald Eco Label/Contractor	PDF	GWP of mix design	HMA GWP contribution in LCA calculation
Construction Equipment	Contractor	Spreadsheet/PDF	Equipment Name, Daily/Total fuel consumption & operating hours, Engine Size, Fuel Consumption Rate (gph)	Contribute to LCA calculation
Trucking Information	Contractor	Spreadsheet/PDF	One-way distance (mi) from plant to job site	LCA transportation calculation
Final Quantities	WSDOT/Contractor	PDF	Final material quantities	Calculate final HMA/joint adhesive quantities for LCA calculation

Table 11 - Additional Project Data Requested (Not Used in Analysis)

Document Name	Origin	Form Received In	Data Desired/Utilized	Reason
SPCC Plans	WSDOT/Contractor	PDF	Spill Prevention, Control, and Countermeasure (SPCC) Plan	Activities not considered in the LCA
Material Sheets	Contractor	PDF	Product sheets for any additional products used on the project (e.g. paint, plastic lines, guardrails, etc.)	Materials defined outside the project's scope
Trucking Information	Contractor	Spreadsheet/PDF	Daily operating haul trucks, Load capacity, Fuel efficiency (mpg), Daily/total fuel consumption, Total operating days	Data requested was more granular than the model allowed

3.3 Data Analysis

Data from the four WSDOT case study projects were evaluated from the A1-A5 stage with a scope of cradle-to-built (Figure 3). Therefore, **the focus of this thesis is to present LCA calculations per case study and analyze the GWP specifically of the HMA pavement materials** and only included the bid item in Table 12. Therefore, auxiliary items (i.e. plastic lines, traffic control, guardrail, etc.) were not considered in the LCA calculations presented.

Table 12 - Bid Items Included in LCA Analysis

Process	9914	9954	XE3404	XE3419
Milling	Planing Bituminous Pavement	Planing Bituminous Pavement	Planing Bituminous Pavement	Planing Bituminous Pavement
HMA	HMA For Pavement Repair Cl. 3/8 in. PG 64H-28	HMA For Pavement Repair Cl. 1/2 in. PG 58H-22	HMA For Pavement Repair Cl. 1/2 in. PG 58H-22	HMA For Pavement Repair Cl. 3/8 in. PG 64V-28
	HMA Cl. 3/8 in. PG 64H-28	HMA Cl. 1/2 in. PG 58H-22	HMA Cl. 1/2 in. PG 58H-22	HMA Cl. 3/8 in. PG 64V-28
		Commercial HMA		
Joint Adhesive	Joint Adhesive for Bituminous Pavement	n/a	n/a	Joint Adhesive for Bituminous Pavement

In the data analysis phase of this study, all documents and data received were organized and data gaps were identified and filled, preparing for input to openLCA modeling.

3.3.1 Data Organization

The first step in the data analysis process was identifying and organizing all the documents and spreadsheets containing information for each project. This included the internal spreadsheets that outlined information gathered in Table 10 and external documentation with trucking and equipment data. To maintain the integrity of the original spreadsheets that were provided, all spreadsheets were copied before any additional calculations or alterations were made.

Construction equipment and trucking specifications shown in Table 10 were taken and compiled into one spreadsheet encompassing all the aforementioned areas. Data across all four case studies were consolidated into one comprehensive spreadsheet, sorted by bid item and project number, and categorized as either trucking or construction. The main information collected was the engine size, operation time, and fuel consumption. Additional material regarding name, model, year, and fuel type was also noted if the information was provided.

3.3.2 Data Gaps

Since not all data received were in the same units, conversions and some data gaps must be filled before inputting data into openLCA. For example, a common calculation that was completed included changing the units of equipment engine sizes. All engine sizes collected were in horsepower (hp). However, the engine size units for the equipment in the FHWA repository was kilowatt (kW). A unit conversion of 1.341 hp/kW was used to obtain the appropriate units. Additionally, different variations of fuel consumption data and operating times were received. Table 13 below shows the units that the data needed to be in when inputting it into openLCA. Proxy data then filled additional data gaps that remained.

Table 13 - Units Received vs openLCA Inputs

Data Type	Units Received In	openLCA Units
Fuel Consumption	Hours (hr) [Daily/Total Operating Time] & Gallons per day/hour (gpd, gph) [Daily/Hourly Consumption]	Total Gallons (gal) [over full project]
Engine Size	Horsepower (hp)	MegaJoule (MJ)
Emulsion/Tack Coat	Gallons (gal)	Short Tons (sh tn)
Emulsion Travel Distance	Miles (mi)	Miles (mi)
One-Way Truck Travel	Miles(mi)	Miles (mi)
Total Asphalt Tonnage	Short Tons (sh tn)	Short Tons (sh tn)

3.3.2.1 Data Gaps in Contract 9914 SR 127 & US 195

Data received from Contract 9914 project consisted of all necessary total operating hours and various fuel consumption data. Approximately half of the equipment had fuel consumption data associated with the hours recorded. Fuel consumption data provided included the consumption in terms of gallons per hour (gph). For the equipment that did not have consumption rates provided, rules of thumb (described in Section 3.3.2.5) were used in conjunction with the reported operating hours to calculate total fuel consumption. Total fuel consumption for the equipment with a reported fuel consumption rate used the provided rate with operating hours to calculate the total fuel consumption throughout the project.

3.3.2.2 Data Gaps in Contract 9954 SR 530 Montague Creek Bridge to Seeman St Vic

Data from Contract 9954 project provided the most comprehensive data regarding equipment and trucking information. Data provided included the specific equipment, identified by provided equipment numbers, individual operation time, and fuel consumption. The only piece of construction equipment that contractors could not provide project-specific information on was their milling machine since the milling operations on this job were subcontracted. Therefore, the contractors did not have accurate firsthand data of fuel consumption and operation time of the milling machine. However, the contractor’s equipment engineer provided approximate hours, fuel consumption rate (gph), and total fuel consumption for the milling machine. The milling machine’s fuel consumption data was composed of the contractor’s compiled historical data and the number of scheduled shifts that the sub-contractors were scheduled to be on site.

3.3.2.3 Data Gaps in Contract XE3404 SR 8 US 12 to US 101

Data received from Contract XE3404 project provided majority of the equipment and trucking data requested. The data represented average operation time and total recorded fuel consumption. Milling was also subcontracted out on this project. Therefore, the contractors did not specifically record operating time and fuel consumption. This job's contractor provided the expected total operating hours for the milling machine. From here, total fuel consumption was calculated based on the gph rate provided by Contract 9954. After reviewing all the data collected, alterations were made to the sweeper data. The original data that was provided showed an unusually high number of operating hours and fuel consumption. Through auxiliary data provided, two sweepers were out for approximately the same amount of time as the paver; adjustments were made to align closer with the paver's operating hours. From the paver hours given, it was assumed that the provided data was increased by a factor of two. Therefore, the sweeper data used in the analysis was reduced by a factor of two from the originally provided data.

3.3.2.4 Data Gaps in Contract XE3419 SR 28 E Wenatchee to Rock Island

Data from the Contract XE3419 project consisted mainly of total operating hours. Total operating hours were recorded for each piece of equipment used on-site for their project. This project's most significant data gap was the lack of equipment fuel consumption data. This was the most significant data gap because fuel consumption was needed as the input for openLCA calculations. To combat this data gap, rules of thumb were created from other project data in this study, and proxy data were used to find estimates of total fuel usage.

All pieces of construction equipment, excluding the grader used on the project, used the calculated rules of thumb. This project was the only one that used a grader during construction activities. Therefore, there was no data to inform a rule of thumb and proxy data was used. The specific fuel consumption for the grader from the proxy data was calculated through interpolation. Engine size of the grader used on site was known. So, the fuel consumption of the graders with engine size closest to the one specified was used to find the approximate fuel consumption of the equipment. Additionally, information regarding milling operations was not provided. Therefore, estimates for hours and rules of thumb were needed to estimate the fuel consumption of the milling machine used on site. Projected operating hours for the milling machine were estimated based on the approximated project area. A weighted average was taken for the three projects with known milling machine data using the miller's total operating hours and the approximate project area. The milling machine's weighted average was used as this project's estimated total operating hours. Total tack coat was also not known for this project. To estimate the total tack coat, the ratio of HMA to the tack coat used in the other three projects was calculated to get a tack coat per HMA with units of short ton/short ton. Then, given the average ratio of tack coat per HMA, using the total HMA tonnage of the project, the tack coat was estimated in both short tons and gallons.

3.3.2.5 Rules of Thumb and Proxy Data

Combined fuel consumption data from all projects forms the basis of the rules of thumb used in contracts 9914, XE3404, and XE3419. For projects that did not report fuel consumption rates in gph, values were calculated using other reported data such as operating hours (per day), days in operation, total operating hours, fuel consumption (gal per day), and total fuel consumption. For types of equipment with various pieces of equipment on the job sites, gph for that equipment was averaged. This provided averaged gph values for the equipment that was used on the construction sites. Once all gph data was compiled per project, an average gph per equipment type was taken to create a rule of thumb. Rule of thumb values are shown in Table 14 below. In the columns under the contract numbers, averaged gph is reported for the specific piece of equipment in the corresponding rows. Fuel consumption for belly dump trucks was the only rule of thumb, and it was not based on other project data for a similar piece of equipment. Since Contract XE3419 was the only project that used belly dump trucks, the rule of thumb was averaged from the end, and super dump truck data was provided in Table 14. The second column shows the average value of gph per specified equipment across all projects that were used to obtain total fuel consumption. Loaders and rollers were separated into two different engine size ranges, 19-56kW and 56kW-560kW because that is the range that is given for trucking in the FHWA repository and is being used for analysis in openLCA.

Table 14 - Fuel Consumption Project Averages

Fuel Consumption (gph)					
		Contract Number			
Equipment Name	**Average**	**9914**	**9954**	**XE3404**	**XE3419**
Backhoe	1.5		1.5		
Dump Truck (Belly)	5.17				
Dump Truck (End)	5.52	6.73	4.31		
Dump Truck (Super)	4.81	5.2	4.425		
Loader(19-56kW)	2	2			
Loader(56-560kW)	4.65	8.3	1		
Milling Machine	16.7		16.7		
MTV	5.87	3.5	7.1	7	
Paver	3.87	3.5	4.6	3.5	
Roller (19-56kW)	1.67	2.5	1	1.5	
Roller (56-560kW)	2.7	3	2.9	2.2	
Sweeper	4.17			4.17	
Tack Truck	2.47		3.94	1	
Water Truck	2.95	4.5	1.4		

Additional proxy data was from MOtor Vehicle Emission Simulator (MOVES) model created by Environmental Protection Agency (EPA). Proxy data was not based on any data received from WSDOT or contractors specifically for these projects being analyzed. The proxy data spreadsheet includes emission and fuel consumption data for construction diesel and gasoline, industrial diesel and gasoline, and gardening equipment for various-sized engines. Proxy data was only used for the equipment with no reported fuel consumption data to be based on the projects being analyzed.

3.3.3 LCA Modeling

LCA modeling uses characterization factors to convert life cycle inventory (LCI) results to the common unit used by impact categories. This thesis focuses primarily on GWP, kg CO_2 eq, as the main impact category of the paving projects. Life cycle stages encompassed in this thesis are A1-A5: A1-A3 production stage and A4-A5 construction stage (cradle-to-build). The A1-A3 production stage calculation for each case study project was completed by the contractor through an environmental product declaration (EPD). The A4-A5 construction stage data was collected during and at the end of each project for work done on-site. Within each stage, the following was considered:

1. A1-A3 (cradle-to-gate)
    a. HMA Mix Design EPD
    b. Tack Coat/Emulsion (including estimated transportation)
    c. Joint Adhesive
2. A4-A5
    a. HMA Haul Distances
    b. Construction Equipment Fuel Consumption
        i. Construction Equipment: Backhoe, Loader, Milling Machine, MTV, Paver, Roller, Sweeper, Tack Truck, and Water Truck

In the industry today, there does not seem to be a large consensus on which stage milling should be included in (personal correspondence with Dr. Amlan Mukherjee). Milling was included in the A5 stage of this study. The decision to include milling in A5 was made as the activity being completed in conjunction with paving. This decision also aligns with A5.1 in the Royal Institution of Chartered Surveyors (RICS) professional standard for whole life carbon assessment for the built environment (RICS 2023).

3.3.3.1 Functional Unit

The functional unit used in this study is "per short ton of asphalt pavement." This functional unit was decided upon after speaking with multiple experts studying pavement construction and the associated LCAs. These experts advised using a functional unit closest to the bid tabulation's reported quantities. The "per short ton of asphalt" unit is the unit of measurement closest to both what the EPD and bid tabulation documents use to quantify asphalt pavement mixture.

3.3.4 openLCA Modeling

This study chose openLCA as the LCA calculation tool due to its overall accessibility and functionality. OpenLCA can be downloaded and run on both Windows and Mac operating systems. It can also support any updates made to the FHWA repository. A platform was created by Dr. Mukherjee for the Climate Challenge with training modules specific to the openLCA software. These modules were specifically designed to evaluate pavement construction projects and apply them to research similarly to the calculations conducted in this thesis. Additionally, openLCA is continuously updated to improve its functionality. One improvement currently being added to openLCA is compatibility with the Embodied Carbon in Construction Calculator (EC3). The integration of EC3 into openLCA will allow integration of published EPD values to be input directly to the LCA modeling processes.

On the Climate Challenge's website they state their objective to be, "support state DOTs and other public agencies explore the use of life cycle assessment (LCA) and Environmental Product Declarations (EPD)s as a standard practice to inform paving material and design selection for enhancing sustainable pavement practices and quantify the emissions and impacts of those practices." (Mukherjee n.d.). This webpage outlines recommended data collection protocols, has learning modules, and resources for anyone wanting to learn more about LCAs and openLCA, openLCA 2.0.2 is the version used in this study. The modules go over the basics of the LCAs, foreground and background data, what the FHWA repository is and how it is used in openLCA, and examples on how to model in openLCA. These modules provide a base understanding for the models that were created for this project.

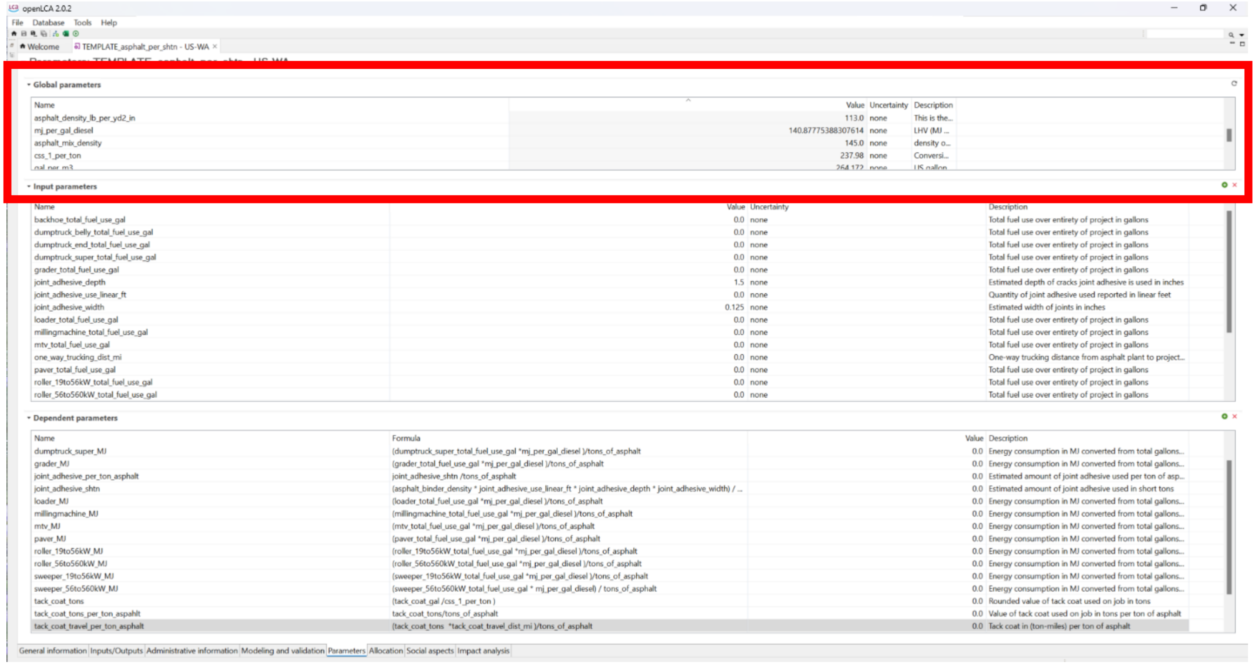
OpenLCA, in conjunction with the FHWA repository, accessible through the LCA Commons, was the program and data set of choice used in this thesis. Within the openLCA application, a dataset, typically with corresponding foreground or upstream data, is imported to inform any LCA calculations of impacts. The FHWA repository is a background dataset informed by industry data created by the FHWA, including common pavement construction activities. OpenLCA takes the upstream data provided by the FHWA repository (i.e., equipment based on engine size and hauling trucks) and the input data (i.e., truck mileage, fuel consumption, etc.) to calculate a GWP in kg of CO_2 eq. Ultimately, openLCA was selected as the calculation software due to its wide availability and access to training videos that provide researchers with a solid foundational understanding of the software, database specificity, and continuous updates.

3.3.4.1 Global Parameters

Global parameters are properties and conversions that remain constant for all analyses. They were utilized when setting up dependent parameter calculations and inputs within the openLCA model (see Appendix E: Variables used in openLCA). Benefits of utilizing global parameters in openLCA were convenience of use and automatic updating where it was referenced. Global parameters used in this model are listed in Table 15 with their associated value and description. Global parameters once input into the database, can be found in the parameters tab of a process in, shown in Figure 35.

Table 15 - Global Parameters

Material and Fuel Properties		
Parameter	**Value/Formula**	**Description/UOM**
Asphalt Density	113	This is the target density of asphalt paving. Units: lb/sq. yd./in of paving mat
Diesel Density	867.30268	Density of diesel in kg/m3
Diesel LHV	42.91	Lower heating value of diesel, unit: MJ/kg
MJ per gal diesel	(diesel lhv * diesel density)/gal per m3	LHV (MJ per kg) * Density (kg per m3) / conversion factor gal per m3
CSS-1 gal per ton	237.98	Gallons per ton of CSS-1 emulsion



Global parameters

Name	Value	Uncertainty	Description
asphalt_density_lb_per_yd2_in	113.0	none	This is the...
mj_per_gal_diesel	140.87775388307614	none	LHV (MJ ...
asphalt_mix_density	145.0	none	density o...
css_1_per_ton	237.98	none	Conversi...
gal_per_m3	264.172	none	US gallon

Input parameters

Name	Value	Uncertainty	Description
backhoe_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
dumptruck_belly_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
dumptruck_end_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
dumptruck_super_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
grader_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
joint_adhesive_depth	1.5	none	Estimated depth of cracks joint adhesive is used in inches
joint_adhesive_use_linear_ft	0.0	none	Quantity of joint adhesive used reported in linear feet
joint_adhesive_width	0.125	none	Estimated width of joints in inches
loader_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
millingmachine_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
mtv_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
one_way_trucking_dist_mi	0.0	none	One-way trucking distance from asphalt plant to project...
paver_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
roller_19to56kW_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
roller_56to560kW_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons

Dependent parameters

Name	Formula	Value	Description
dumptruck_super_MJ	(dumptruck_super_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
grader_MJ	(grader_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
joint_adhesive_per_ton_asphalt	joint_adhesive_shtn /tons_of_asphalt	0.0	Estimated amount of joint adhesive used per ton of asp...
joint_adhesive_shtn	(asphalt_binder_density * joint_adhesive_use_linear_ft * joint_adhesive_depth * joint_adhesive_width) / ...	0.0	Estimated amount of joint adhesive used in short tons
loader_MJ	(loader_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
millingmachine_MJ	(millingmachine_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
mtv_MJ	(mtv_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
paver_MJ	(paver_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
roller_19to56kW_MJ	(roller_19to56kW_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
roller_56to560kW_MJ	(roller_56to560kW_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
sweeper_19to56kW_MJ	(sweeper_19to56kW_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
sweeper_56to560kW_MJ	(sweeper_56to560kW_total_fuel_use_gal * mj_per_gal_diesel) / tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
tack_coat_tons	(tack_coat_gal /css_1_per_ton)	0.0	Rounded value of tack coat used on job in tons
tack_coat_tons_per_ton_aspahlt	tack_coat_tons/tons_of_asphalt	0.0	Value of tack coat used on job in tons per ton of asphalt
tack_coat_travel_per_ton_asphalt	(tack_coat_tons *tack_coat_travel_dist_mi)/tons_of_asphalt	0.0	Tack coat in (ton-miles) per ton of asphalt

Figure 35 - openLCA Global Parameters

3.3.5 Manual Addition of EPDs

OpenLCA is working with EC3, a tool that assists anyone looking at a project's embodied carbon, to streamline the addition of an EPD into the model from an online database. However, since the EPDs used in this study were relatively new, the EC3 database has not yet added them to the system. All EPD data used in this study was added manually to each model as a separate flow and process. A new reference flow was made to represent the EPD for the asphalt mixture in the project's LCA. This one flow was used as the reference for each project's EPD process. The unit of choice for this flow representing EPDs is mass. Mass is the appropriate unit because the environmental impact results were reported per short ton of asphalt. Once this flow was made, a new process could be used in the project's LCA. Resource use indicator quantities in

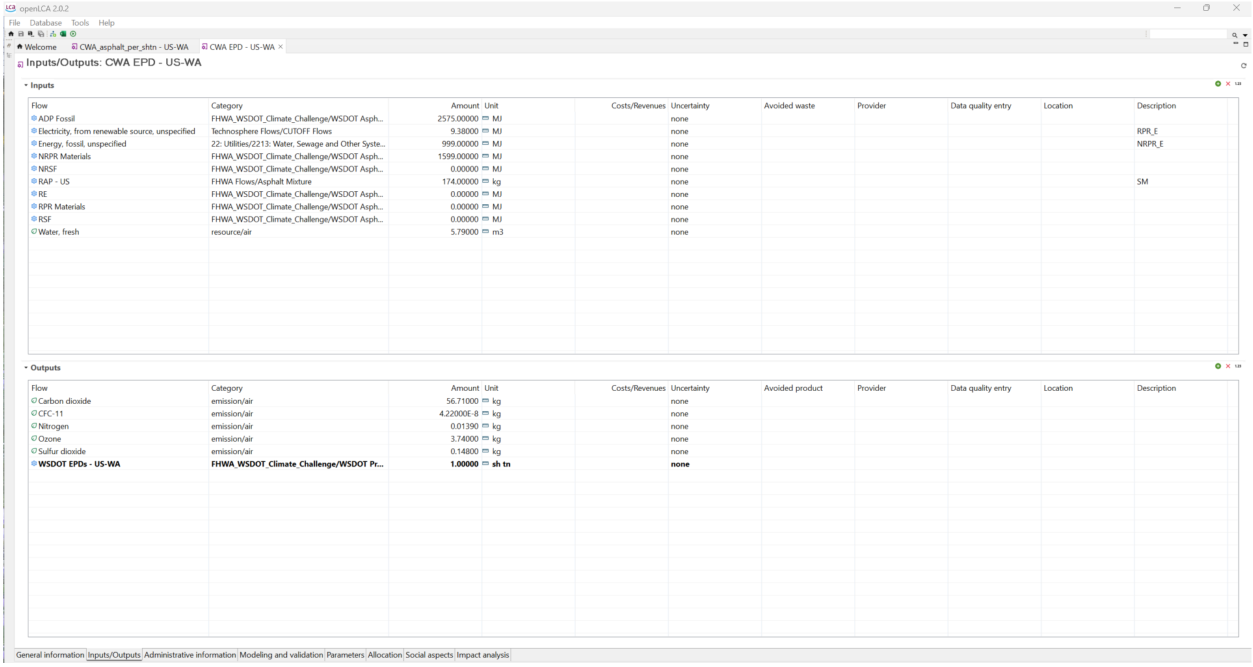
Table 16 were entered in the process's input section (Figure 36). The corresponding process added life cycle impact indicators in Table 17 as output flows (Figure 36). Flows added were a combination of existing flows from the FHWA repository and new flows created to represent indicators not already present.

Table 16 - EPD Resource Use Indicators from Emerald EcoLabel EPDs

Acronym	Indicator	Unit	openLCA associated flow
RPR_E	Renewable primary resources used as an energy carrier (fuel)	MJ	Electricity, from renewable source, unspecified
RPR_M	Renewable primary resources with energy content used as material	MJ	New flow: RPR 1Materials
NRPR_E	Non-renewable primary resources used as an energy carrier (fuel)	MJ	Energy, fossil, unspecified
NRPR_M	Non-renewable primary resources used as a material (fuel)	MJ	New flow: NRPR Materials
SM	Secondary (recycled) materials	Kg	RAP
RSF	Renewable secondary fuels	MJ	New flow: RSF
NRSF	Non-renewable secondary fuels	MJ	New flow: NRSF
RE	Recovered Energy	MJ	New flow: RE
FW	Consumption of fresh water	m^3	Water, fresh
ADP_fossil	Abiotic depletion potential for fossil resources	MJ	New flow

Table 17 - Life Cycle Impact Indicators for Emerald EcoLabel EPDs

Acronym	Indicator	Unit	FHWA Repository Flow
GWP	Global warming potential, incl. biogenic CO_2	kg CO_2Equiv.	Carbon dioxide
ODP	Ozone depletion potential	kg CFC-11 Equiv.	CFC-11
EP	Eutrophication potential	kg N Equiv.	Nitrogen
AP	Acidification potential	kg SO_2 Equiv.	Ozone
POCP	Photochemical ozone creation potential	kg O_3 Equiv.	Sulfur dioxide



Inputs/Outputs: CWA EPD - US-WA

Inputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entry	Location	Description
ADP Fossil	FHWA_WSDOT_Climate_Challenge/WSDOT Asph...	2575.00000	MJ		none					
Electricity, from renewable source, unspecified	Technosphere Flows/CUTOFF Flows	9.38000	MJ		none					RPR_E
Energy, fossil, unspecified	22: Utilities/2213: Water, Sewage and Other Syste...	999.00000	MJ		none					NRPR_E
NRPR Materials	FHWA_WSDOT_Climate_Challenge/WSDOT Asph...	1599.00000	MJ		none					
NRSF	FHWA_WSDOT_Climate_Challenge/WSDOT Asph...	0.00000	MJ		none					
RAP - US	FHWA Flows/Asphalt Mixture	174.00000	kg		none					SM
RE	FHWA_WSDOT_Climate_Challenge/WSDOT Asph...	0.00000	MJ		none					
RPR Materials	FHWA_WSDOT_Climate_Challenge/WSDOT Asph...	0.00000	MJ		none					
RSF	FHWA_WSDOT_Climate_Challenge/WSDOT Asph...	0.00000	MJ		none					
Water, fresh	resource/air	5.79000	m3		none					

Outputs

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
Carbon dioxide	emission/air	56.71000	kg		none					
CFC-11	emission/air	4.22000E-8	kg		none					
Nitrogen	emission/air	0.01390	kg		none					
Ozone	emission/air	3.74000	kg		none					
Sulfur dioxide	emission/air	0.14800	kg		none					
WSDOT EPDs - US-WA	**FHWA_WSDOT_Climate_Challenge/WSDOT Pr...**	**1.00000**	**sh tn**		**none**					

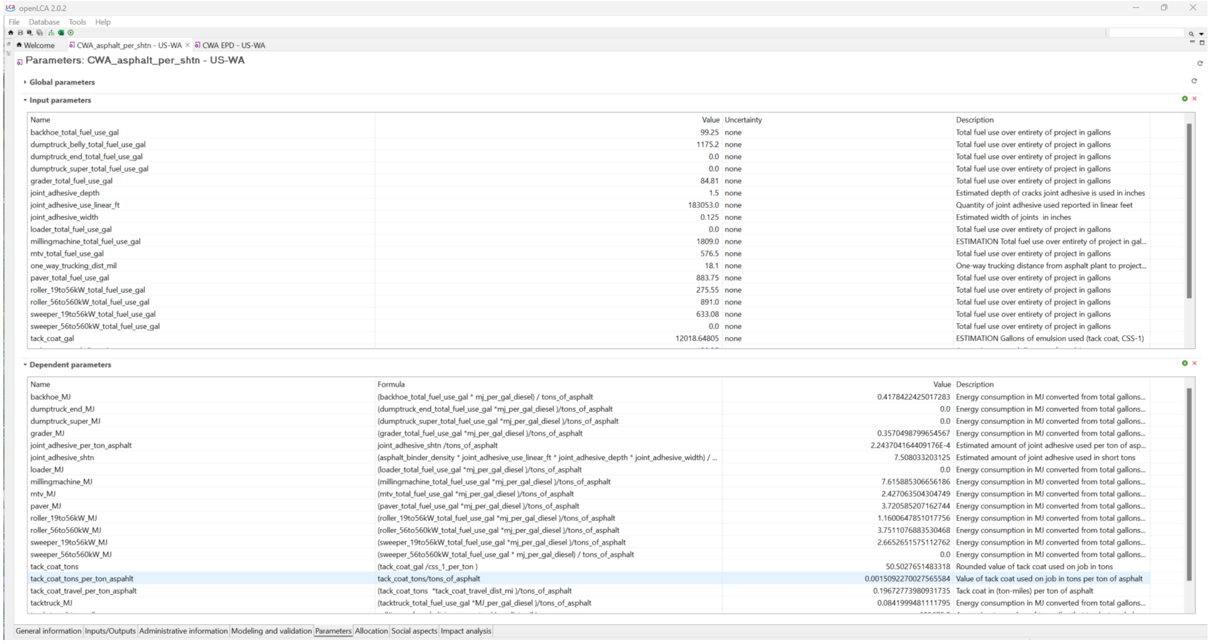
Figure 36 - openLCA EPD Input/Outputs

3.3.6 Project Specific LCA Model

A new flow and process in openLCA was created for each specific asphalt paving project. Since the projects were so similar, once one process outlining the life cycle of the project from module A1 to A5 was created, it could be duplicated for the remaining projects. The parameter values input to the process should be the only values that need to be changed for each project. In each new process and flow created, appropriate metadata should be specified to describe what is represented. Metadata included information regarding general project information and links to data where applicable, as well as input, output, and global parameters used. Additionally, specific time and geographic data should be defined where possible. Time is documented in dates, so paving dates were entered for the projects with a specified location of United States – Washington.

3.3.6.1 Processes Parameters

The parameters section of the process is where all the project data will be input from the data analysis stage. This will be the only area where numerical data organized in the data analysis should be used. The input parameters should include any value that does not need any conversions or calculations. Dependent parameters have a formula section where numbers, as well as global and input parameters, can be used to calculate a value. Input parameters included total fuel consumption for construction equipment, one-way travel distance (from plant to site) for asphalt pavement trucks, total travel distance of emulsion, total amount of emulsion used, and total tons of asphalt used on the project (Figure 37). Dependent parameters include the energy consumption of each piece of construction equipment, tons of emulsion, and the ton-miles of emulsion, all per short ton (Figure 37).



Parameters: CWA_asphalt_per_shtn - US-WA

Global parameters

Input parameters

Name	Value	Uncertainty	Description
backhoe_total_fuel_use_gal	99.25	none	Total fuel use over entirety of project in gallons
dumptruck_belly_total_fuel_use_gal	1175.2	none	Total fuel use over entirety of project in gallons
dumptruck_end_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
dumptruck_super_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
grader_total_fuel_use_gal	84.81	none	Total fuel use over entirety of project in gallons
joint_adhesive_depth	1.5	none	Estimated depth of cracks joint adhesive is used in inches
joint_adhesive_use_linear_ft	183053.0	none	Quantity of joint adhesive used reported in linear feet
joint_adhesive_width	0.125	none	Estimated width of joints in inches
loader_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
millingmachine_total_fuel_use_gal	1809.0	none	ESTIMATION Total fuel use over entirety of project in gal...
mtv_total_fuel_use_gal	576.5	none	Total fuel use over entirety of project in gallons
one_way_trucking_dist_mil	18.1	none	One-way trucking distance from asphalt plant to project...
paver_total_fuel_use_gal	883.75	none	Total fuel use over entirety of project in gallons
roller_19to56kW_total_fuel_use_gal	275.55	none	Total fuel use over entirety of project in gallons
roller_56to560kW_total_fuel_use_gal	891.0	none	Total fuel use over entirety of project in gallons
sweeper_19to56kW_total_fuel_use_gal	633.08	none	Total fuel use over entirety of project in gallons
sweeper_56to560kW_total_fuel_use_gal	0.0	none	Total fuel use over entirety of project in gallons
tack_coat_gal	12018.64805	none	ESTIMATION Gallons of emulsion used (tack coat, CSS-1)

Dependent parameters

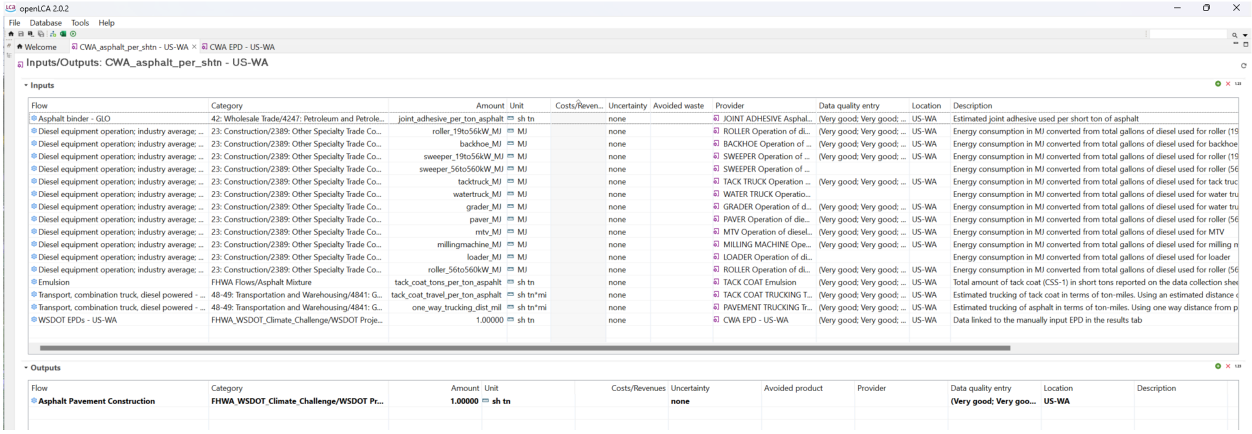
Name	Formula	Value	Description
backhoe_MJ	(backhoe_total_fuel_use_gal * mj_per_gal_diesel) / tons_of_asphalt	0.4178422425017283	Energy consumption in MJ converted from total gallons...
dumptruck_end_MJ	(dumptruck_end_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
dumptruck_super_MJ	(dumptruck_super_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
grader_MJ	(grader_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.3570498799654567	Energy consumption in MJ converted from total gallons...
joint_adhesive_per_ton_asphalt	joint_adhesive_shtn /tons_of_asphalt	2.243704164409176E-4	Estimated amount of joint adhesive used per ton of asp...
joint_adhesive_shtn	(asphalt_binder_density * joint_adhesive_use_linear_ft * joint_adhesive_depth * joint_adhesive_width) / ...	7.508033203125	Estimated amount of joint adhesive used in short tons
loader_MJ	(loader_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
millingmachine_MJ	(millingmachine_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	7.615885306656186	Energy consumption in MJ converted from total gallons...
mtv_MJ	(mtv_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	2.427063504304749	Energy consumption in MJ converted from total gallons...
paver_MJ	(paver_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	3.720585207162744	Energy consumption in MJ converted from total gallons...
roller_19to56kW_MJ	(roller_19to56kW_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	1.1600647851017756	Energy consumption in MJ converted from total gallons...
roller_56to560kW_MJ	(roller_56to560kW_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	3.7511076883530468	Energy consumption in MJ converted from total gallons...
sweeper_19to56kW_MJ	(sweeper_19to56kW_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	2.6652651575112762	Energy consumption in MJ converted from total gallons...
sweeper_56to560kW_MJ	(sweeper_56to560kW_total_fuel_use_gal * mj_per_gal_diesel) / tons_of_asphalt	0.0	Energy consumption in MJ converted from total gallons...
tack_coat_tons	(tack_coat_gal /css_1_per_ton)	50.5027651483318	Rounded value of tack coat used on job in tons
tack_coat_tons_per_ton_aspahlt	tack_coat_tons/tons_of_asphalt	0.0015092270027565584	Value of tack coat used on job in tons per ton of asphalt
tack_coat_travel_per_ton_asphalt	(tack_coat_tons *tack_coat_travel_dist_mi)/tons_of_asphalt	0.19672773980931735	Tack coat in (ton-miles) per ton of asphalt
tacktruck_MJ	(tacktruck_total_fuel_use_gal *MJ_per_gal_diesel)/tons_of_asphalt	0.0841999481111795	Energy consumption in MJ converted from total gallons...

Figure 37 - openLCA Process Parameters

3.3.6.2 Input and Output Data

Flows from the FHWA repository, aside from the flow created for EPD data, were the primary input sources. Diesel construction equipment flows, emulsion (used as tack coat), truck transport (for asphalt pavement and emulsion), and the previously created EPD flow were the primary input sources for the projects. Each piece of construction equipment required its separate flow. For instance, if the data entered was for five various pieces of equipment, five separate diesel construction flows should be added. Similarly, trucking for asphalt and emulsion should also have separate input flows. By separating each piece of equipment and providing a separate flow, their individual fuel consumption contribution could be identified in the final results. Each flow has an associated product system that becomes the "provider" for the input flow. For the final LCA impact results to be separated by input (emulsion, pavement mix, construction equipment, or trucking), each input must have its specific provider. Emulsion and the pavement should already be separated since there are no similar flows. However, the construction equipment and trucking will initially use the same FHWA repository flow as their provider. For each input flow to have its own provider, copies of the original FHWA flows can be made and renamed to the appropriate piece of corresponding equipment and set as the corresponding provider. Copying the pre-made FHWA flow will allow the model to retain all the background data input into the associated process from the repository but calculate their impact separately.

Once all the flows and providers had been appropriately identified, descriptions were added for each flow. Units were also appropriately identified in the input variable's naming convention. The units for the construction equipment are in megajoules (MJ), emulsion is in short tons, trucking for asphalt pavement and emulsion are in ton-miles, and EPD data should also be in short tons. The "amount" section of the input table is where the calculations done in the parameters stage will be input (Figure 38). Referencing the parameter's name will link the associated value to the input. Linking the parameter means the value will automatically change if any numbers or calculations change in the input and dependent parameters.



Inputs/Outputs: CWA_asphalt_per_shtn - US-WA

Inputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided waste	Provider	Data quality entry	Location	Description
Asphalt binder - GLO	42: Wholesale Trade/4247: Petroleum and Petrole...	joint_adhesive_per_ton_asphalt	sh tn		none		JOINT ADHESIVE Asphal...	(Very good; Very good; ...	US-WA	Estimated joint adhesive used per short ton of asphalt
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	roller_19to56kW_MJ	MJ		none		ROLLER Operation of di...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for roller (19
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	backhoe_MJ	MJ		none		BACKHOE Operation of ...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for backhoe
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	sweeper_19to56kW_MJ	MJ		none		SWEEPER Operation of ...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for roller (19
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	sweeper_56to560kW_MJ	MJ		none		SWEEPER Operation of ...			Energy consumption in MJ converted from total gallons of diesel used for roller (56
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	tacktruck_MJ	MJ		none		TACK TRUCK Operation ...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for tack truc
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	watertruck_MJ	MJ		none		WATER TRUCK Operatio...			Energy consumption in MJ converted from total gallons of diesel used for water tru
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	grader_MJ	MJ		none		GRADER Operation of d...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for water tru
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	paver_MJ	MJ		none		PAVER Operation of die...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for roller (56
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	mtv_MJ	MJ		none		MTV Operation of diesel...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for MTV
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	millingmachine_MJ	MJ		none		MILLING MACHINE Ope...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for milling n
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	loader_MJ	MJ		none		LOADER Operation of di...			Energy consumption in MJ converted from total gallons of diesel used for loader
Diesel equipment operation; industry average; ...	23: Construction/2389: Other Specialty Trade Co...	roller_56to560kW_MJ	MJ		none		ROLLER Operation of di...	(Very good; Very good; ...	US-WA	Energy consumption in MJ converted from total gallons of diesel used for roller (56
Emulsion	FHWA Flows/Asphalt Mixture	tack_coat_tons_per_ton_aspahlt	sh tn		none		TACK COAT Emulsion	(Very good; Very good; ...	US-WA	Total amount of tack coat (CSS-1) in short tons reported on the data collection shee
Transport, combination truck, diesel powered - ...	48-49: Transportation and Warehousing/4841: G...	tack_coat_travel_per_ton_asphalt	sh tn*mi		none		TACK COAT TRUCKING T...	(Very good; Very good; ...	US-WA	Estimated trucking of tack coat in terms of ton-miles. Using an estimated distance c
Transport, combination truck, diesel powered - ...	48-49: Transportation and Warehousing/4841: G...	one_way_trucking_dist_mil	sh tn*mi		none		PAVEMENT TRUCKING Tr...	(Very good; Very good; ...	US-WA	Estimated trucking of asphalt in terms of ton-miles. Using one way distance from p
WSDOT EPDs - US-WA	FHWA_WSDOT_Climate_Challenge/WSDOT Proje...	1.00000	sh tn		none		CWA EPD - US-WA	(Very good; Very good; ...	US-WA	Data linked to the manually input EPD in the results tab

Outputs

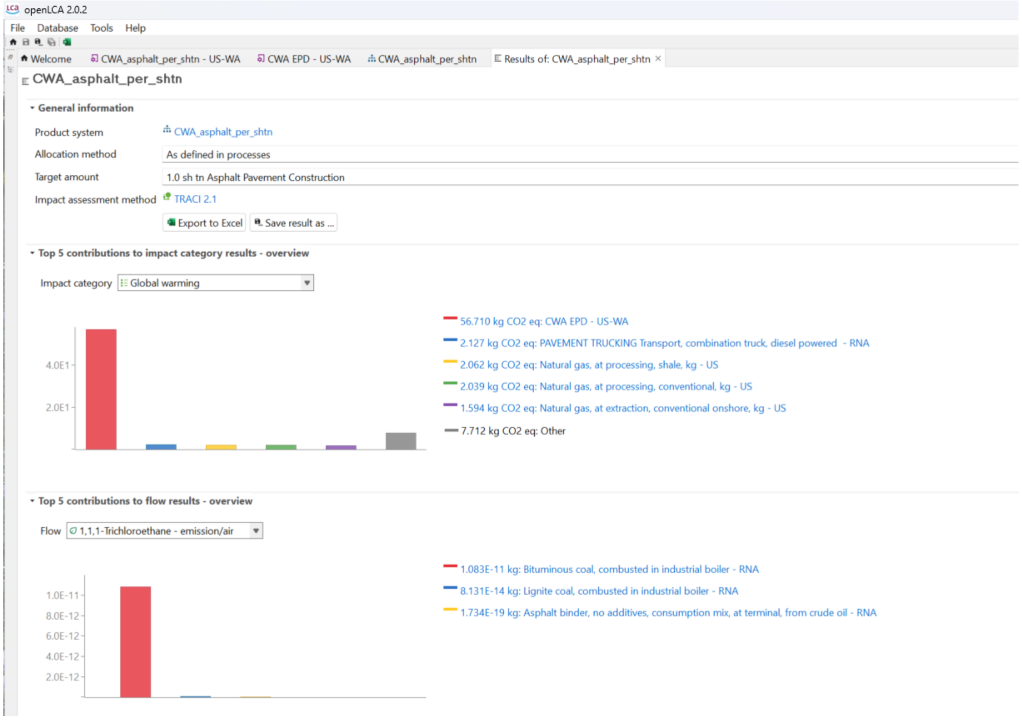
Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entry	Location	Description
Asphalt Pavement Construction	**FHWA_WSDOT_Climate_Challenge/WSDOT Pr...**	**1.00000**	**sh tn**		**none**			**(Very good; Very goo...**	**US-WA**	

Figure 38 - openLCA Process Input/Output

3.3.6.3 Final LCA Calculation

From the process that was just made, a product system can be created directly with all the project-specific data added. Once a product system is made, a model graph will be created for it. The model graph shows all the flows, their providers, and the associated upstream flows that contribute to the overall output flow.

The final environmental impact results were calculated using the product system. OpenLCA will calculate the environmental impacts of the processes linked to the product system based on the selected impact assessment method. This study used the TRACI 2.1 impact assessment method to evaluate projects GWP. Following calculation completion, environmental impacts were presented in multiple different formats. To see individual impacts that each flow contributed to the overall impact, the contribution tree broke down each provider by percentage of the total impact (Figure 39 and Figure 40).



CWA_asphalt_per_shtn

General information

Product system: CWA_asphalt_per_shtn
Allocation method: As defined in processes
Target amount: 1.0 sh tn Asphalt Pavement Construction
Impact assessment method: TRACI 2.1

Top 5 contributions to impact category results - overview

Impact category: Global warming

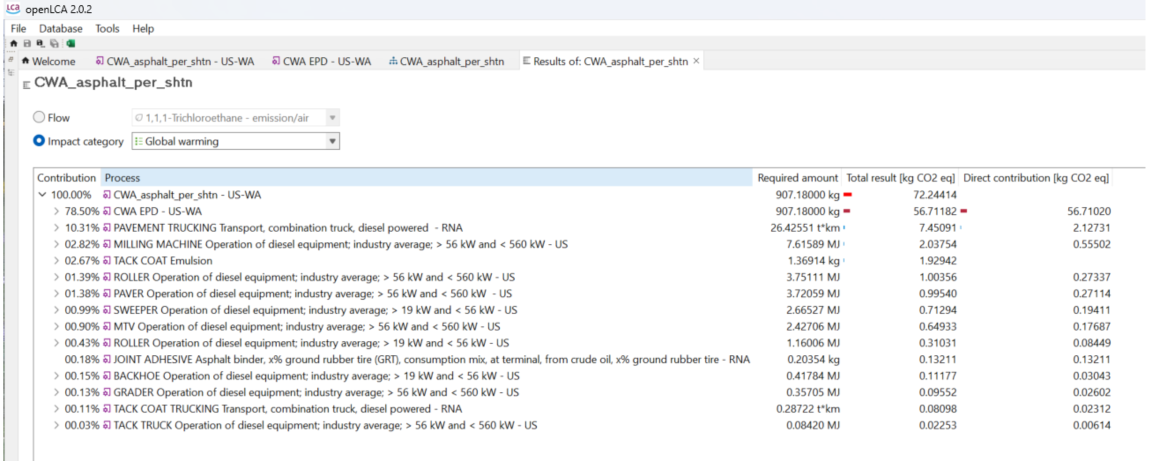
- 56.710 kg CO2 eq: CWA EPD - US-WA
- 2.127 kg CO2 eq: PAVEMENT TRUCKING Transport, combination truck, diesel powered - RNA
- 2.062 kg CO2 eq: Natural gas, at processing, shale, kg - US
- 2.039 kg CO2 eq: Natural gas, at processing, conventional, kg - US
- 1.594 kg CO2 eq: Natural gas, at extraction, conventional onshore, kg - US
- 7.712 kg CO2 eq: Other

Top 5 contributions to flow results - overview

Flow: 1,1,1-Trichloroethane - emission/air

- 1.083E-11 kg: Bituminous coal, combusted in industrial boiler - RNA
- 8.131E-14 kg: Lignite coal, combusted in industrial boiler - RNA
- 1.734E-19 kg: Asphalt binder, no additives, consumption mix, at terminal, from crude oil - RNA

Figure 39 - openLCA Calculation Result Graphs



CWA_asphalt_per_shtn

○ Flow: 1,1,1-Trichloroethane - emission/air
● Impact category: Global warming

Contribution	Process	Required amount	Total result [kg CO2 eq]	Direct contribution [kg CO2 eq]
100.00%	CWA_asphalt_per_shtn - US-WA	907.18000 kg	72.24414	
78.50%	CWA EPD - US-WA	907.18000 kg	56.71182	56.71020
10.31%	PAVEMENT TRUCKING Transport, combination truck, diesel powered - RNA	26.42551 t*km	7.45091	2.12731
02.82%	MILLING MACHINE Operation of diesel equipment; industry average; > 56 kW and < 560 kW - US	7.61589 MJ	2.03754	0.55502
02.67%	TACK COAT Emulsion	1.36914 kg	1.92942	
01.39%	ROLLER Operation of diesel equipment; industry average; > 56 kW and < 560 kW - US	3.75111 MJ	1.00356	0.27337
01.38%	PAVER Operation of diesel equipment; industry average; > 56 kW and < 560 kW - US	3.72059 MJ	0.99540	0.27114
00.99%	SWEEPER Operation of diesel equipment; industry average; > 19 kW and < 56 kW - US	2.66527 MJ	0.71294	0.19411
00.90%	MTV Operation of diesel equipment; industry average; > 56 kW and < 560 kW - US	2.42706 MJ	0.64933	0.17687
00.43%	ROLLER Operation of diesel equipment; industry average; > 19 kW and < 56 kW - US	1.16006 MJ	0.31031	0.08449
00.18%	JOINT ADHESIVE Asphalt binder, x% ground rubber tire (GRT), consumption mix, at terminal, from crude oil, x% ground rubber tire - RNA	0.20354 kg	0.13211	0.13211
00.15%	BACKHOE Operation of diesel equipment; industry average; > 19 kW and < 56 kW - US	0.41784 MJ	0.11177	0.03043
00.13%	GRADER Operation of diesel equipment; industry average; > 56 kW and < 560 kW - US	0.35705 MJ	0.09552	0.02602
00.11%	TACK COAT TRUCKING Transport, combination truck, diesel powered - RNA	0.28722 t*km	0.08098	0.02312
00.03%	TACK TRUCK Operation of diesel equipment; industry average; > 56 kW and < 560 kW - US	0.08420 MJ	0.02253	0.00614

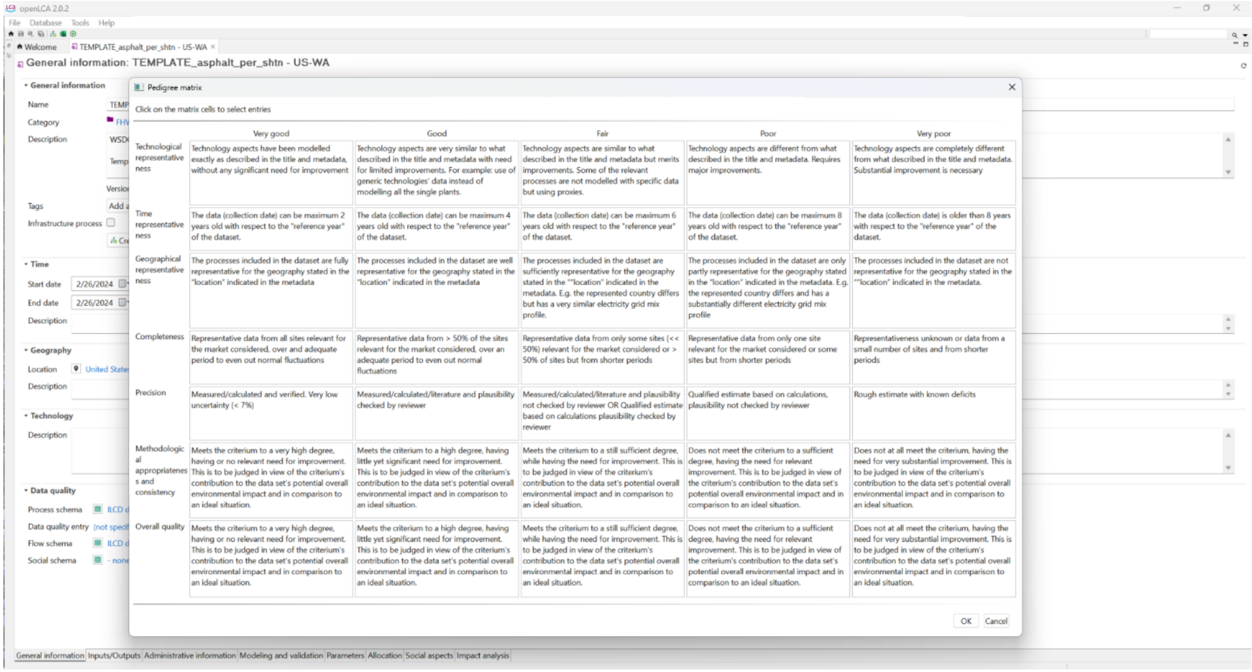
Figure 40 - openLCA Calculation Result Contribution Tree

3.4 Data Quality Analysis

Data quality analysis was completed for the input variables at the end of the data collection and LCA calculation process. Input variables were assessed based on openLCA's pedigree matrix from the ILCD data quality systems and the FHWA Climate Challenge's Data Quality Assessment for Background Data document (Mukherjee n.d.). Input variables were given a rating for each of the categories in Table 19 based on the descriptions in the matrix and the questions presented in Table 20. Since the categories of Table 20 do not directly match with Table 19, the following rows were grouped together (Table 18). Figure 41 shows an example of how the pedigree matrix of Table 19 was utilized in openLCA.

Table 18 - Data Quality Assessment Category Correlations

openLCA Pedigree Matrix	FHWA Data Quality Assessment Associated Categories
Technological Representativeness	Technology of Data
Time Representativeness	Time Period of Data
Geographical Representativeness	Geography of Data
Completeness	Process Completeness Process Review Data Collection Methods
Precision	Reliability of Data
Methodological Appropriateness and Consistency	n/a
Overall Quality	n/a



Click on the matrix cells to select entries

	Very good	Good	Fair	Poor	Very poor
Technological representativeness	Technology aspects have been modelled exactly as described in the title and metadata, without any significant need for improvement	Technology aspects are very similar to what described in the title and metadata with need for limited improvements. For example: use of generic technologies' data instead of modelling all the single plants.	Technology aspects are similar to what described in the title and metadata but merits improvements. Some of the relevant processes are not modelled with specific data but using proxies.	Technology aspects are different from what described in the title and metadata. Requires major improvements.	Technology aspects are completely different from what described in the title and metadata. Substantial improvement is necessary
Time representativeness	The data (collection date) can be maximum 2 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the dataset.	The data (collection date) is older than 8 years with respect to the "reference year" of the dataset.
Geographical representativeness	The processes included in the dataset are fully representative for the geography stated in the "location" indicated in the metadata	The processes included in the dataset are well representative for the geography stated in the "location" indicated in the metadata	The processes included in the dataset are sufficiently representative for the geography stated in the ""location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.	The processes included in the dataset are only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different electricity grid mix profile	The processes included in the dataset are not representative for the geography stated in the ""location" indicated in the metadata.
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Precision	Measured/calculated and verified. Very low uncertainty (< 7%)	Measured/calculated/literature and plausibility checked by reviewer	Measured/calculated/literature and plausibility not checked by reviewer OR Qualified estimate based on calculations plausibility checked by reviewer	Qualified estimate based on calculations, plausibility not checked by reviewer	Rough estimate with known deficits
Methodological appropriateness and consistency	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a still sufficient degree, while having the need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Overall quality	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a still sufficient degree, while having the need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.

Figure 41 - openLCA Data Quality Entry Example

Table 19 - openLCA Pedigree Matrix (ILCD)

	Very Good	Good	Fair	Poor	Very Poor
Technological Representatives	Technology aspects have been modelled exactly as described in the title and metadata, without any significant need for improvement	Technology aspects are very similar to what described in the title and metadata with need for limited improvements. For example: use of generic technologies' data instead of modelling all the single plants.	Technology aspects are similar to what described in the title and metadata but merits improvements. Some of the relevant processes are not modelled with specific data but using proxies.	Technology aspects are different from what described in the title and metadata. Requires major improvements.	Technology aspects are completely different from what described in the title and metadata. Substantial improvement in necessary.
Time Representativeness	The data (collection date) can be maximum 2 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the dataset.	The data (collection date) is older than 8 years with respect to the "reference year" of the dataset.
Geographical Representativeness	The processes included in the dataset are fully representative for the geography stated in the "location" indicated in the metadata	The processes included in the dataset are well representative for the geography stated in the "location" indicated in the metadata	The processes included in the dataset are sufficiently representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.	The processes included in the dataset are only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different electricity grid mix profile	The processes included in the dataset not representative for the geography stated in the "location" indicated in th metadata.
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Precision	Measured/calculated and verified. Very low uncertainty (< 7%)	Measured/calculated/literature and plausibility checked by reviewer	Measured/calculated/literature and plausibility not checked by reviewer OR Qualified estimate based on calculations plausibility checked by reviewer	Qualified estimate based on calculations, plausibility not checked by reviewer	Rough estimate with known deficits
Methodological Appropriateness and Consistency	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact an in comparison to an ideal situation.
Overall Quality	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact an in comparison to an ideal situation.

Table 20 - FHWA Data Quality Assessment (Mukherjee n.d.)

Reliability	Is the inventory data checked for mass/ energy balance, recalculation etc.?	Verified data based on measurements	Verified data based on a calculation or unverified data based on measurements	Non-verified data based on a calculation	Documented estimate	Undocumented estimate
	What is the status quo for the ownership and continuous support of data?	Hosts and Owns	Owns but does not host	Hosts but does not owns	Hosts and owns partially	Does not host or own
	Is the data regularly updated?	Regular updates	Less frequent updates	No updates		
	Is the data of deterministic nature or are there statistically established confidence intervals stated for the data?	Confidence Intervals developed considering parameter, scenario and model uncertainty based on directly measured or calculated data	Confidence Intervals developed considering either of parameter, scenario and model uncertainty based on assumed probability distribution	Deterministic value provided	n/a	n/a
Data Collection Methods	How representative is the data of the market?	Representative data from >80% of the relevant market, over an adequate period	Representative data from 60-79% of the relevant market, over an adequate period OR representative data from >80% of the relevant market, over a shorter period	Representative data from 40-59% of the relevant market, over an adequate period OR representative data from 60-79% of the relevant market, over a shorter period	Representative data from <40% of the relevant market, over an adequate period OR representative data from 40-59% of the relevant market, over a shorter period	Unknown OR data from a small number of sites and from shorter periods
	How compatible is the life-cycle inventory data with TRACI 2.1 impact assessment method from LCA Commons?	Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method	Life-cycle inventory data is enough to calculate only 6 out of 9 mid-point indicators as per TRACI 2.1 impact assessment method	Life-cycle inventory data is enough to calculate only 3 out of 9 mid-point indicators as per TRACI 2.1 impact assessment method	Life-cycle inventory data is not compatible with TRACI 2.1 impact assessment method from LCA Commons	n/a
Time Period of Data	Does the data capture seasonal variations?	All three (fall, spring and summer) seasons are covered	Only two out of three seasons are covered	Only one season is covered	Not Specified	n/a
	How well is the time period the data correlated with the data quality objective?	Less than 3 years of difference	Less than 6 years of difference	Less than 10 years of difference	Less than 10 years of difference	Age of data unknown or more than 15 years
	How old is the data at the time of data quality assessment?	Less than 3 years old	Less than 6 years old	Less than 10 years old	Less than 12 years old	Age of data unknown or more than 15 years
Geography of Data	How well is the geography of the data correlated with the data quality objective?	Data from same resolution AND same area of study	Within one level of resolution AND a related area of study	Within two levels of resolution AND a related area of study	Outside of two levels of resolution BUT a related area of study	From a different or unknown area of study
	What is the regional granularity associated with the data	State level	Country level	Continental level	Global level	Data granularity unknown
Technology of Data	How well is the technology of the data correlated with the data quality objective?	All technology categories are equivalent	Three of the technology categories are equivalent	Two of the technology categories are equivalent	One of the technology categories are equivalent	None of the technology categories are equivalent
	How well is the technology of the data described?	Specified	Not Specified	n/a	n/a	n/a
Process Review	How well is the process reviewed?	The process has documented reviews by a minimum of two types of third-party reviewers	The process has documented reviews by a minimum of two types of reviewers, with one being a third party	The process has documented review by a third-party reviewer	The process has documented review by an internal reviewer	The process has no documented review
Process Completeness	How complete is the process?	>80% of determined flows within the process have been evaluated and given a value	60-79% of determined flows within the process have been evaluated and given a value	40-59% of determined flows within the process have been evaluated and given a value	<40% of determined flows within the process have been evaluated and given a value	Process completeness not scored

4 RESULTS

This section will present an overview of each case study project information, description of work, pre-work condition, equipment used on the project site, calculated LCA GWP results, and a comparison of all four project's LCA results.

4.1 Contract 9914 Results

Table 21 shows the calculated environmental impact of the project's paving activities per short ton of asphalt, not the impact of the project in its entirety. Table 22, Figure 54, Figure 55, and Figure 56 shows the calculated GWP impact for Contract 9914 normalized per short ton of asphalt, the total GWP for the entire project, and the specific percent contribution for each piece of equipment/material modeled. Table 22 also categories each material and piece of equipment utilized in the environmental impact calculations into the following life cycle stages: material (A1-A3), transportation (A4), or construction (A5), shown in Figure 57. Figure 42 then shows a Sankey diagram which visually depicts the flows and corresponding processes through the LCA stages for the global warming impact category.

Table 21 - 9914 TRACI 2.1 Impact Category Results Per Short Ton

TRACI 2.1 Impact Category	Impact	Unit
Acidification	0.34	kg SO_2 eq
Eutrophication	0.013	kg N eq
Freshwater ecotoxicity	6.81	CTUeco
Global warming	81.86	kg CO_2 eq
Human health - cancer	3.52E-09	CTUcancer
Human health - non-cancer	5.64E-07	CTUnoncancer
Human health - particulate matter	0.014	PM 2.5 eq
Ozone depletion	1.25E-07	kg CFC-11 eq
Smog formation	5.71	kg O_3 eq

Table 22 - 9914 Categorized GWP Results

LCA Stage - Associated Equipment/Material	**GWP [kg CO_2 eq] per short ton**	**Total GWP [kg CO_2 eq]**	**% contribution [kg CO_2 eq]**
Construction (A5) - Milling Machine	2.01	66,404.46	2.45%
Construction (A5) - MTV	0.73	24,272.48	0.90%
Construction (A5) - Paver	1.00	33,044.88	1.22%
Construction (A5) - Roller	1.85	61,425.23	2.27%
Construction (A5) - Tack Truck	0.35	11,660.12	0.43%
Construction (A5) - Backhoe	0.00	0.00	0.00%
Construction (A5) - Water Truck	0.56	18,581.26	0.69%
Construction (A5) - Loader	1.55	51,184.22	1.89%
Construction (A5) - Sweeper	0.08	2,668.20	0.10%
Construction (A5) - Grader	0.00	0.00	0.00%
Material (A1-A3) - Asphalt Emulsion	2.14	70,909.68	2.62%
Material (A1-A3) - Joint Adhesive	0.08	2,644.26	0.10%
Transportation (A4) - HMA Trucking	12.97	429,446.02	15.84%
Transportation (A4) - Asphalt Emulsion Trucking	0.11	3,729.63	0.14%
Material (A1) - HMA	38.63	1,279,358.00	47.20%
Material (A2) - HMA	0.82	27,156.97	1.00%
Material (A3) - HMA	18.97	628,253.20	23.18%
Grand Total	81.85	2,710,738.61	100.00%

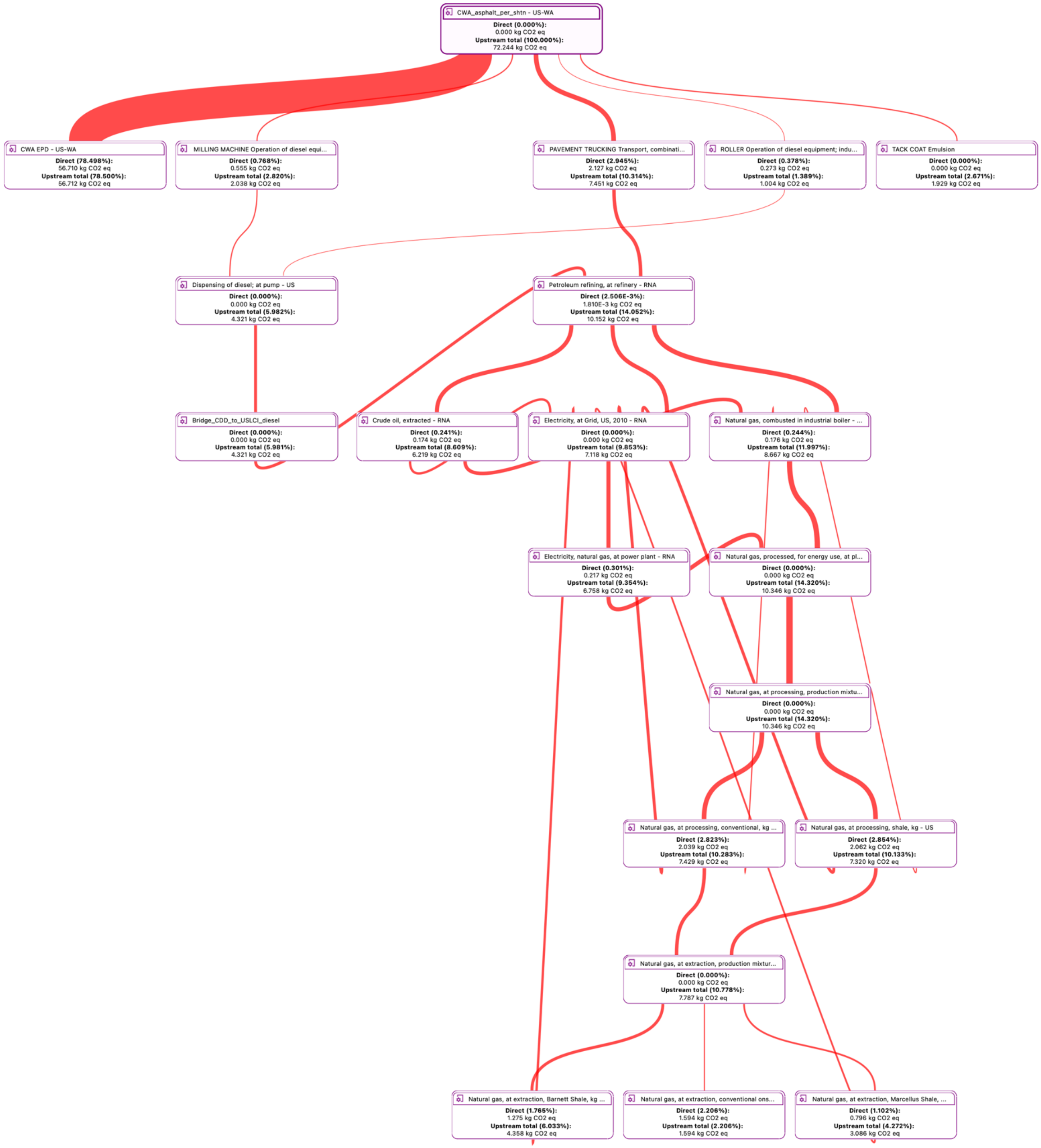


Figure 42 - 9914 GWP Sankey Diagram

4.2 Contract 9954 Results

Table 23 shows the calculated environmental impact of the project's paving activities per short ton of asphalt, not the impact of the project in its entirety. Table 24, Figure 58, Figure 59, and Figure 60 show the calculated GWP impact for Contract 9954 normalized per short ton of asphalt, the total GWP for the entire project, and the specific contribution for each piece of equipment/material modeled. Table 24 also categories each material and piece of equipment utilized in the environmental impact calculations into the following life cycle stages: material (A1-A3), transportation (A4), or construction (A5), shown in Figure 61. Figure 43 then shows a Sankey diagram which visually depicts the flows and corresponding processes through the LCA stages for the global warming impact category.

Table 23 - 9954 TRACI 2.1 Impact Category Results Per Short Ton

TRACI 2.1 Impact Category	**9954**	**Unit**
Acidification	0.31	kg SO_2 eq
Eutrophication	0.013	kg N eq
Freshwater ecotoxicity	7.10	CTUeco
Global warming	66.05	kg CO_2eq
Human health - cancer	3.28E-09	CTUcancer
Human health - non-cancer	5.61E-07	CTUnoncancer
Human health - particulate matter	0.012	PM 2.5 eq
Ozone depletion	8.95E-08	kg CFC-11 eq
Smog formation	6.04	kg O_3 eq

Table 24 - 9954 Categorized GWP Results

LCA Stage - Associated Equipment/Material	GWP [kg CO_2eq] per short ton	Total GWP [kg CO_2eq]	% contribution [kg CO_2eq]
Construction (A5) - Milling Machine	2.91	71,122.61	4.40%
Construction (A5) - MTV	1.93	47,246.49	2.93%
Construction (A5) - Paver	1.45	35,333.15	2.19%
Construction (A5) - Roller	1.24	30,305.95	1.88%
Construction (A5) - Tack Truck	0.71	17,301.53	1.07%
Construction (A5) - Backhoe	0.33	7,983.97	0.49%
Construction (A5) - Water Truck	0.03	745.30	0.05%
Construction (A5) - Loader	0.02	418.28	0.03%
Construction (A5) - Sweeper	0.00	0.00	0.00%
Construction (A5) - Grader	0.00	0.00	0.00%
Material (A1-A3) - Asphalt Emulsion	1.54	37,634.88	2.33%
Material (A1-A3) - Joint Adhesive	0.00	0.00	0.00%
Transportation (A4) - HMA Trucking	14.41	352,299.78	21.82%
Transportation (A4) - Asphalt Emulsion Trucking	0.05	1,202.16	0.07%
Material (A1) - HMA	21.35	522,049.35	32.33%
Material (A2) - HMA	2.63	64,308.65	3.98%
Material (A3) - HMA	17.46	426,931.22	26.44%
Grand Total	66.04	1,614,883.31	100.00%

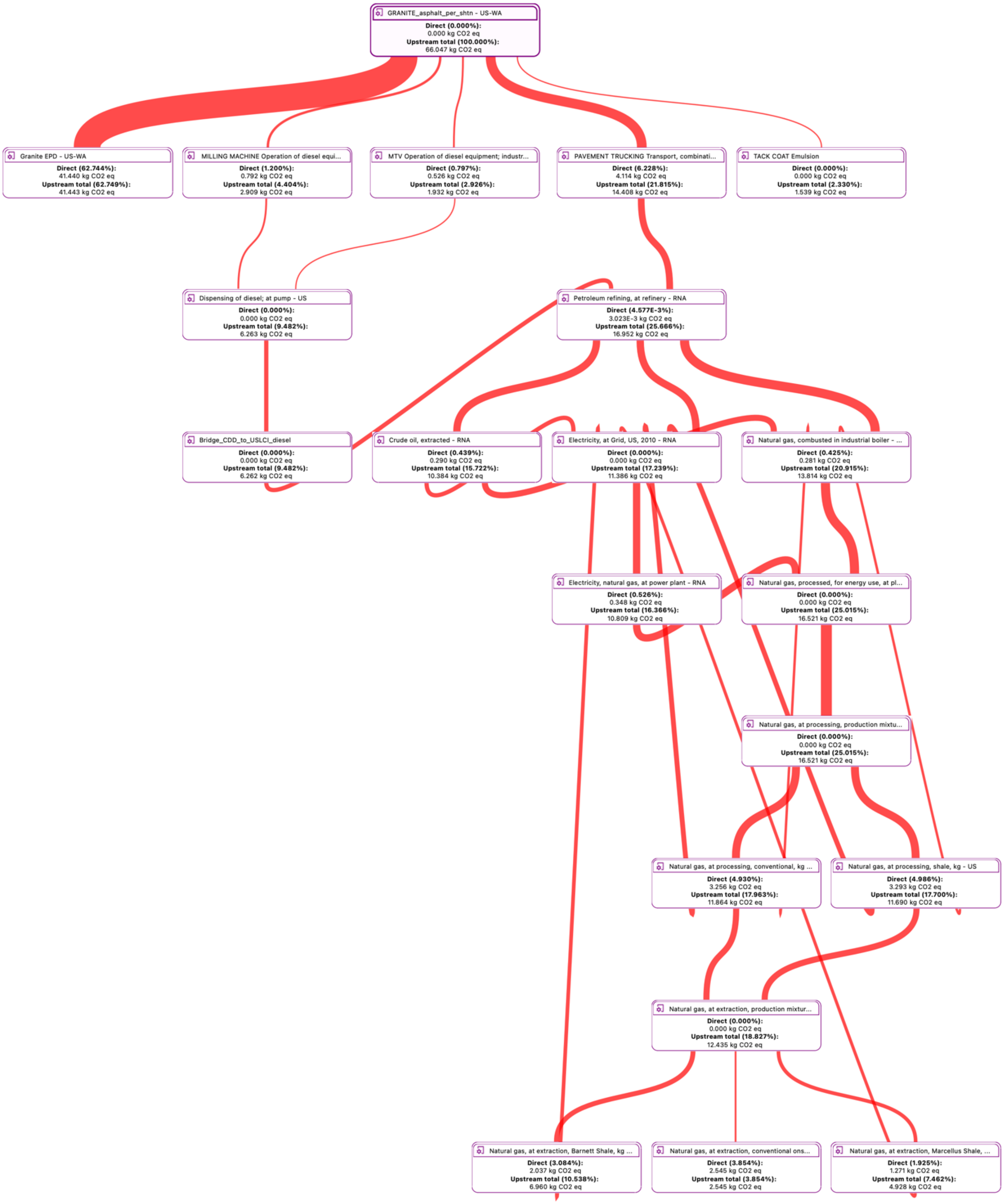


Figure 43 - 9954 GWP Sankey Diagram

4.3 Contract XE3404 Results

Table 25 shows the calculated environmental impact of the project's paving activities per short ton of asphalt, not the impact of the project in its entirety. Figure 62, Figure 63, and Figure 64 shows the calculated GWP impact for Contract XE3404 normalized per short ton of asphalt, the total GWP for the entire project, and the specific percent contribution for each piece of equipment/material modeled.

Table 26 also categories each material and piece of equipment utilized in the environmental impact calculations into the following life cycle stages: material (A1-A3), transportation (A4), or construction (A5), shown in Figure 65. Figure 44 then shows a Sankey diagram which visually depicts the flows and corresponding processes through the LCA stages for the global warming impact category.

Table 25 - XE3404 TRACI 2.1 Impact Category Results Per Short Ton

TRACI 2.1 Impact Category	Impact	Unit
Acidification	0.37	kg SO_2 eq
Eutrophication	0.015	kg N eq
Freshwater ecotoxicity	8.33	CTUeco
Global warming	78.29	kg CO_2 eq
Human health - cancer	4.04E-09	CTUcancer
Human health - non-cancer	6.7E-07	CTUnoncancer
Human health - particulate matter	0.014	PM 2.5 eq
Ozone depletion	9.9E-08	kg CFC-11 eq
Smog formation	7.05	kg O_3 eq

Table 26 - XE3404 Categorized GWP Results

LCA Stage - Associated Equipment/Material	GWP [kg CO_2 eq] per short ton	Total GWP [kg CO_2 eq]	% contribution [kg CO_2 eq]
Construction (A5) - Milling Machine	3.20	92,340.97	4.09%
Construction (A5) - MTV	1.89	54,613.09	2.42%
Construction (A5) - Paver	1.05	30,340.60	1.34%
Construction (A5) - Roller	1.77	51,143.38	2.26%
Construction (A5) - Tack Truck	0.30	8,668.74	0.38%
Construction (A5) - Backhoe	0.00	0.00	0.00%
Construction (A5) - Water Truck	0.00	0.00	0.00%
Construction (A5) - Loader	0.00	0.00	0.00%
Construction (A5) - Sweeper	1.88	54,179.65	2.40%
Construction (A5) - Grader	0.00	0.00	0.00%
Material (A1-A3) - Asphalt Emulsion	2.11	60,827.61	2.69%
Material (A1-A3) - Joint Adhesive	0.00	0.00	0.00%
Transportation (A4) - HMA Trucking	16.47	475,078.64	21.03%
Transportation (A4) - Asphalt Emulsion Trucking	0.09	2,553.12	0.11%
Material (A1) - HMA	30.14	869,597.17	38.50%
Material (A2) - HMA	1.84	53,087.55	2.35%
Material (A3) - HMA	17.55	506,351.37	22.42%
Grand Total	78.29	2,258,781.89	100.00%

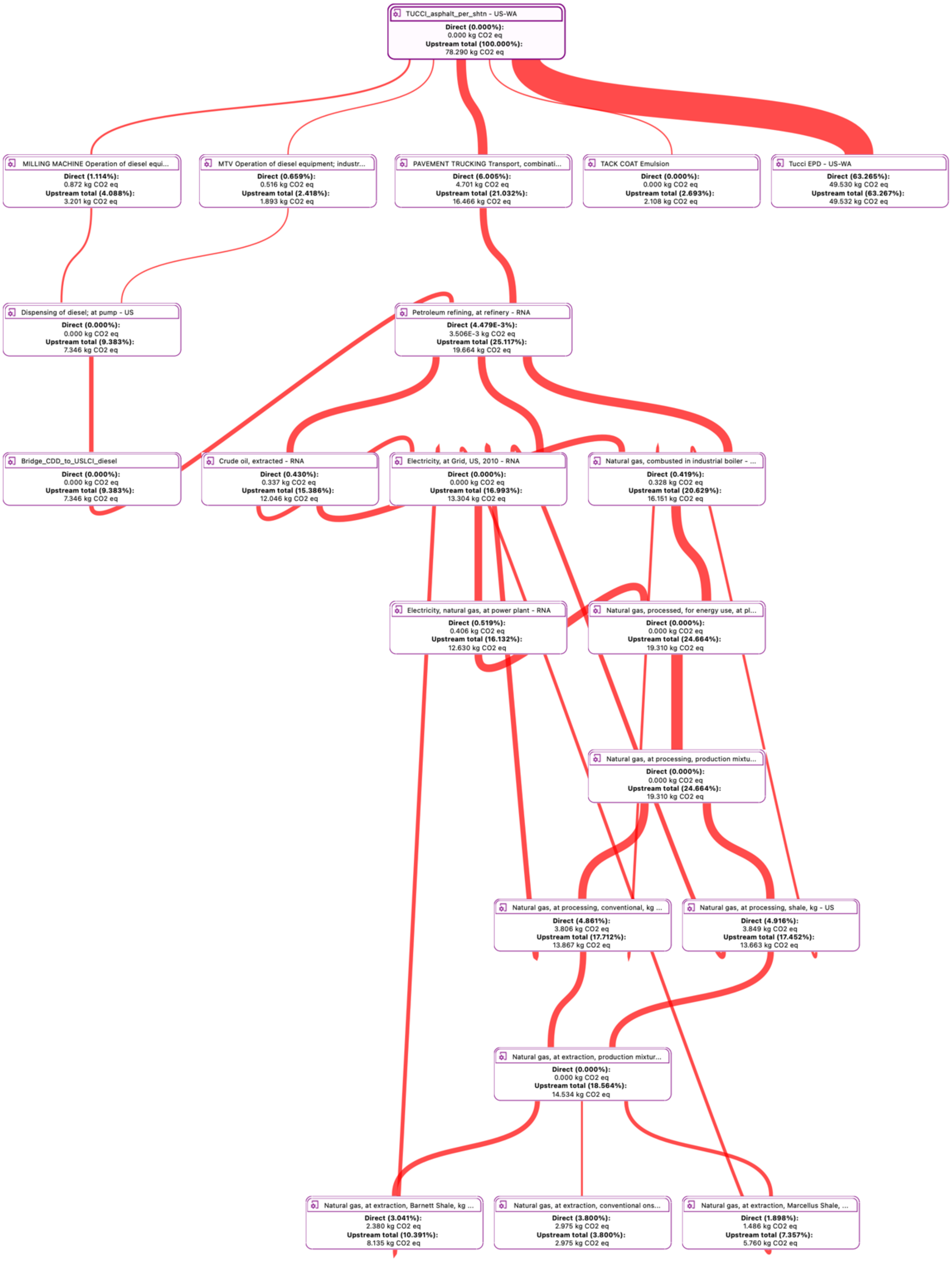


Figure 44 - XE3404 GWP Sankey Diagram

4.4 Contract XE3419 Results

Table 27 shows the calculated environmental impact of the project's paving activities per short ton of asphalt, not the impact of the project in its entirety. Table 28, Figure 66, Figure 67, and Figure 68 shows the calculated GWP impact for Contract XE3419 normalized per short ton of asphalt, the total GWP for the entire project, and the specific percent contribution for each piece of equipment/material modeled. Table 28 also categories each material and piece of equipment utilized in the environmental impact calculations into the following life cycle stages: material (A1-A3), transportation (A4), or construction (A5), shown in Figure 69. Figure 45 then shows a Sankey diagram which visually depicts the flows and corresponding processes through the LCA stages for the global warming impact category.

Table 27 - XE3419 TRACI 2.1 Impact Category Results Per Short Ton

TRACI 2.1 Impact Category	Impact	Unit
Acidification	0.28	kg SO2 eq
Eutrophication	0.0094	kg N eq
Freshwater ecotoxicity	4.54	CTUeco
Global warming	72.24	kg CO_2 eq
Human health - cancer	2.88E-09	CTUcancer
Human health - non-cancer	3.97E-07	CTUnoncancer
Human health - particulate matter	0.013	PM 2.5 eq
Ozone depletion	7.5E-07	kg CFC-11 eq
Smog formation	3.75	kg O_3 eq

Table 28 - XE3419 Categorized GWP Results

LCA Stage - Associated Equipment/Material	GWP [kg CO_2 eq] per short ton	Total GWP [kg CO_2 eq]	% contribution [kg CO_2 eq]
Construction (A5) - Milling Machine	2.04	68,181.56	2.81%
Construction (A5) - MTV	0.65	21,728.40	0.89%
Construction (A5) - Paver	1.00	33,308.71	1.37%
Construction (A5) - Roller	1.31	43,965.73	1.81%
Construction (A5) - Tack Truck	0.34	11,307.19	0.47%
Construction (A5) - Backhoe	0.11	3,740.12	0.15%
Construction (A5) - Water Truck	0.00	0.00	0.00%
Construction (A5) - Loader	0.00	0.00	0.00%
Construction (A5) - Sweeper	0.71	23,856.85	0.98%
Construction (A5) - Grader	0.10	3,196.51	0.13%
Material (A1-A3) - Asphalt Emulsion	1.93	64,563.52	2.66%
Material (A1-A3) - Joint Adhesive	0.13	4,420.61	0.18%
Transportation (A4) - HMA Trucking	7.45	249,327.29	10.27%
Transportation (A4) - Asphalt Emulsion Trucking	0.08	2,709.92	0.11%
Material (A1) - HMA	31.09	1,040,354.41	43.85%
Material (A2) - HMA	1.55	51,867.14	2.14%
Material (A3) - HMA	24.07	805,446.47	33.17%
Grand Total	72.24	2,427,974.40	100.00%

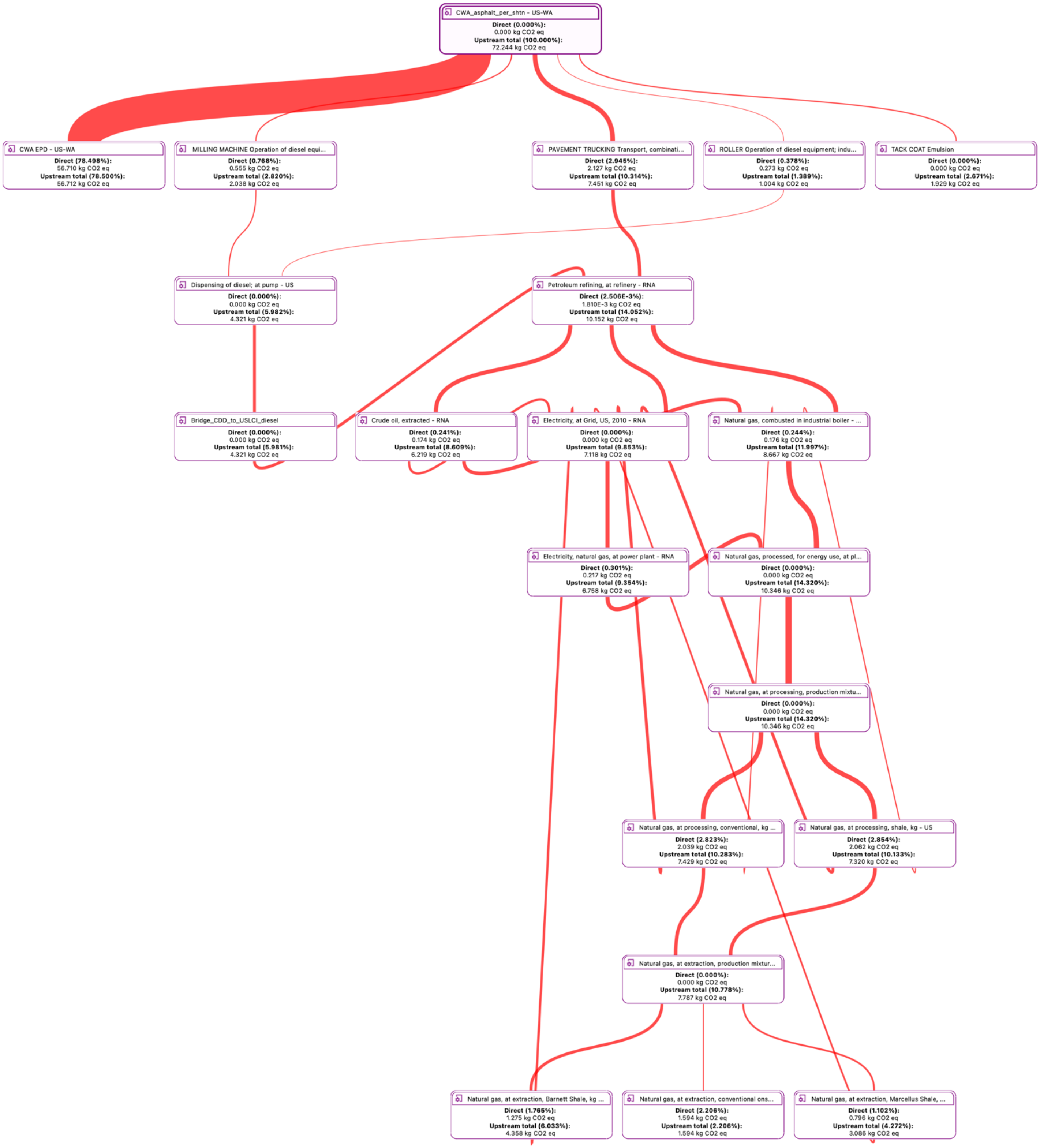


Figure 45 - XE3419 GWP Sankey Diagram

4.5 Project Comparison

The tables and figures in this section contain all the values shown in the individual project's section and compare them to each other. Additionally, an averaged calculation of the 4 different projects is shown in the second column of the tables and first bar of the graphs. These comparisons show the calculated GWP impact per contract normalized per short ton of asphalt, the total GWP for the entire project, the specific percent contribution for each piece of equipment/material modeled, and the project's breakdown by life cycle stage.

Table 29 – GWP (kg CO_2 eq) Per Short Ton Asphalt Comparison

LCA Stage - Associated Equipment/Material	Average	9914	9954	XE3404	XE3419
Construction (A5) - Milling Machine	2.54	2.01	2.91	3.20	2.04
Construction (A5) - MTV	1.30	0.73	1.93	1.89	0.65
Construction (A5) - Paver	1.12	1.00	1.45	1.05	1.00
Construction (A5) - Roller	1.55	1.85	1.24	1.77	1.31
Construction (A5) - Tack Truck	0.42	0.35	0.71	0.30	0.34
Construction (A5) - Backhoe	0.11	0.00	0.33	0.00	0.11
Construction (A5) - Water Truck	0.15	0.56	0.03	0.00	0.00
Construction (A5) - Loader	0.39	1.55	0.02	0.00	0.00
Construction (A5) - Sweeper	0.67	0.08	0.00	1.88	0.71
Construction (A5) - Grader	0.02	0.00	0.00	0.00	0.10
Material (A1-A3) - Asphalt Emulsion	1.93	2.14	1.54	2.11	1.93
Material (A1-A3) - Joint Adhesive	0.05	0.08	0.00	0.00	0.13
Transportation (A4) - HMA Trucking	12.82	12.97	14.41	16.47	7.45
Transportation (A4) - Asphalt Emulsion Trucking	0.08	0.11	0.05	0.09	0.08
Material (A1) - HMA	30.30	38.63	21.35	30.14	31.09
Material (A2) - HMA	1.71	0.82	2.63	1.84	1.55
Material (A3) - HMA	19.51	18.97	17.46	17.55	24.07
Grand Total	74.61	81.85	66.04	78.29	72.24

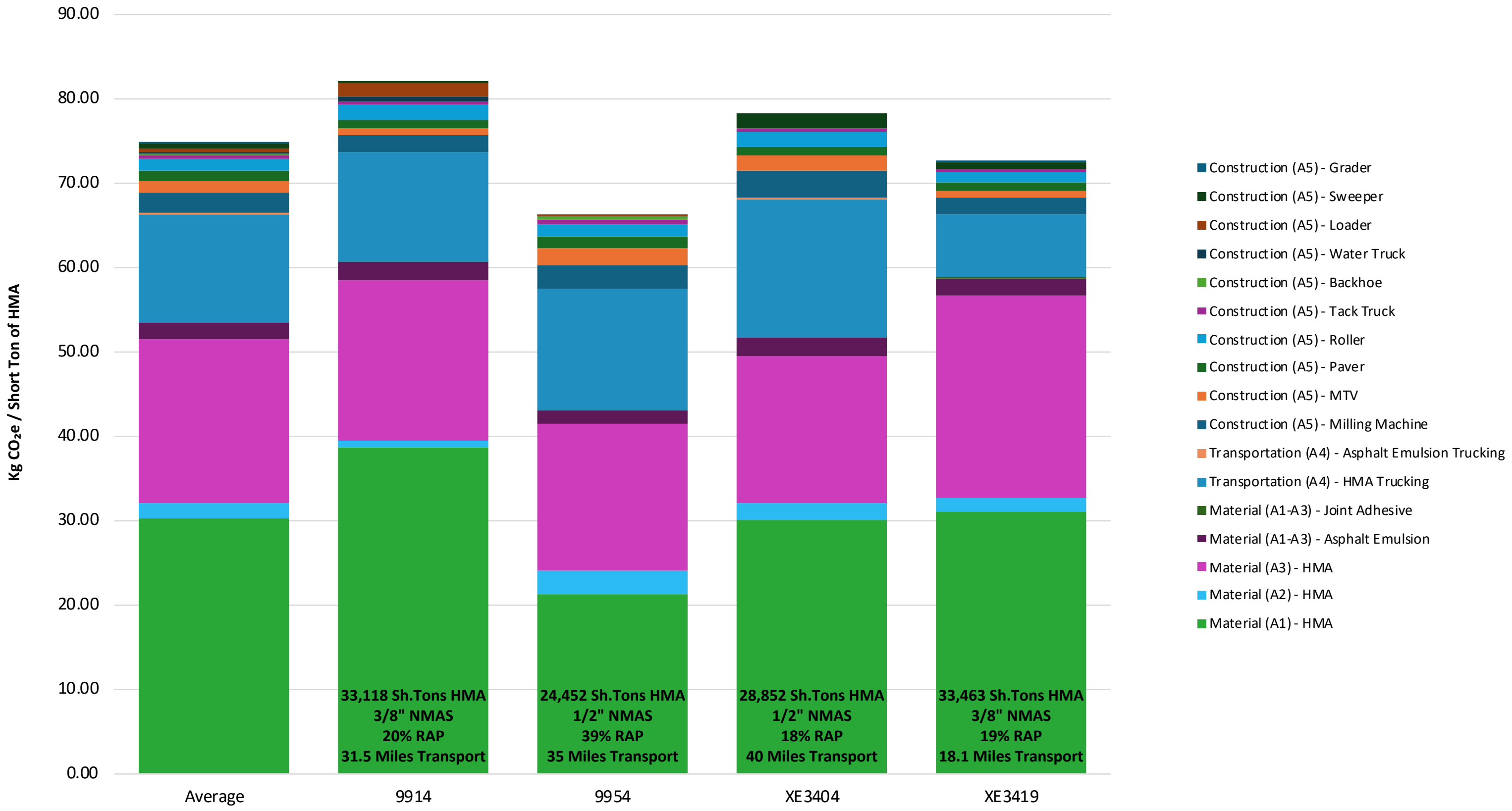


Figure 46 - GWP (kg CO_2 eq) Per Short Ton Asphalt Comparison

Table 30 - Project Total GWP (kg CO_2 eq) Comparison

LCA Stage - Associated Equipment/Material	Average	9914	9954	XE3404	XE3419
Construction (A5) - Milling Machine	74,512.40	66,404.46	71,122.61	92,340.97	68,181.56
Construction (A5) - MTV	36,965.11	24,272.48	47,246.49	54,613.09	21,728.40
Construction (A5) - Paver	33,006.83	33,044.88	35,333.15	30,340.60	33,308.71
Construction (A5) - Roller	46,710.07	61,425.23	30,305.95	51,143.38	43,965.73
Construction (A5) - Tack Truck	9,596.05	11,660.12	17,301.53	8,668.74	11,307.19
Construction (A5) - Backhoe	2,931.02	0.00	7,983.97	0.00	3,740.12
Construction (A5) - Water Truck	4,831.64	18,581.26	745.30	0.00	0.00
Construction (A5) - Loader	12,900.63	51,184.22	418.28	0.00	0.00
Construction (A5) - Sweeper	20,176.17	2,668.20	0.00	54,179.65	23,856.85
Construction (A5) - Grader	799.13	0.00	0.00	0.00	3,196.51
Material (A1-A3) - Asphalt Emulsion	58,483.92	70,909.68	37,634.88	60,827.61	64,563.52
Material (A1-A3) - Joint Adhesive	1,766.22	2,644.26	0.00	0.00	4,420.61
Transportation (A4) - HMA Trucking	376,537.93	429,446.02	352,299.78	475,078.64	249,327.29
Transportation (A4) - Asphalt Emulsion Trucking	2,548.71	3,729.63	1,202.16	2,553.12	2,709.92
Material (A1) - HMA	927,839.73	1,279,358.00	522,049.35	869,597.17	1,040,354.41
Material (A2) - HMA	49,105.08	27,156.97	64,308.65	53,087.55	51,867.14
Material (A3) - HMA	591,745.57	628,253.20	426,931.22	506,351.37	805,446.47
Grand Total	2,250,456.21	2,710,738.61	1,614,883.31	2,258,781.89	2,427,974.40

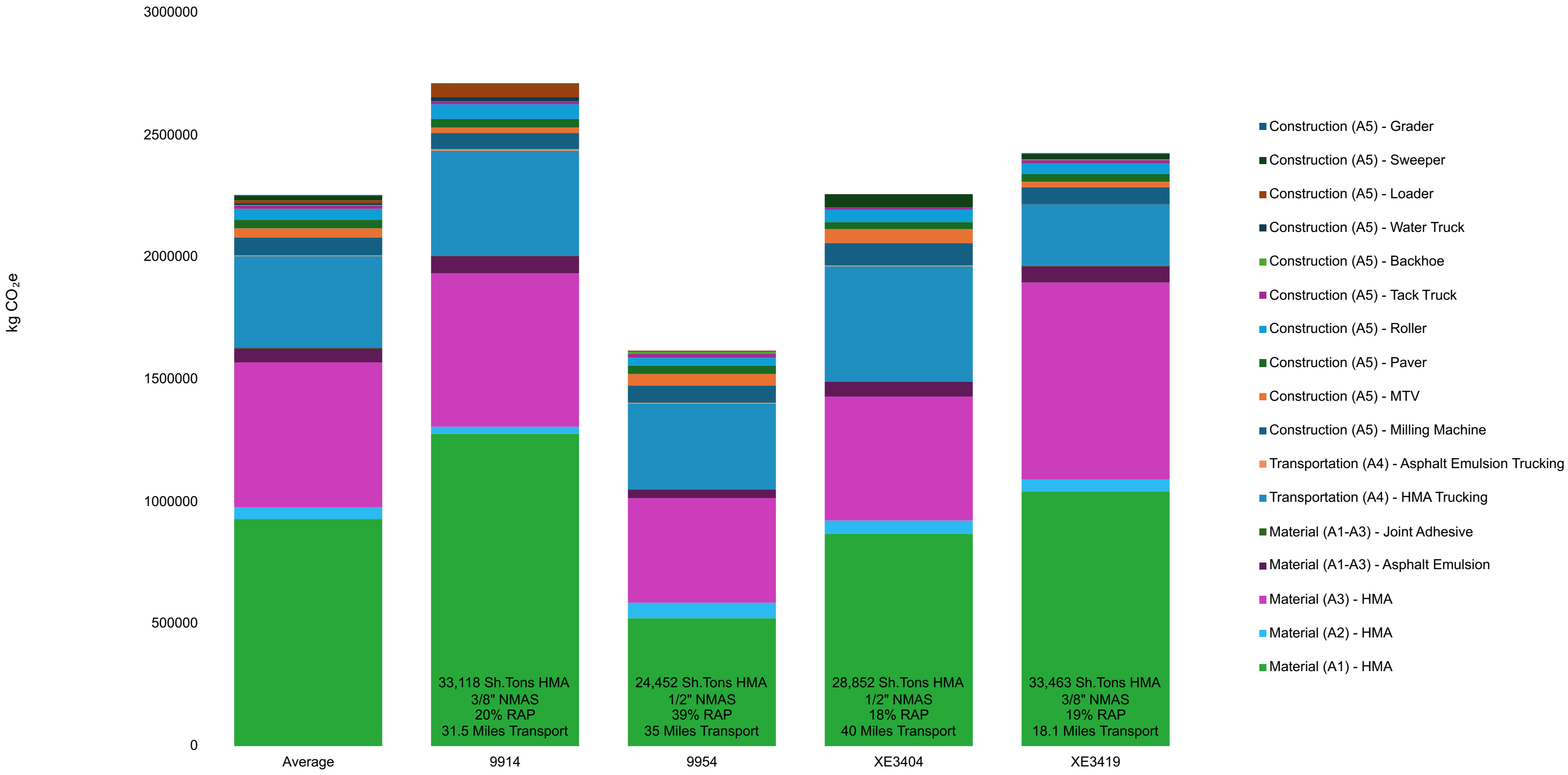


Figure 47 - Project Total GWP (kg CO$_2$ eq) Comparison

Table 31 - GWP (kg CO_2 eq) Precent Contribution Comparison

LCA Stage - Associated Equipment/Material	**Average**	**9914**	**9954**	**XE3404**	**XE3419**
Construction (A5) - Milling Machine	3.44%	2.45%	4.40%	4.09%	2.81%
Construction (A5) - MTV	1.78%	0.90%	2.93%	2.42%	0.89%
Construction (A5) - Paver	1.53%	1.22%	2.19%	1.34%	1.37%
Construction (A5) - Roller	2.06%	2.27%	1.88%	2.26%	1.81%
Construction (A5) - Tack Truck	0.48%	0.43%	1.07%	0.38%	0.47%
Construction (A5) - Backhoe	0.16%	0.00%	0.49%	0.00%	0.15%
Construction (A5) - Water Truck	0.18%	0.69%	0.05%	0.00%	0.00%
Construction (A5) - Loader	0.48%	1.89%	0.03%	0.00%	0.00%
Construction (A5) - Sweeper	0.87%	0.10%	0.00%	2.40%	0.98%
Construction (A5) - Grader	0.03%	0.00%	0.00%	0.00%	0.13%
Material (A1-A3) - Asphalt Emulsion	2.58%	2.62%	2.33%	2.69%	2.66%
Material (A1-A3) - Joint Adhesive	0.07%	0.10%	0.00%	0.00%	0.18%
Transportation (A4) - HMA Trucking	17.25%	15.84%	21.82%	21.03%	10.27%
Transportation (A4) - Asphalt Emulsion Trucking	0.11%	0.14%	0.07%	0.11%	0.11%
Material (A1) - HMA	40.26%	47.20%	32.33%	38.50%	42.85%
Material (A2) - HMA	2.37%	1.00%	3.98%	2.35%	2.14%
Material (A3) - HMA	26.34%	23.18%	26.44%	22.42%	33.17%
Grand Total	100.00%	100.00%	100.00%	100.00%	100.00%

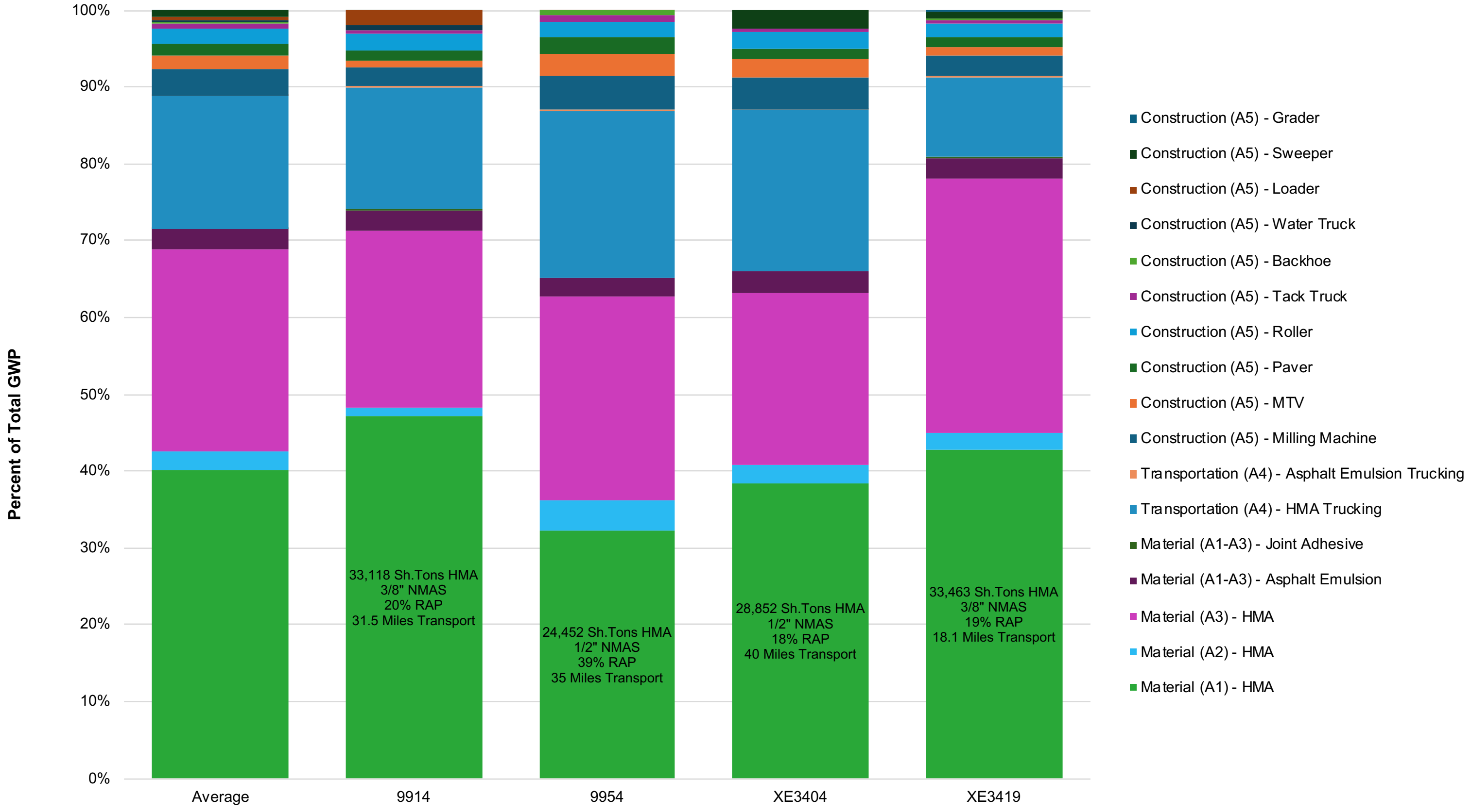


Figure 48 - GWP (kg CO$_2$ eq) Precent Contribution Comparison

Table 32 - GWP (kg CO_2 eq) by Life Cycle Stage Percent Contribution Comparison

Life Cycle Stage	Average	9914	9954	XE3404	XE3419
Material (A1-A3)	72%	74%	65%	66%	81%
Construction (A5)	11%	10%	13%	13%	9%
Transportation (A4)	17%	16%	22%	21%	10%

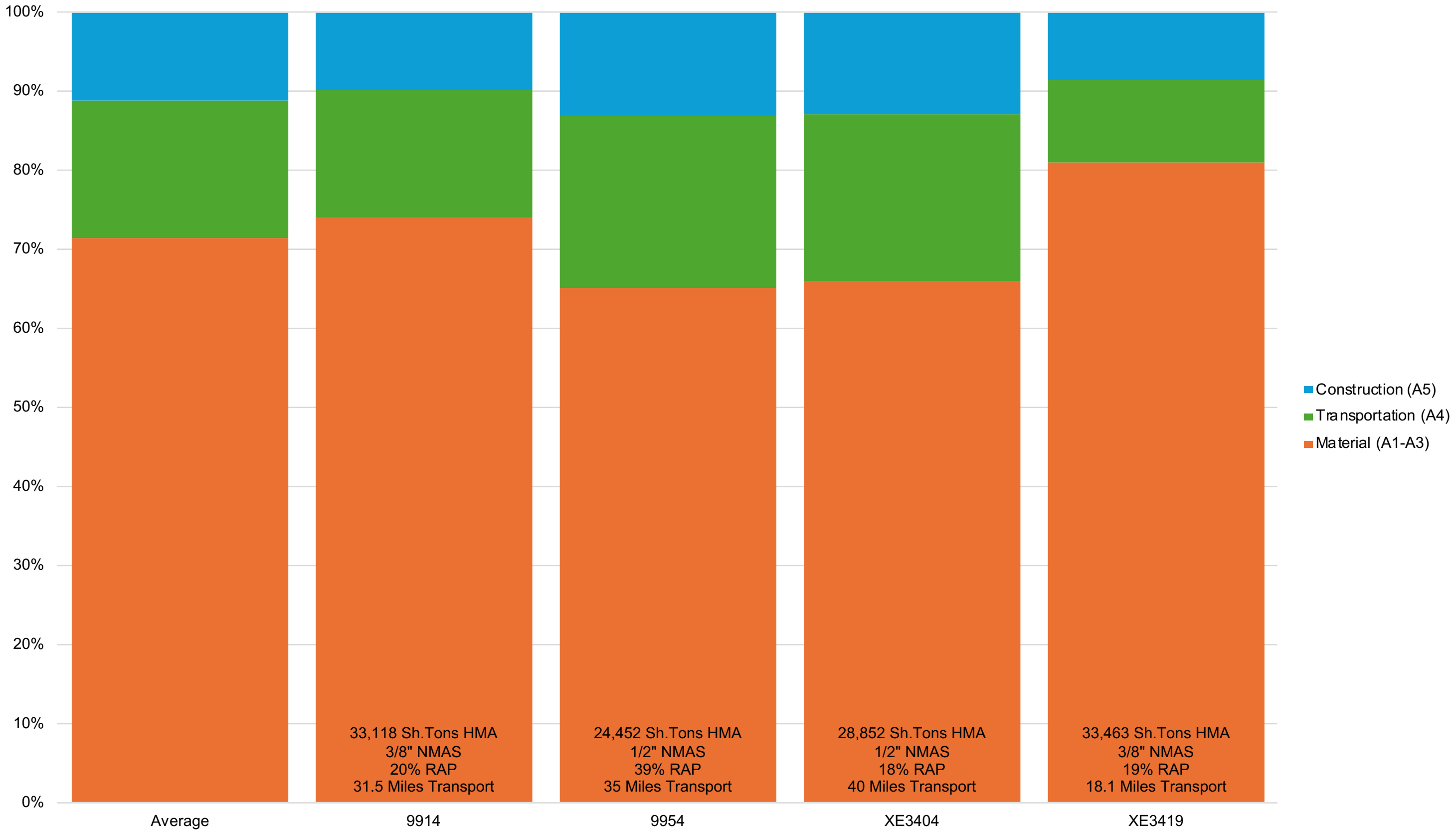


Figure 49 - GWP (kg CO_2 eq) by Life Cycle Stage Percent Contribution Comparison

5 DISCUSSION

5.1 General Category Contribution

Material production, specifically the asphalt pavement mixture, contributed the most to a project's overall A1-A5 GWP. The average HMA upstream material production impact of the project was 71.6%. Contract 9954 had the lowest EPD GWP impact of 65.1%. Contract XE3404 had the second lowest and contributed 66%, followed by Contract 9914 with 74.1%, and Contract XE3419 had the highest GWP impact at 81.4%. A1-A3 was mainly comprised of the HMA EPD data. Aside from the EPD data, the A1-A3 stages also include estimated asphalt emulsion (tack coat) and joint adhesive data.

Table 33 - LCA Stage Percent Contribution by Low, Average, and High

LCA Stage	Low	Average	High
Material (A1-A3)	65.08% (9954)	71.62%	81.00% (XE3419)
Transportation (A4)	10.43% (XE3419)	17.28%	21.89% (9954)
Construction (A5)	8.62% (XE3419)	11.08%	13.03% (9954)

Breaking down the EPD's material production LCA stages, **A1, raw material extraction, and manufacturing, is the highest contributor to the materials stage and the overall project**. A3, HMA production and plant operations, extraction, refining, and transport of fuels, was the second highest contributor; followed by the A1-A3 for asphalt emulsion; A2, transport of raw material to the asphalt plant; and last the A1-A3 for joint adhesive.

Table 34 - Material (A1-A3) Percent Contribution Comparison

Percent Contribution	Average	9914	9954	XE3404	XE3419
Material (A1) - HMA	40.26%	47.20%	32.33%	38.50%	42.85%
Material (A3) - HMA	26.34%	23.18%	26.44%	22.42%	33.17%
Material (A1-A3) - Asphalt Emulsion	2.58%	2.62%	2.33%	2.69%	2.66%
Material (A2) - HMA	2.37%	1.00%	3.98%	2.35%	2.14%
Material (A1-A3) - Joint Adhesive	0.14%	0.10%	0.00%	0.00%	0.18%

Table 35 - Material (A1-A3) kg CO_2 per sh ton of asphalt

Kg CO_2 eq Per Short Ton of Asphalt	Average	9914	9954	XE3404	XE3419
Material (A1) - HMA	30.30	38.63	21.35	30.14	31.09
Material (A3) - HMA	19.51	18.97	17.46	17.55	24.07
Material (A1-A3) - Asphalt Emulsion	1.93	2.14	1.54	2.11	1.93
Material (A2) - HMA	1.71	0.82	2.63	1.84	1.55
Material (A1-A3) - Joint Adhesive	0.093	0.080	0	0	0.13

5.2 Contribution Trends

Amount of virgin asphalt binder within the HMA mix design has a large influence on emissions. Asphalt on average was 4.9% by weight of the total mix. Without including the high RAP mix design, binder makes up approximately 5.4% by weight of the total mix. Therefore, items that influence virgin binder content will likely have a significant impact on the project's total emission. Two items identified in this study are RAP content and nominal maximum aggregate size (NMAS).

Table 36 - RAP, Pb, GWP Project Comparison

Contract Number	Average	9914	9954	XE3404	XE3419
RAP Content (%)	24	20	39	18	19
Virgin Percent Binder (Pb) (By Wt. Total Mix)	4.9	5.4	3.4	5.5	5.3
HMA GWP [kg CO_2 eq] per short ton	51.53	58.43	41.44	49.53	56.71

5.2.1 Virgin Asphalt Binder

The percent of virgin asphalt binder (by weight of the total mix) was one of the main drivers of the HMA's GWP. Contract 9914 used a 3/8" NMAS and 20% RAP in its HMA mix design and had a higher GWP per short ton of asphalt than Contract XE3419, which also used a 3/8" NMAS and 19% RAP. This seems to be mainly attributed to the asphalt binder content. Contract 9914 used a binder content of 5.4%, whereas Contract XE3419 used an asphalt binder content of 5.3%. Having a higher asphalt binder content ultimately raised the GWP for that HMA mix design. Ultimately, this can also be seen in comparison with contracts 9954 and XE3404. 9954's mix design reported a total binder content of 5.3%. However, only 3.4% of the total 5.3% binder by weight of total mix was virgin binder. This brings down the virgin binder content of this mix design, thus lowering the GWP of the mix's A1 stage. The lower binder content is apparent when comparing it to Contract XE3404, which had a virgin binder content of 5.5%, and GWP was approximately 8 kg CO_2 eq

5.2.1.1 Asphalt Binder Additives

Use of a modified binder over an unmodified binder increased the GWP of an asphalt mixture. The two 3/8" projects used an SBS modified – 3.5% styrene-butadiene-styrene binder. Adding an SBS-modified binder will likely increase the pavement's lifespan but add more upstream processes encompassing the modifier's (SBS) embodied carbon. The four projects analyzed in this study used either a mix of ½" NMAS, RAP & unmodified binder, or 3/8" NMAS, RAP & SBS modified binder.

5.2.2 Nominal Maximum Aggregate Size (NMAS)

The selected projects used two nominal maximum aggregate sizes (NMAS), ½" and 3/8", which are typical in Washington State. Contracts 9954 and XE3404 used a ½" NMAS, and contracts 9914 and XE3419 utilized a 3/8" NMAS. Looking at the different projects, the aggregate size and the amount of RAP used in each mix design impacted the GWP impact of the project's EPD or mix design. The ½" NMAS calculated a lower GWP than the 3/8" NMAS. Since a ½" NMAS is larger than the 3/8", less asphalt binder would be needed to cover the aggregate in the mix design (Brown and Bassett 1990).

Additionally, if higher percentages of RAP are used in the mix design, less virgin asphalt is required since there is already an asphalt binder on the RAP that can be used instead of virgin binder.

5.2.3 Asphalt Emulsion/Tack Coat

Table 37 - Material (A1-A3) Tack Coat Comparison by Low, Average, High

Material (A1-A3) - Asphalt Emulsion/Tack Coat	Low	Average	High
Percent Contribution	2.33% (9954)	2.58%	2.69% (XE3404)
kg CO_2 eq Per Short Ton of Asphalt	1.54 (9954)	1.93	2.14 (9914)

The tack coat used on the project had a noticeable impact as the 4th highest overall contributor to a project's GWP. Uniformly across the 4 projects tack coat was consistently 2.5-2.6% of the project's overall contribution and approximately 2 kg CO_2 eq. The average impact was 1.93 kg CO_2 eq and 2.58%. Tack coat was not a separate line item in the project's bid tabulation. Therefore, the amount of tack coat that contractors used seemed to be variable and up to the contractor's records and not tied to a billed quantity. However, it seems that all contractors used a similar amount of tack coat per short ton of asphalt they placed on their project regardless.

5.2.4 Material Transportation

On average, hauling HMA contributed 12.8 kg CO_2 eq per short ton of asphalt and approximately 0.412 kg of CO_2 eq per short ton of HMA for every mile trucked. Transportation of materials, specifically HMA, was the second largest contributor to the project's overall GWP impact. Main contributors to the transportation impact calculation were the distance from the asphalt plant to the project's site and the total amount of HMA used on the project. On average, transportation of materials (HMA and tack coat) contributed 17% of the project's total CO2eq. The project with the lowest transportation impact was Contract XE3419, which contributed 10.4%. This was followed by Contract 9914 with a 16% impact, Contract XE3404 with a 21.2% impact, and Contract 9954 with the highest transportation impact of 21.9%.

Table 38 - Transportation (A4) Comparison by Low, Average, High

Transportation (A4) - HMA Trucking	Low	Average	High
Percent Contribution	10.31%	17.25%	21.82%
kg CO_2 eq Per Short Ton of Asphalt	7.45	12.82	16.47

Tack coat trucking averaged a 0.11% impact and 0.083 kg CO_2 eq across all projects, making it one of the lowest recorded impacts. Although it traveled long distances, tack coat transport did not have a significant impact on the GWP calculations. Therefore, tack coat travel could probably be excluded from future pavement LCA calculations due to its small impact and the large number of assumptions made during the calculation.

5.2.5 Construction Activities

Construction activities in LCA stage A5 comprised approximately 11% of the project's GWP impact. All construction equipment analysis was based on the equipment's recorded fuel consumption and hours provided by the project's primary contractor. The construction A5 stage had the smallest GWP impact within the study's system boundary of A1-A5. Milling was considered within the system boundary of this study. It was included within the A5 stage and contributed the most to the project's A5 GWP.

Table 39 - Construction (A5) Comparison by Equipment Type

Equipment	Percent Contribution	Kg CO_2 eq per short ton of asphalt
Construction (A5) - Milling Machine	3.44%	2.54
Construction (A5) - Roller	2.06%	1.55
Construction (A5) - MTV	1.78%	1.30
Construction (A5) - Paver	1.53%	1.12
Construction (A5) - Sweeper	0.87%	0.67
Construction (A5) - Tack Truck	0.48%	0.39
Construction (A5) - Loader	0.48%	0.35
Construction (A5) - Water Truck	0.18%	0.15
Construction (A5) - Backhoe	0.16%	0.11
Construction (A5) - Grader	0.03%	0.02

5.2.5.1 Milling Activities

Milling activities were included in the A5 construction stage of the LCA. The current PCR specifies milling activities to be included in the end-of-life stage C1 Deconstruction/Demolition (National Asphalt Pavement Association 2022a). Milling was included in A5 construction because it was a construction activity included in the current project's work and was needed to lay down the new pavement. The current PCR considers milling as a C1 activity as it is technically the end-of-life of the previous project. Additionally, by including milling to A5 instead of C1, the most accurate data is being used to represent milling operations. Otherwise, milling and end-of-life activities would be predictions of activities that would happen 20 years in the future. Additionally, including milling activities under the current LCA also gives contractors, who have autonomy over the work, the incentive and drive to reduce emissions and alter practices if rewarded.

5.3 Study Limitations

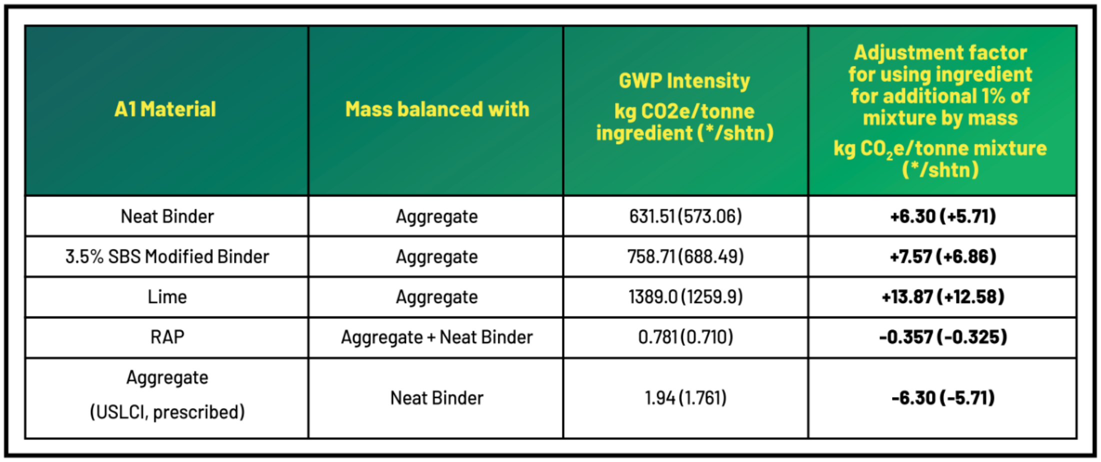
The biggest limitation of this study was that only four projects were analyzed. **National or Washington state roadway construction GWP generalizations should not be based solely off this study** due to the lack of variability in data points. However, the results of this study coincides with the previous studies done on roadway construction GWP.

5.3.1.1 Comparison with Previous Work

This year, a benchmarking study completed by WAP Sustainability considered different mix design characteristics (Miller et al. 2024). Adjustment factors presented in this study was for an extra 1% of neat binder, 3.5% SBS modified binder, lime, RAP, and aggregate (USLCI, prescribed) on top of a baseline mix design in the A1 stage (Figure 50). Providing adjustment factors to be used on top of a baseline HMA mix allows for customization of the baseline to represent any specific mix more accurately. In this benchmarking study, adjustments were made for A2 (Table 42**Error! Reference source not found.**) and A3 (Table 43) stages for the different climate regions (dry freeze, dry no freeze, wet freeze, wet no freeze) with Florida and Louisiana's data separated from other state averages (Miller et al. 2024). Climate regions were delineated per AASHTO standards to consider the impacts of different climates on the mix design's GWP. Additionally, Florida and Louisiana data were both separated out from the other states due to their data being large outliers in the national data.

From the benchmarking study completed by WAP Sustainability, the mix design that used only RAP estimated an A1 of 28.74 kg CO_2 eq/tonne or 26.08 kg CO_2 eq/short ton (Miller et al. 2024). Mix designs incorporating RAP and SBS modified binder estimated an A1 GWP of 34.21 kg CO_2 eq/tonne or 31.04 kg CO_2 eq/short ton (Miller et al. 2024). Case study projects that used only RAP ranged from 21-30 kg CO_2 eq, and projects that utilized RAP and SBS modified binder ranged from 31-38 kg CO_2 eq (Table 40). Comparisons between the EPD Benchmarking study with this thesis were based solely on the A1-A3 GWP collected from the project's EPDs.

Compared to the benchmarking study, the A1 impacts of this study's projects EPDs are reasonable. Some projects reported higher values than the ones presented by the benchmarking study. This could be due to differences in the mix design analyzed by the benchmarking study. The benchmarking study's mix design utilized 21.87% RAP, which had a higher RAP content than three of the four projects EPDs analyzed. Additionally, the quantity of modified binder in the benchmarking study's mix was 4.3%. On the other hand, this study's projects utilized a 4-5% percent binder quantity. Considering calculation adjustments shown in Figure 50, the estimated GWP for the A1 stage of each project typically only had a difference of 1-2% from the EPD's reported A1 GWP (Table 41, Figure 51). It is apparent that the HMA mixes utilized in these case studies are similar to other comparable HMA mix designs in the US.



A1 Material	Mass balanced with	GWP Intensity kg CO2e/tonne ingredient (*/shtn)	Adjustment factor for using ingredient for additional 1% of mixture by mass kg CO$_2$e/tonne mixture (*/shtn)
Neat Binder	Aggregate	631.51 (573.06)	**+6.30 (+5.71)**
3.5% SBS Modified Binder	Aggregate	758.71 (688.49)	**+7.57 (+6.86)**
Lime	Aggregate	1389.0 (1259.9)	**+13.87 (+12.58)**
RAP	Aggregate + Neat Binder	0.781 (0.710)	**-0.357 (-0.325)**
Aggregate (USLCI, prescribed)	Neat Binder	1.94 (1.761)	**-6.30 (-5.71)**

Figure 50 – A1 Asphalt Mixture Component Impacts (per unit mass) (Miller et al. 2024)

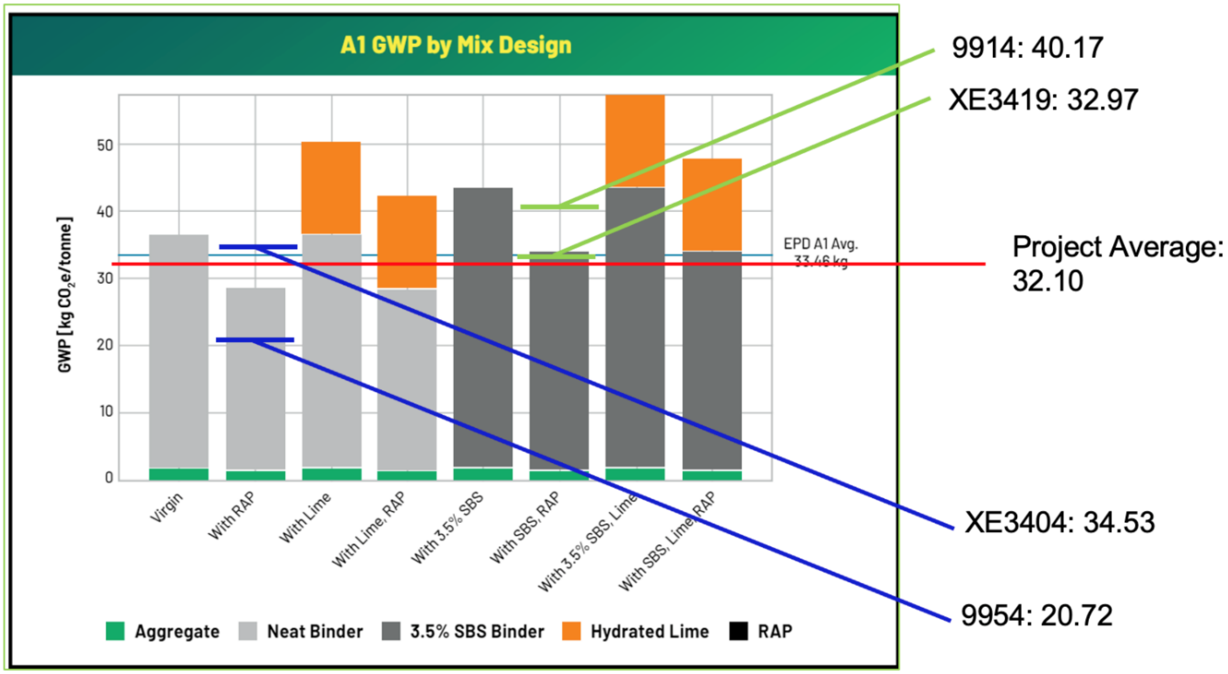


Figure 51 - Benchmarking Study A1 Comparison (Miller et al. 2024)

WAP Sustainability's benchmarking study also addressed trends within the A2 (Figure 52) and A3 (Figure 53) stages. When this study's project averages were compared against the Washington State data, they were below the estimated state average.

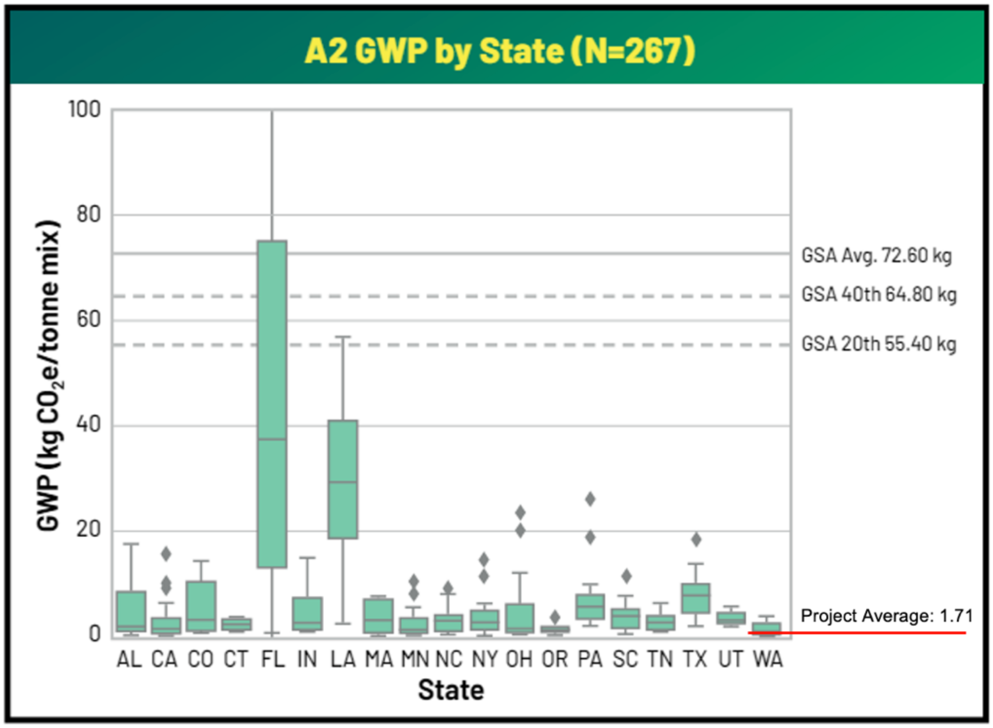


Figure 52 - Benchmarking Study A2 Comparison (Miller et al. 2024)

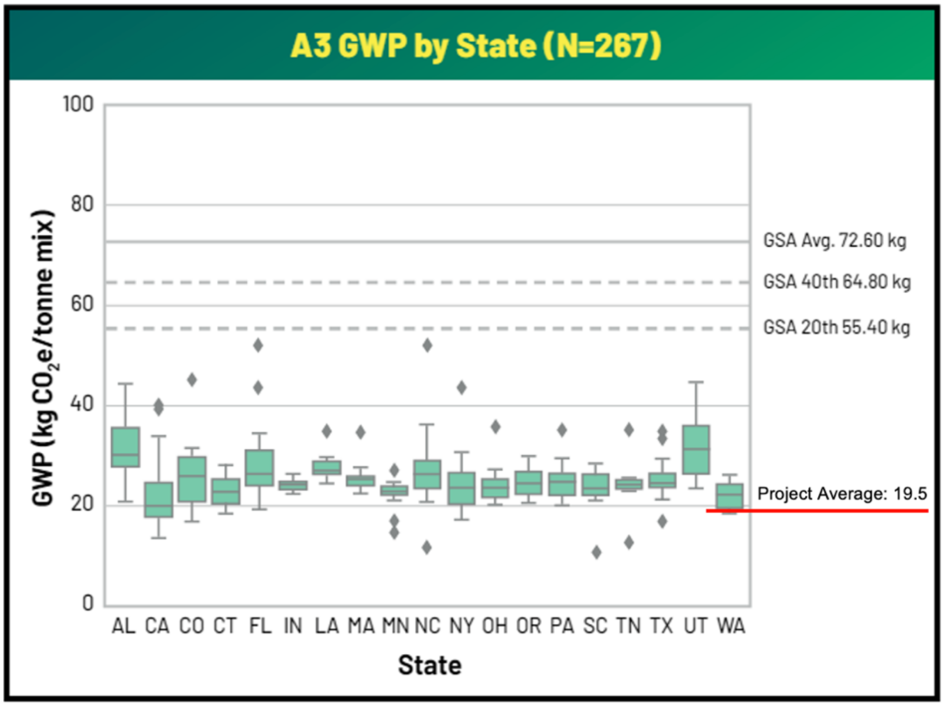


Figure 53 - Benchmarking Study A3 Comparison (Miller et al. 2024)

Looking at A2, all projects were in the top 50% of GWP impacts, with one project being in the top 20% and two others in the top 40%. Regarding A3, projects in the wet no-freeze region (9954, and XE3404) were all in the top 20% (Table 42). The projects in the dry-freeze region (9914, and XE3419) were both above average with one project in the top 20% of mix designs analyzed by the benchmarking study (Table 43). Using these case studies as a gauge, meeting the EPD averages set by the benchmarking study seems like a reasonable target, as all the projects analyzed have been either at or above the averages set.

Table 40 - Project's EPD A1-A3 GWP Contribution (kg CO_2 eq per ton Asphalt Mixture)

	A1	A2	A3	Total GWP
9914	38.63	0.82	18.97	58.43
9954	21.35	2.63	17.46	41.44
XE3404	30.14	1.84	17.55	49.53
XE3419	31.09	1.55	24.07	56.71

Table 41 - A1 Project to Benchmarking Study Comparison (Miller et al. 2024)

	Aggregate (% mixture mass)	**Neat Binder (% mixture mass)**	**Modified Binder (% mixture mass))**	**RAP (% mixture mass)**	**EPD A1 GWP Kg CO_2 eq/tonne**	**EPD A1 GWP Kg CO_2 eq/sh ton**	**ESTIMATED FROM BENCHMARK A1 GWP Kg CO_2 eq/sh ton**
With RAP	73.83	4.3	0	21.87	28.74	26.08	
With SBS, RAP	73.83	0	4.3	21.87	34.21	31.04	
9914	74		5	20	42.59	38.65	36.45
9954	58	4		39	23.53	21.35	18.80
XE3404	78	5		18	33.23	30.15	31.33
XE3419	77		4	19	34.27	31.10	29.92

Table 42 - A2 Project to Benchmarking Study Comparison (Miller et al. 2024)

A2 (kg CO2e/shtn)	**Benchmarking Study**	**Associated Project (kg CO2 eq /shtn)**
20%	0.9	9914 (0.82)
40%	1.9	XE3404 (1.84), XE3419 (1.55)
50%	2.7	9954 (2.63)
Average	4.2	

Table 43 - A3 Project to Benchmarking Study Comparison (Miller et al. 2024)

A3 (kg CO_2e/shtn)	**Wet Nonfreeze**	**Associated Project (kg CO_2 eq /shtn)**	**Dry Freeze**	**Associated Project (kg CO_2 eq /shtn)**
20%	21.1	9954 (17.46), XE3404 (17.55)	19.8	9914 (18.97)
40%	23.2		22.1	
50%	23.7		23.8	
Average	24.9		24.7	XE3419 (24.07)

In this study, two projects used a ½” NMAS, and two used a 3/8” NMAS. GWP impact calculations found that the mix designs with a 3/8” NMAS recorded higher carbon emissions than ½” NMAS mix designs. There are multiple reasons that the 3/8” NMAS projects reported higher GWP impacts, but the smaller size aggregate was a contributing factor. The use of smaller aggregate sizes requires more energy in the crushing processes to get the appropriate NMAS. More energy exerted in the crushing process slightly increases the GWP (Gettu and Buttlar 2024), which can be attributed to the differences between the ½” and 3/8” NMAS mix designs. Additionally, smaller aggregate sizes will require more asphalt binder to cover all aggregate in the asphalt mixes (Brown and Bassett 1990). As it has been seen in this study, when more asphalt binder is required in a mixture, there will be a corresponding increase in a project’s GWP. Higher energy expenditure during the crushing process and increased amounts of asphalt binder usage both contribute to 3/8” NMAS having a higher GWP impact.

The four projects considered in this case study confirmed what previous studies have concluded: materials significantly impact a project’s GWP. Materials, specifically the asphalt binder, have large amounts of upstream emissions or embodied carbon due to their production. Therefore, the choice of materials should be a main consideration when looking to reduce GHG (Noland and Hanson 2015).

Another reason the projects that used a 3/8” NMAS had a higher GWP impact can be credited to the modified binder. The two mix designs that used a ½” NMAS did utilize a modified binder. However, the 3/8” NMAS mix designs used an SBS modified binder. Mukherjee showed through his research that SBS modified binders had higher A1-A3 carbon emissions than unmodified binders by 8.6% (Mukherjee 2022). Research done at WAP Sustainability also found that SBS modified binder, on average, contributed an additional 1.15 kg CO_2 eq per short ton than neat or unmodified asphalt binder (Miller et al. 2024).

The A1 stage also had the highest variability among the EPD stages. This makes sense since materials have the highest variability between RAP usage, asphalt binder requirements, and where plants are sourcing their materials. A3 had the next highest contribution to the GWP. Stage A3 includes the production of the HMA and the corresponding plant operations (extraction, refining, and transport of fuels). This portion of the HMA EPD remained consistent regardless of the mix design. Since this refers to the asphalt plant’s operation, it could vary exponentially based on the asphalt plant’s fuel source. A2, which is comprised of the transport of raw material to the asphalt plant, was the lowest contributing section of the EPD and remained consistent across the various mix designs. Similar findings were drawn in a case study completed at the University of Missouri. Their case study states, “It can also be observed that the main differences are due to the impact of the A1 phase, while the impacts of the A3 phase is almost the same for all cases, as may be expected, since the same plant and mixing process are used.” (Gettu and Buttlar 2024).

5.4 Data Collection Issues

Granularity of data collected was the largest hurdle faced in the data collection process. All contractors collected varying fuel consumption levels, hours, etc., from the work completed. Some contractors could provide the exact hours and fuel consumption of their equipment, while others were not. To combat this, the actions were taken, as described in the Data Gaps section, to obtain a reasonable estimate.

Additionally, **crack sealing material and operations were not considered in this study**. Estimation of the material used for crack sealing in the final pay quantities reported crack sealing in cubic meters. However, to input this operation into openLCA for calculation, quantities must be in terms of tons. Due to the difficulty of calculation, crack sealing was not considered within the project’s boundaries.

5.5 Model Limitations

The calculation method utilized by the FHWA's repository did not support the full granularity of data on trucking fuel consumption and engine sizes. Calculations for trucking were completed in ton-miles, meaning that direct fuel consumption was not used. While some projects reported fuel consumption data for all trucks used, this information could not be utilized due to the FHWA repository's limitations. Ultimately this limited the accuracy of transportation GWP estimates for the projects. Additionally, engine size ranges for diesel construction equipment were broad, with majority of the analyzed equipment falling into the range of 56-560kW. As a result, all engine sizes within this range were treated the same, even if they differed significantly, impacting the precision of the data.

5.5.1 Trucking Transportation Limitations

Double cycling and backhauling of trucks were also not considered in this study. Double-cycling trucks refer to trucks hauling material to and from the job site. Trucks transport the HMA mix from the asphalt plant to the project site and RAP, from the site, back to the plant. This means that trucks do not run an empty backhaul. Double cycling reduces the number of truck trips needed as milled material, and HMA are transported in one trip by the same truck. It has been estimated that running trucks with an empty backhaul can be calculated at 1.35 times the one-way distance (National Asphalt Pavement Association 2022a). If backhaul was considered, which it is not in this study, contractors could save 35% of the trucking needed by double-cycling their trucks. Current PCR for asphalt mixtures includes RAP with an assumed haul distance of 33 miles with an empty back-haul in the C2 life cycle stage (Mukherjee 2022; National Asphalt Pavement Association 2022b).

5.5.2 Uncertainty Analysis

Uncertainty analysis was not considered in this study. Ultimately, there is uncertainty in the data collection process and quality. Although the numbers and final calculations in this study are presented as exact numbers, underlying uncertainty was not explicitly expressed. Since we did not know the specific uncertainty or where it could come from, a conscious decision was made to exclude this parameter to avoid any predictions being used in the LCA calculation. Ideally, uncertainty should be viewed as an accounting process. Data collection will always have inherent uncertainty as not all data is collected the same way by every contractor. If decisions in the LCA process follow an agreed upon manner, the uncertainty of each separate study should be similar and, therefore, already accounted for by the process itself.

6 Conclusions/Recommendations

The research question posed at the beginning of this study was: *What are the GHG emissions associated with materials production, transport to the jobsite, and construction operations for asphalt pavement in Washington State?* This thesis considered the environmental impacts of asphalt paving projects in terms of GWP measured in kg CO_2 eq. Four projects across Washington State were chosen to investigate this question by collecting HMA mix EPDs, materials, transportation, and construction data.

6.1 Generalized Conclusions

The following observations were concluded from these case studies.

- Lack of working knowledge surrounding EPDs was a hurdle to getting EPDs completed by contractors. However, with a WSDOT issued change order that paid for the EPD formulation, and support from WAPA regarding its generation, collecting EPDs for each project was attainable.
- Having the support of WSDOT and the contractors on projects made it possible to estimate the A4 and A5 GWP from field data using a standard data collection method.
- Generally, it is hard to expect contractors to complete extra work that they do not get credit for or does not correspond to a direct financial gain (e.g., double cycling).
- The range of GWP contributions per LCA stage was:
    - A1-A3: 65-80%
    - A4: 10-20%
    - A5: 8-13%
- The EPD (A1-A3) is dominated by virgin asphalt (A1), and plant heating (A3).
    - Future initiatives aimed at reducing embodied carbon (e.g. those encouraged by the FHWA's Low Carbon Transportation Materials (LCTM) grants or similar initiatives) likely will concentrate on decreasing virgin asphalt content and reducing or eliminating the asphalt plant's heating.
- A1 had the largest variability within the LCA stages encompassed in the EPD since its impact fluctuated with the amount of virgin binder that was included in the mix design.
- When looking specifically at the GWP contribution per short ton of asphalt, the contributions of the A5 impacts are consistent.
- Trucking distances for A4 is valuable because GWP is dependent on the distance that was traveled from the plant to site.
    - The proxy value of 0.412 kg of CO_2 eq per short ton of HMA for every mile trucked can be used to estimate the trucking impact.
- From the literature and these case study projects, the most important information to collect is the mix design's EPD and trucking distance.
    - Specific A5 data seems to be most valuable when looking at the percent contributions of each stage (A1-A5) and when projects are using low amounts virgin asphalt binder and/or high RAP content.
    - When the A1-A3 stage is lower, the percent contribution of the A4 and A5 stage rises.

- In a market that is incentivized to lower the embodied carbon of asphalt pavements, it would be reasonable to expect higher RAP concentrations, a transition to larger NMAS, utilization of less absorbent aggregates, exploration of alternative products that can replace virgin asphalt binder, and potentially adjusted mix designs that reduce the asphalt content within the mix. However, feasibility of these measures is often reliant on local availability. While various asphalt mix constituents can be economically feasible, they may not be physically feasible to transport them (many are heavy, which results in high economic and carbon emission costs), which limits alternatives to what is locally available.

6.2 Recommendations for Study Replicability

Realistically, it may not be feasible to collect all the information that was collected for this study to estimate a project's environmental impact; it might not be necessary either. Each project's LCA was based on a standard model and assumptions. Therefore, the amounts of energy, fuel, and materials were the only varying pieces within the LCA model. Based on the 4 case study projects analyzed in this thesis, the following information was the most pertinent as it had the largest overall contributions to the GWP and what I think should be collected from each LCA stage:

1. HMA Mix EPD (A1-A3): The EPD compiles and analyzes specific mix information, specifically the RAP, virgin asphalt binder content, and plant information, that greatly impact the GWP of the asphalt pavement project.
2. Transport Distance (A4): Specifically, the distance from the asphalt plant where the HMA is generated to the midpoint (as an average) of the project's area. Behind the EPD contribution, trucking of the material had the largest impact on the project's GWP. Longer material transport distances will correspond to a higher GWP contribution.
3. Construction Equipment Fuel Consumption (A5): Milling machine operations consistently had the highest equipment contribution to GWP over all 4 projects. The MTV, Paver, and Rollers on site were the largest contributors related to construction GWP during paving operations.

The percent contribution of the tack coat used by each project was generally within the 2.6-2.7% contribution range and 1.93 kg CO_2eq to the project's total. Therefore, the 2.58% average value shown in the Table 31 may be used as a generalization for similar paving focused projects. Additionally, from the data provided in Table 29, it can be concluded that generally, there is not much variability between the kg CO_2 eq emitted and the pieces of construction equipment. Therefore, the reported averaged values could be used as a baseline for similar projects (specifically, for equipment that did not have as large an impact on GWP mentioned above). If data for only two pieces of equipment can be collected, I would suggest collecting fuel consumption data from the milling machine and MTV as they had the largest variability and impact in GWP of the four pieces of equipment listed above.

6.3 Looking Towards Future Work

Awareness of embodied carbon and working towards carbon reduction are becoming more widely recognized as crucial steps to tackle climate change's effects. To achieve the future goal of net-zero by 2050 in asphalt pavement construction, major steps will need to be taken towards carbon reduction. Recommendations to WSDOT and researchers about future work that should be pursued are listed below.

6.3.1 WSDOT Future Considerations

Following the completion of this portion of the Climate Challenge, some recommended actions that WSDOT can take to work towards lowering the carbon emissions of asphalt pavement construction are listed below.

- Establish a standard process to obtain, store, and analyze EPDs for asphalt mixtures in the regular contracts.
  - Specify the granularity of the information being requested by contractors to ensure all primary data will be used in future LCA calculations.
- Establish embodied carbon reduction policies that prevent an over-focus on A1-A3 values in place of long-term performance.
- Identify specific life cycles for each type of roadway. For example, if a roadway that experiences high wear and tear is expected to be rehabilitated every 2 years, set the design standard to match. Then, high strength material that may have higher embodied carbon, can be saved for roadways that are expected to last for the full design life.
- Consider estimated project's GWP in combination with the low-bid proposal when selecting the winning contractor.
  - Collaborate with contractors to come up with ideas on how to optimize design while keeping costs low.
  - Work towards policy that values lower GWP through an incentive/compensation program or something similar.

6.3.2 General Work Considerations

Future work considerations to expand upon the work presented in this thesis and recommendations regarding facilitating databases for accessible asphalt pavement LCA calculations are listed below.

- Develop a standard data collection database that encompasses all the data that would be need from contractors to calculate a pavement construction LCA.
  - Ensure all data granularity is consistent.
- Get data collected and models created used in this thesis third-party reviewed so that they can be shared and used by others doing similar work.
- Analyze the relationship between bid price and GWP contributions. Previous research established correlations between a project's bid price and the estimated GWP (Zokaei Ashtiani and Muench 2024). Seeing if these 4 projects also followed the trends presented would be an interesting follow up.
- Develop framework to translate work between data quality assessment results and uncertainty analysis more accurately.
- Create platform where data collected, and models created can be uploaded and shared. There currently is not a streamlined process to export models and metadata within the openLCA application which makes data and model sharing difficult.
- Build up database of EPDs so that generalizable conclusions can be reached. Use these conclusions to inform an embodied carbon policy.

- Expand the FHWA repository to include updated comprehensive data of various materials (e.g. emulsion, joint adhesive, crack sealant), construction equipment (e.g. engine size ranges), and trucking reference units (e.g. fuel consumption, energy used).
- Restructure the pavement PCR to be able to accurately include RAP transport/double-cycling per project.
- Come to a consensus regarding where the inclusion of milling activities should be placed in a LCA.

7 Appendix A: 9954 Result Graphs

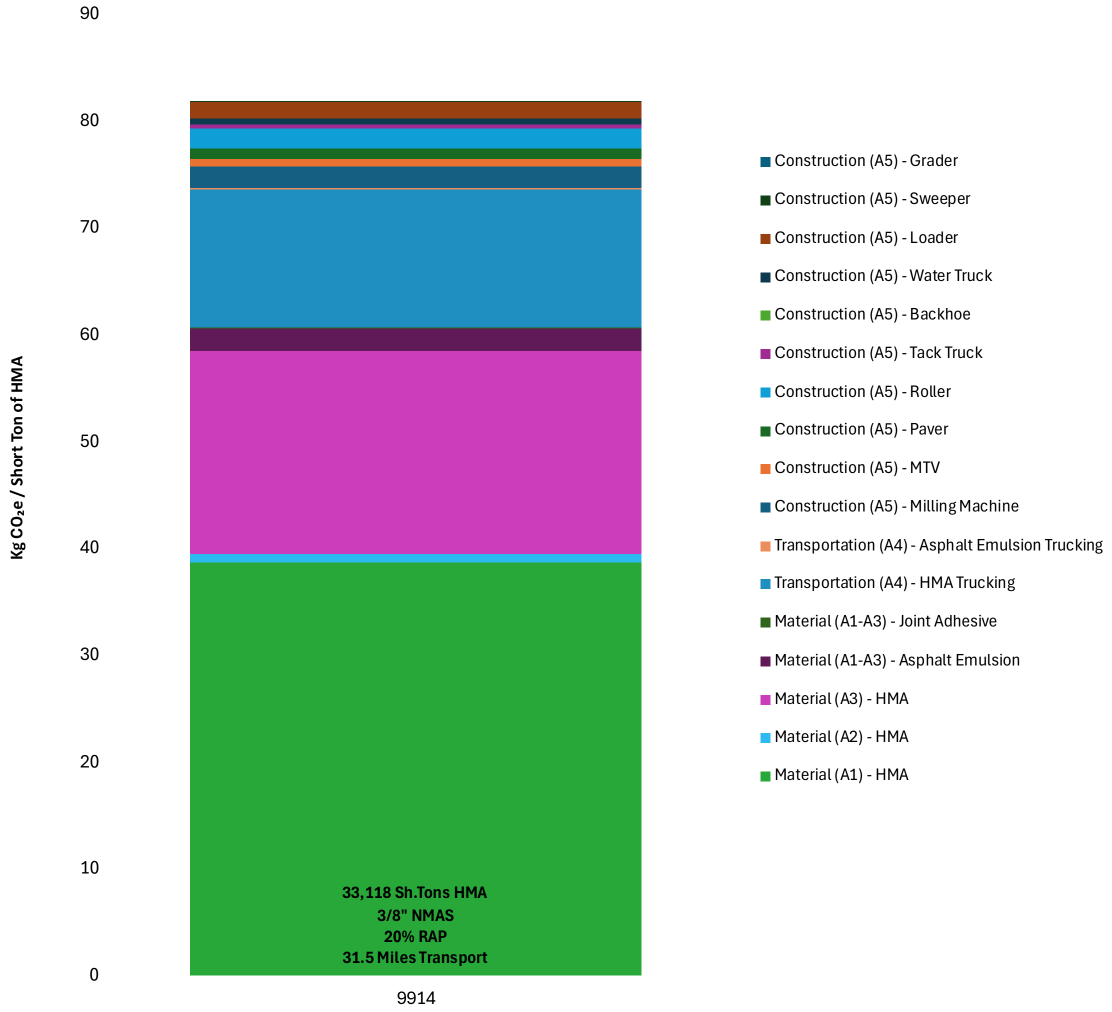


Figure 54 - 9914 GWP Per Short Ton of Asphalt

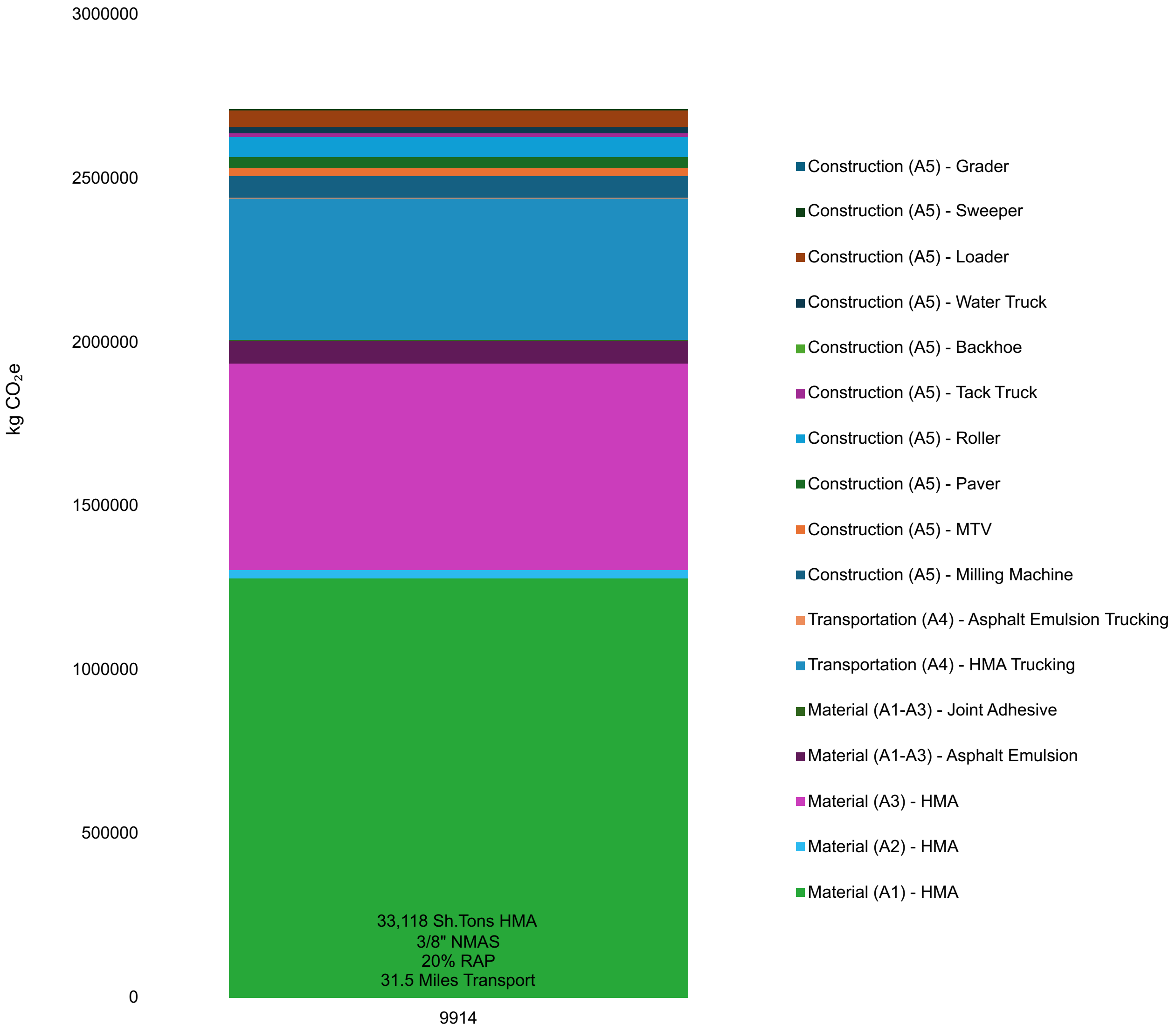


Figure 55 - 9914 Project Total GWP

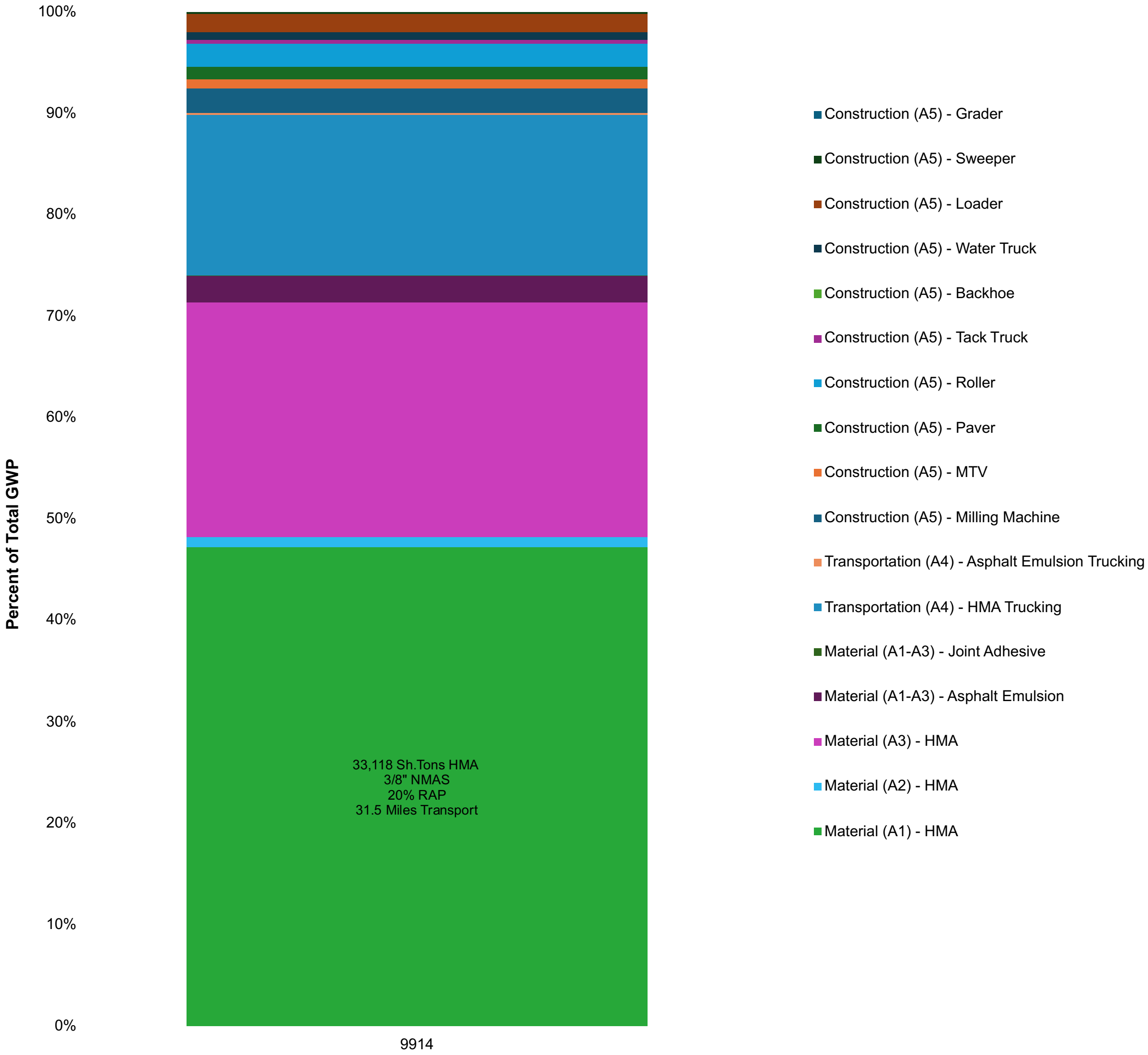


Figure 56 - 9914 GWP Percent Contribution

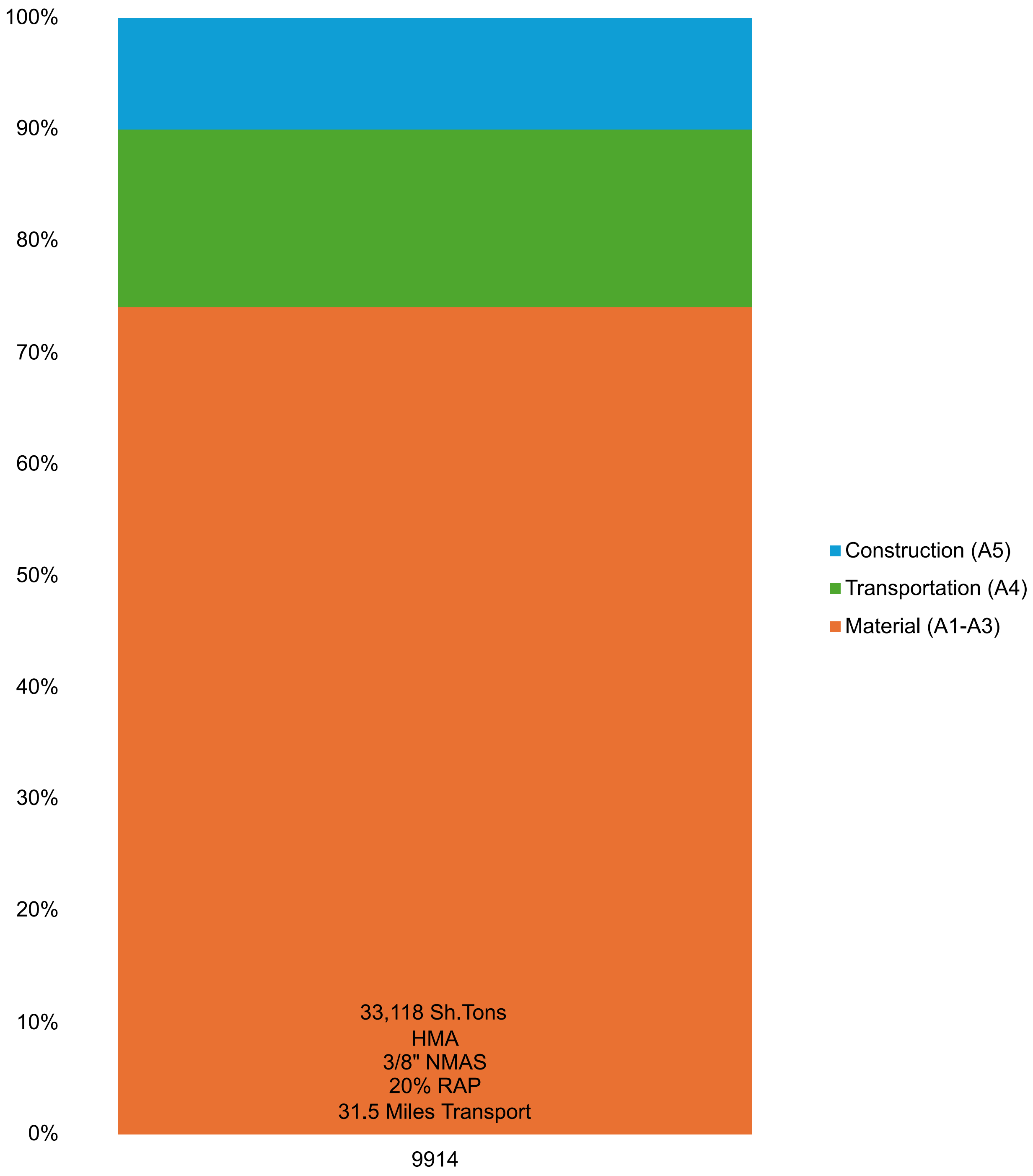


Figure 57 - 9914 GWP by Life Cycle Stage Percent Contribution

8 Appendix B: 9954 Result Graphs

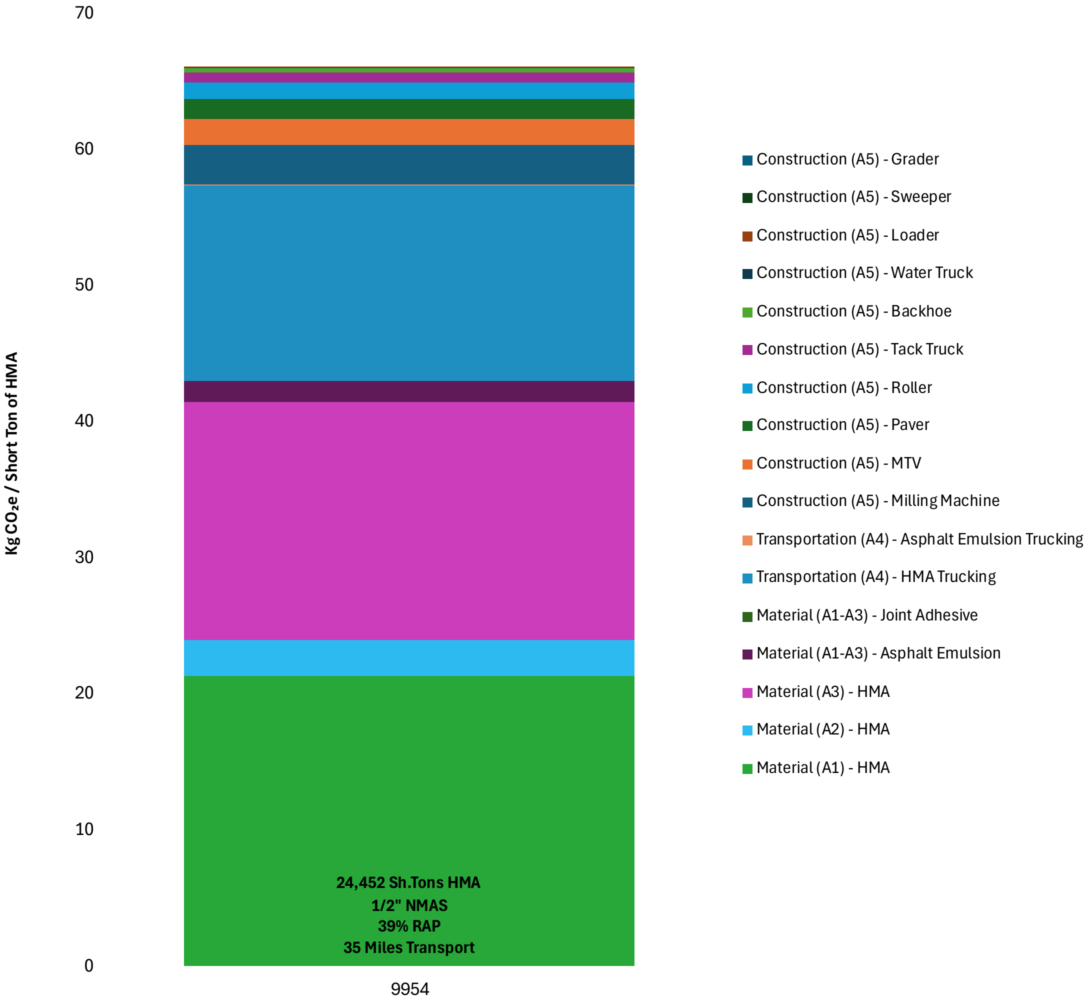


Figure 58 - 9954 GWP Per Short Ton of Asphalt

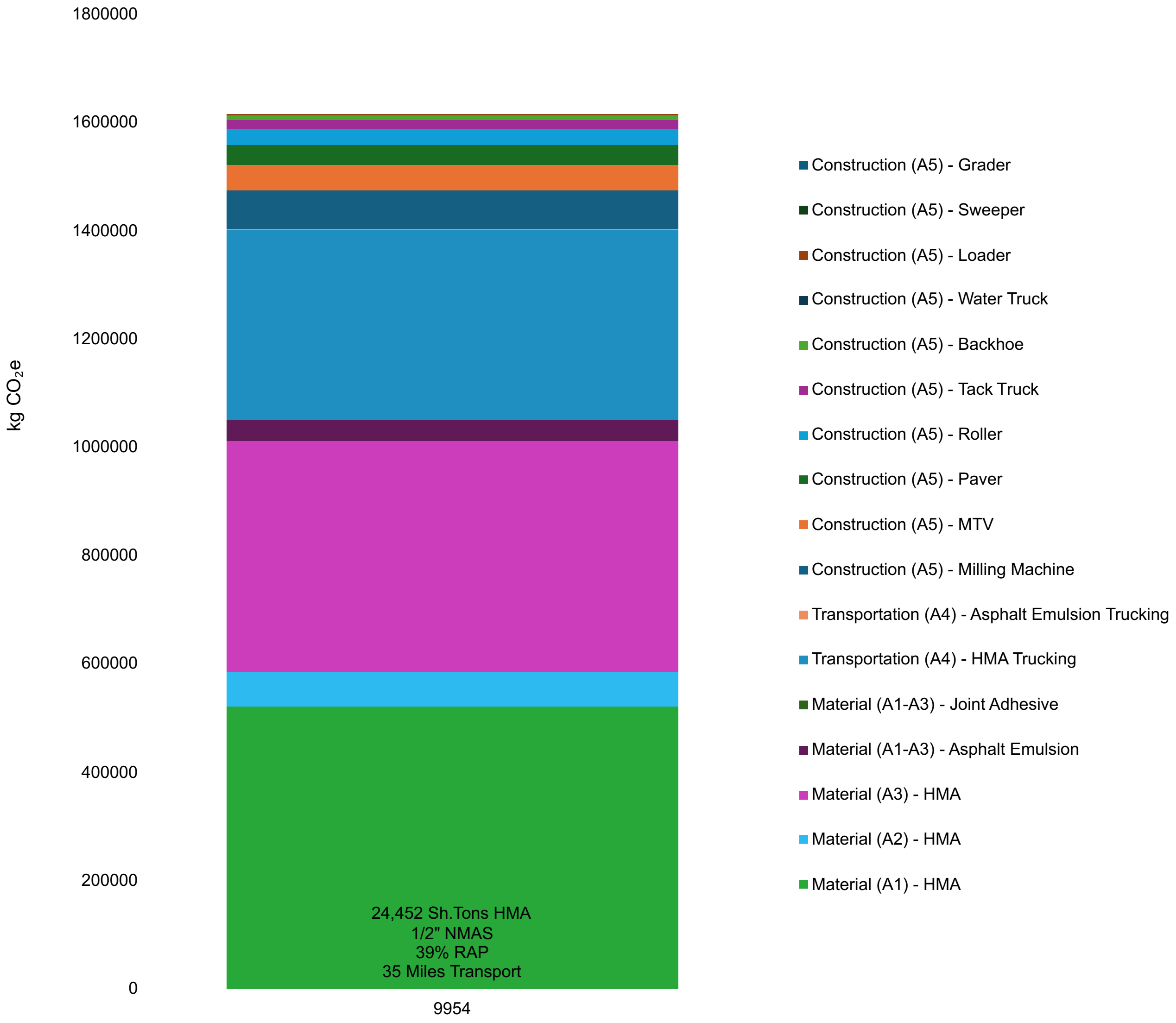


Figure 59 - 9954 Project Total GWP

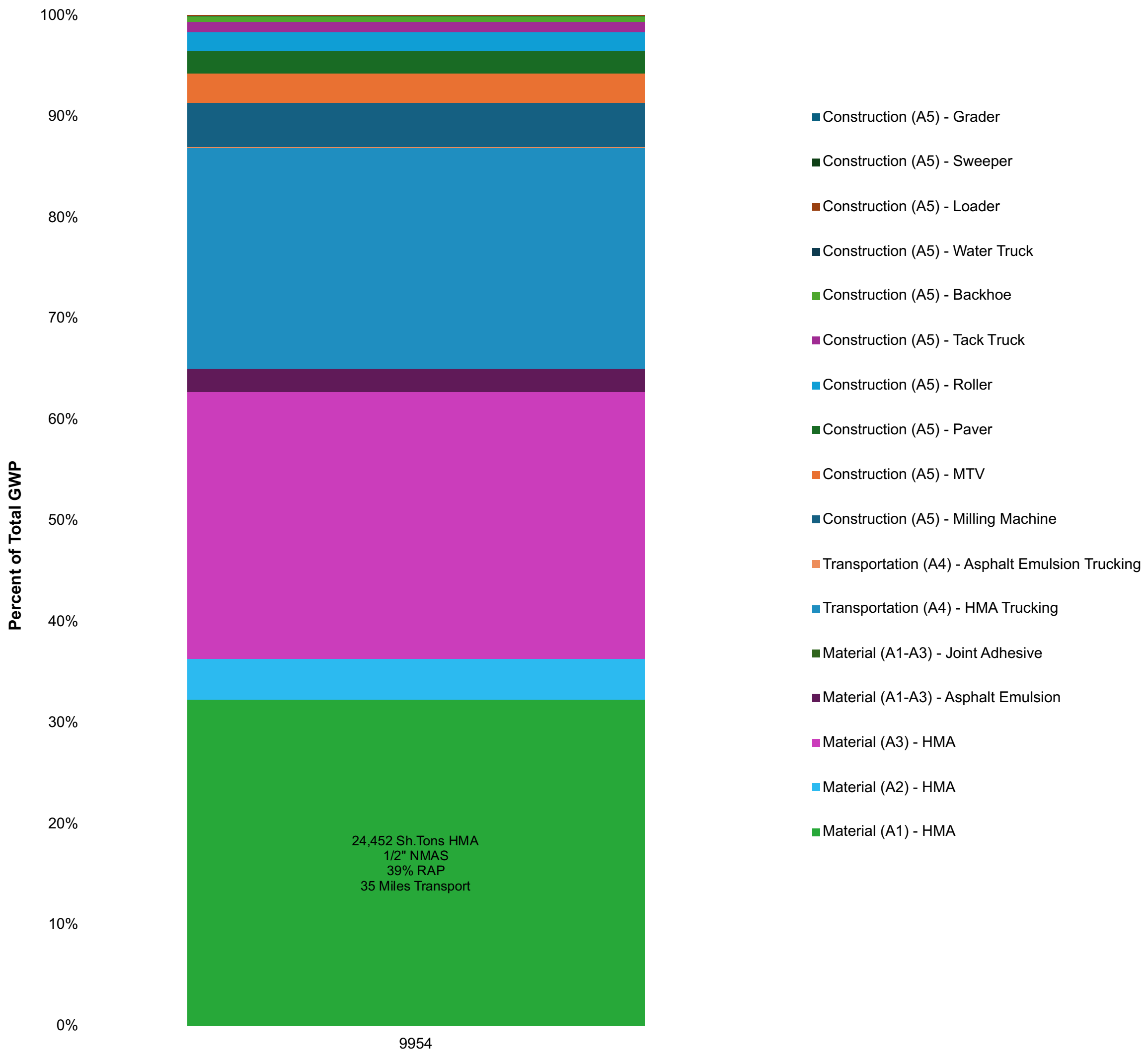


Figure 60 - 9954 GWP Percent Contribution

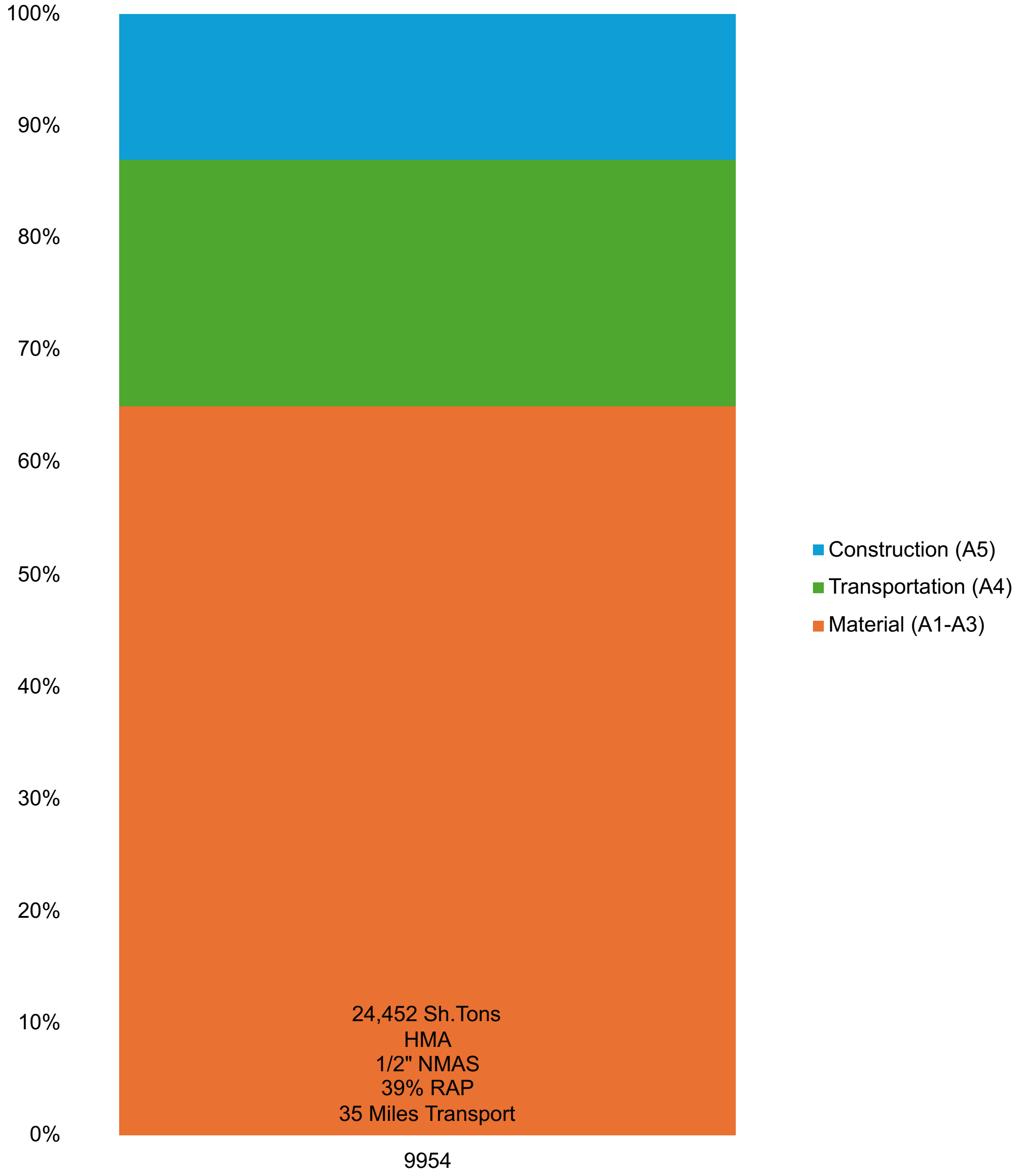


Figure 61 – 9954 GWP by Life Cycle Stage Percent Contribution

9 Appendix C: XE3404 Result Graphs

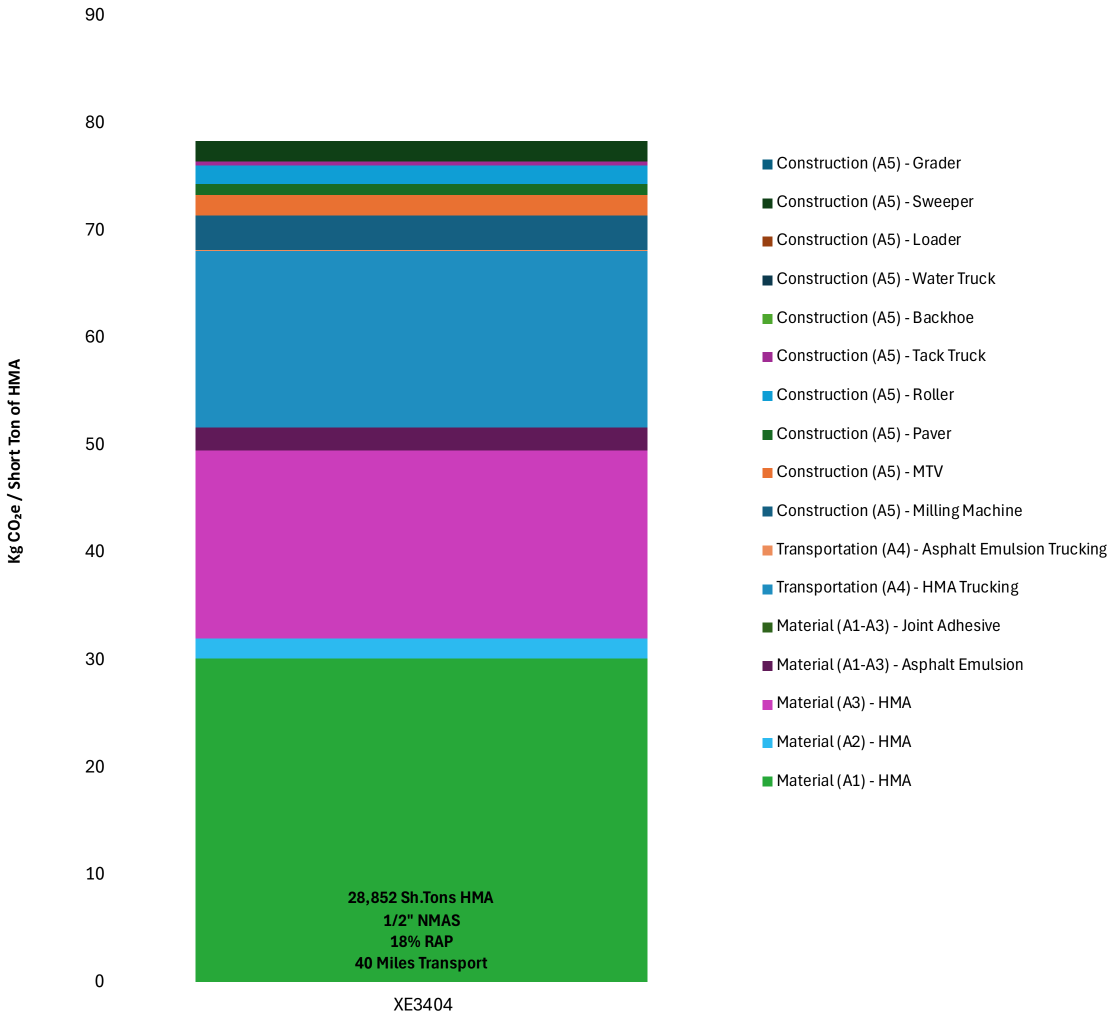


Figure 62 - XE3404 GWP Per Short Ton of Asphalt

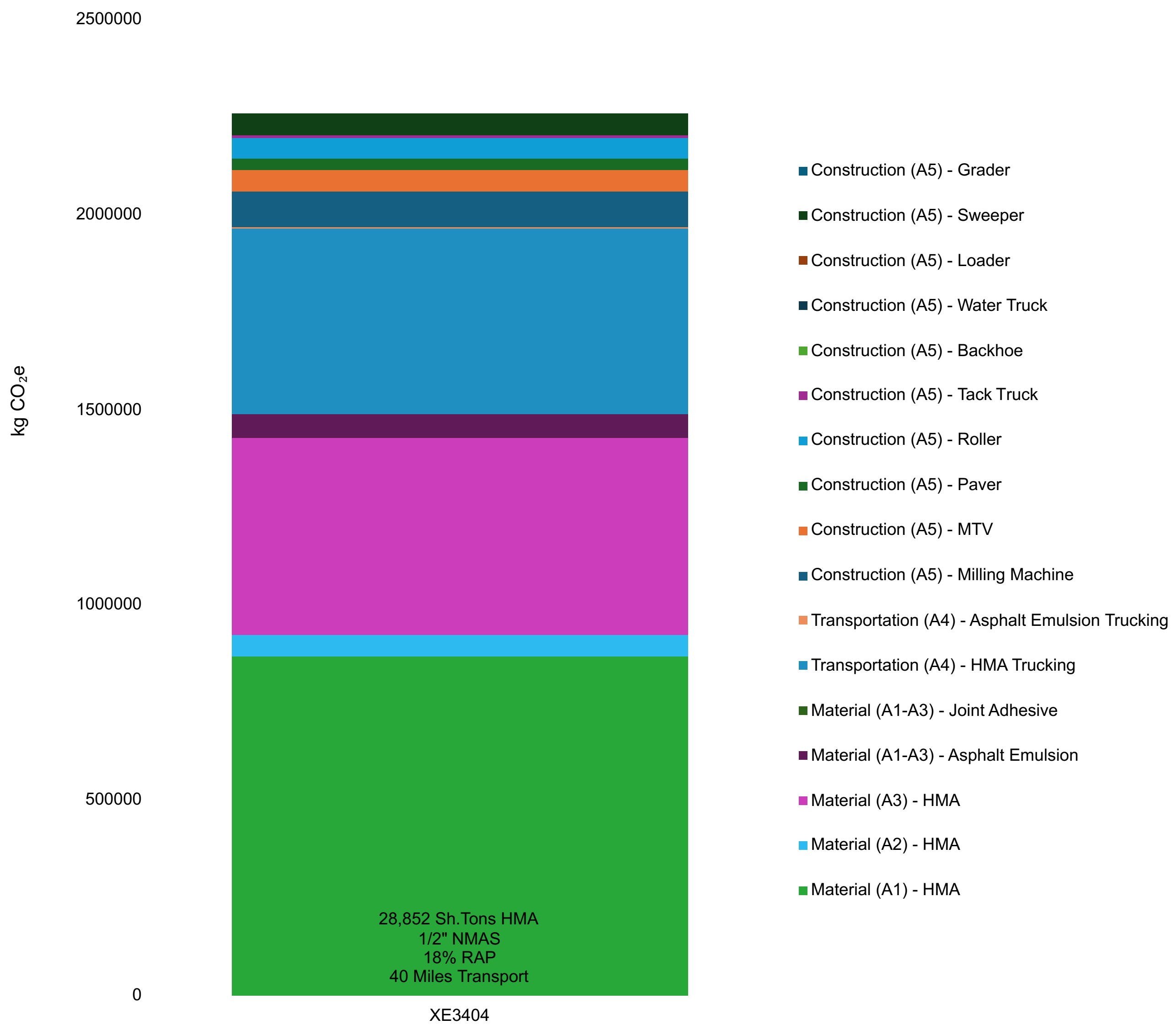


Figure 63 - XE3404 Project Total GWP

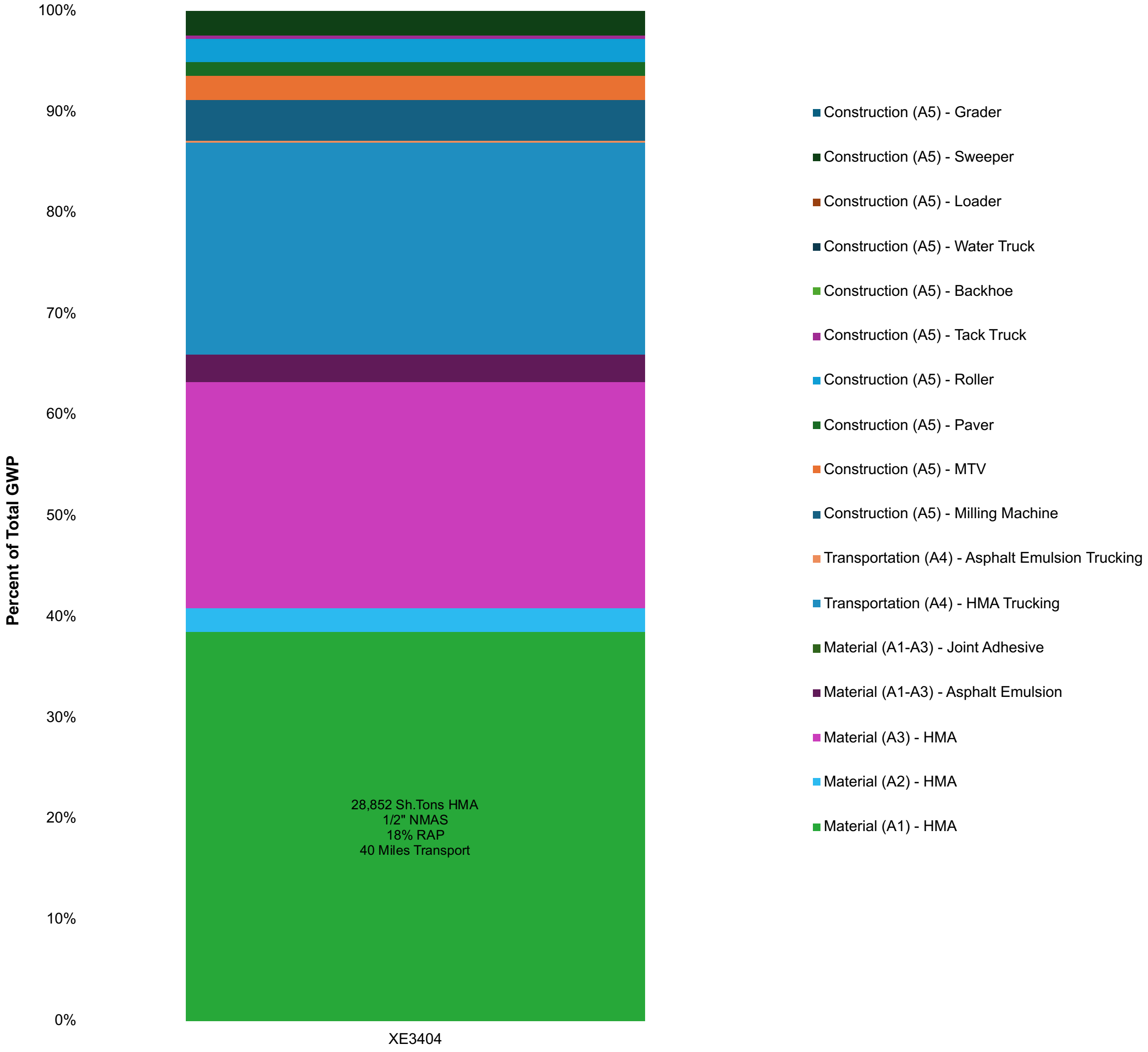


Figure 64 - XE3404 GWP Percent Contribution

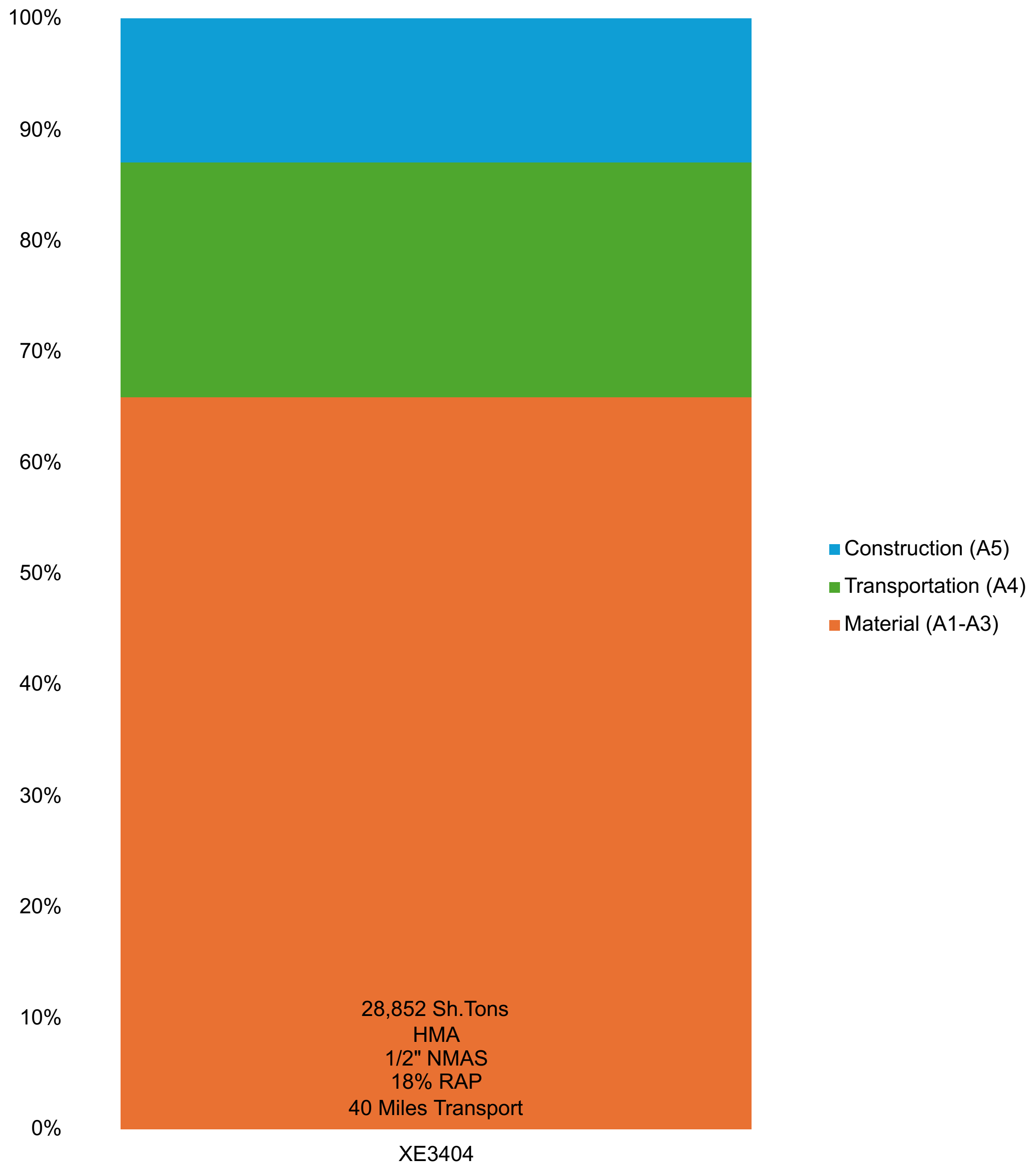


Figure 65 - XE3404 GWP by Life Cycle Stage Percent Contribution

10 Appendix D: XE3419 Results Graph

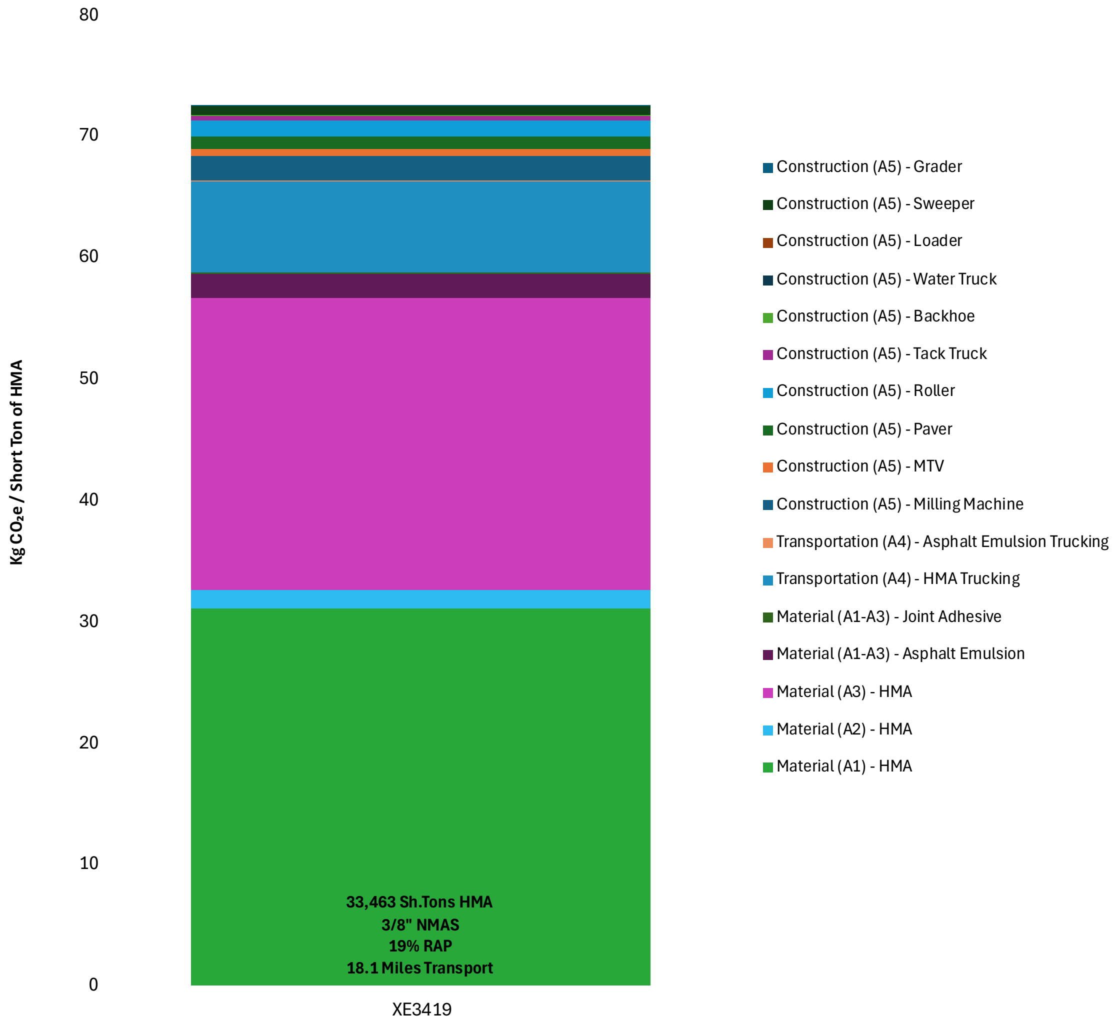


Figure 66 - XE3419 GWP Per Short Ton of Asphalt

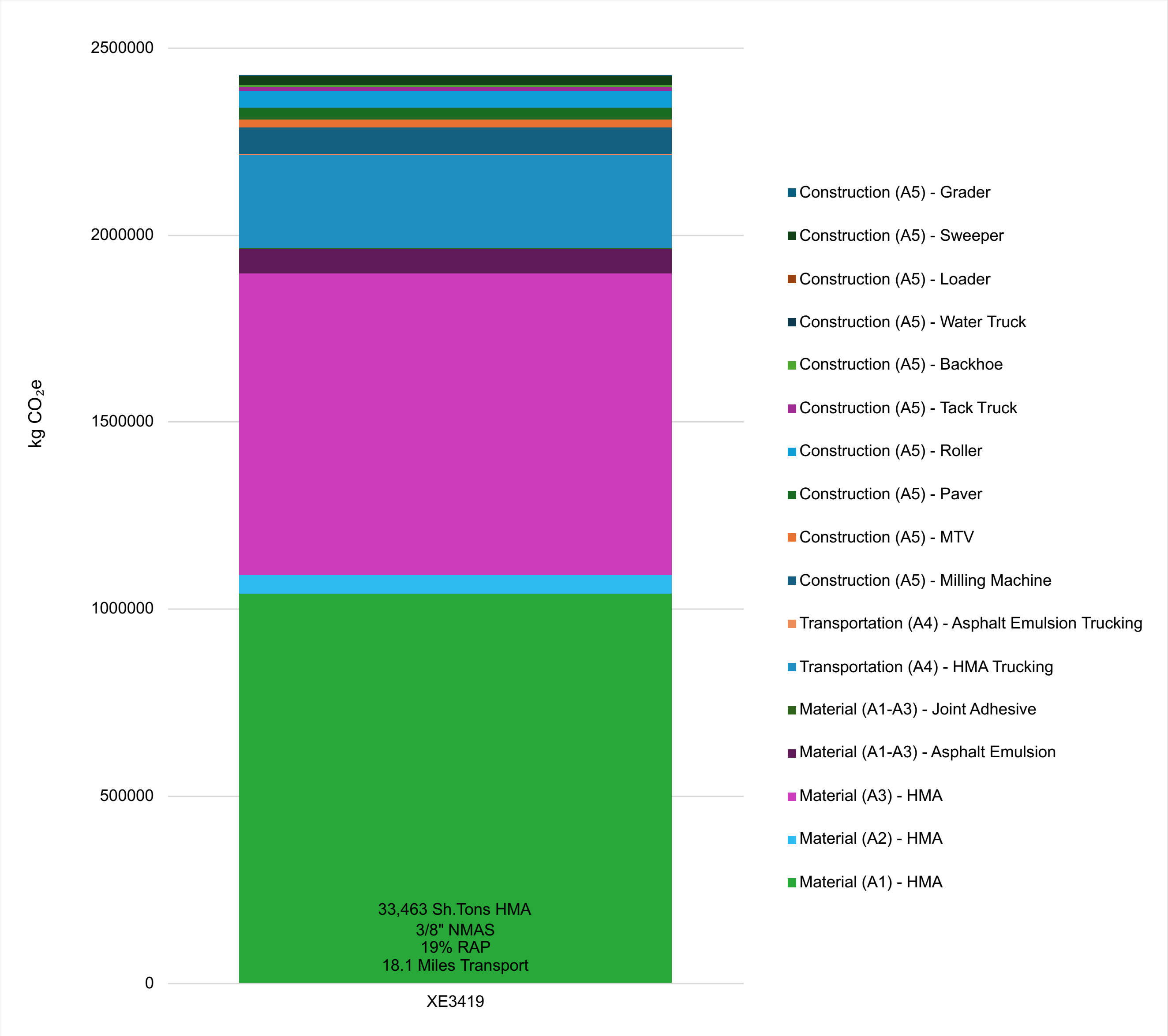


Figure 67 - XE3419 Project Total GWP

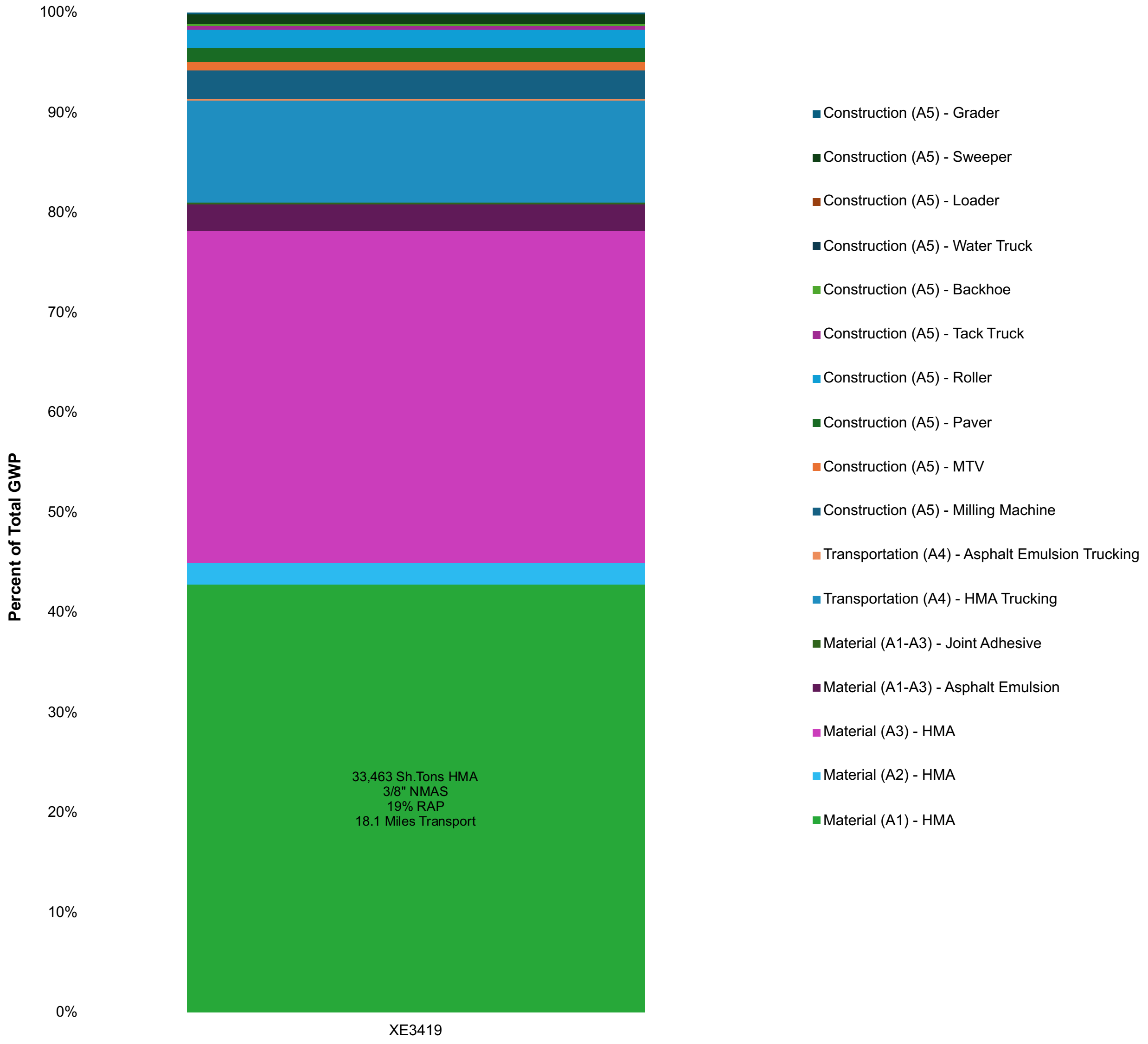


Figure 68 - XE3419 GWP Percent Contribution

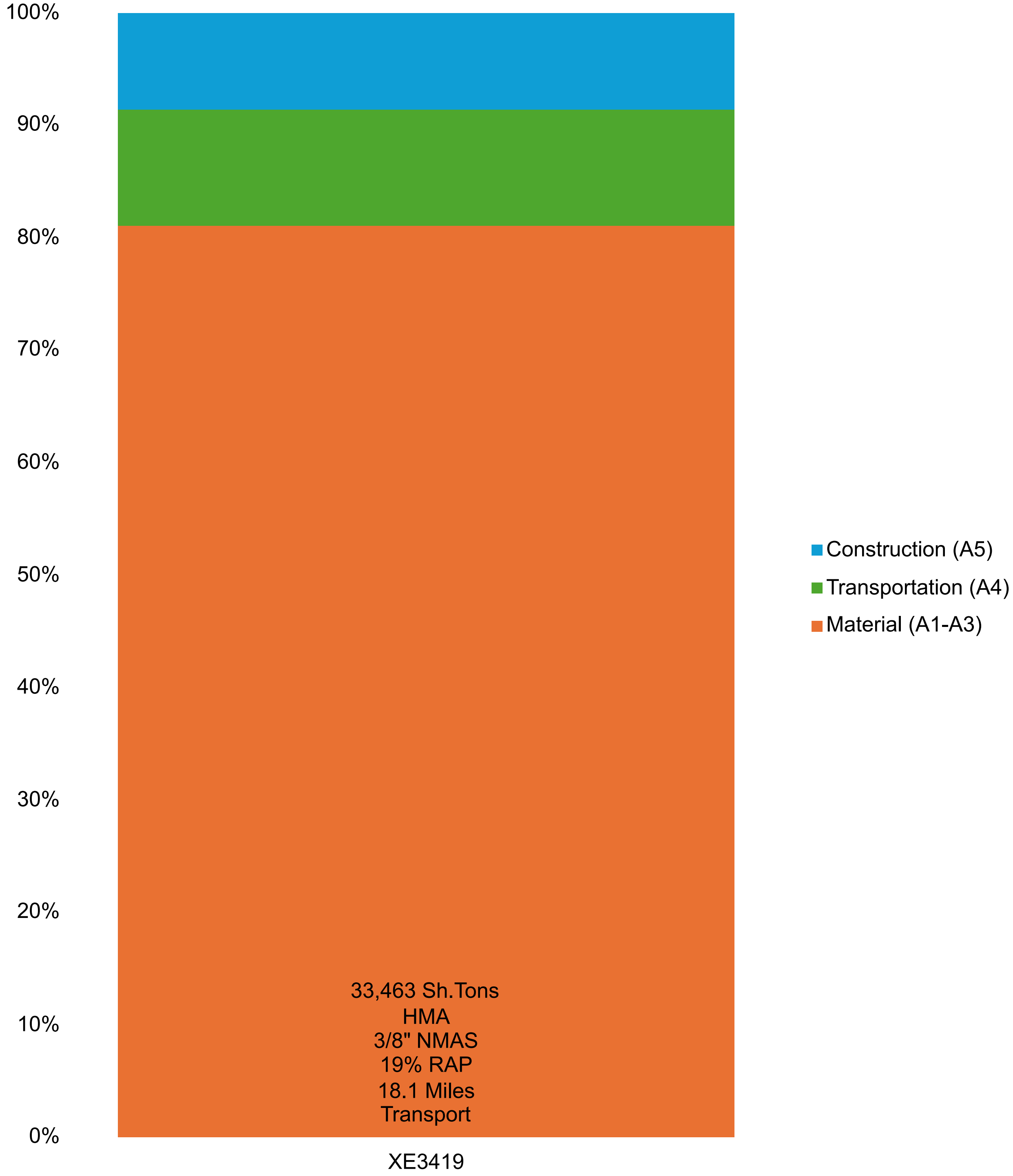


Figure 69 - XE3419 GWP by Life Cycle Stage Percent Contribution

11 Appendix E: Variables used in openLCA

Table 44 - openLCA Input Parameters

Name	Description
backhoe_total_fuel_use_gal	Total fuel use over entirety of project in gallons
dumptruck_belly_total_fuel_use_gal	Total fuel use over entirety of project in gallons
dumptruck_end_total_fuel_use_gal	Total fuel use over entirety of project in gallons
dumptruck_super_total_fuel_use_gal	Total fuel use over entirety of project in gallons
grader_total_fuel_use_gal	Total fuel use over entirety of project in gallons
loader_total_fuel_use_gal	Total fuel use over entirety of project in gallons
millingmachine_total_fuel_use_gal	Total fuel use over entirety of project in gallons
mtv_total_fuel_use_gal	Total fuel use over entirety of project in gallons
one_way_trucking_dist_mil	One-way trucking distance from asphalt plant to project site
paver_total_fuel_use_gal	Total fuel use over entirety of project in gallons
roller_19to56kW_total_fuel_use_gal	Total fuel use over entirety of project in gallons
roller_56to560kW_total_fuel_use_gal	Total fuel use over entirety of project in gallons
sweeper_total_fuel_use_gal	Total fuel use over entirety of project in gallons
tack_coat_gal	Gallons of emulsion used (tack coat, CSS-1)
tack_coat_travel_dist_mi	Approximate travel distance of emulsion
tacktruck_total_fuel_use_gal	Total fuel use over entirety of project in gallons
tons_of_asphalt	Total asphalt use in project
watertruck_total_fuel_use_gal	Total fuel use over entirety of project in gallons

Table 45 - openLCA Dependent Parameters

Name	Formula	Description
backhoe_MJ	(backhoe_total_fuel_use_gal * mj_per_gal_diesel) / tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
dumptruck_end_MJ	(dumptruck_end_total_fuel_use_gal *mj_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
dumptruck_super_MJ	(dumptruck_super_total_fuel_use_gal *mj_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
grader_MJ	(grader_total_fuel_use_gal *mj_per_gal_diesel)/ tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
loader_MJ	(loader_total_fuel_use_gal *mj_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
millingmachine_MJ	(millingmachine_total_fuel_use_gal *mj_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
mtv_MJ	(mtv_total_fuel_use_gal *mj_per_gal_diesel)/tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
paver_MJ	(paver_total_fuel_use_gal *mj_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
roller_19to56kW_MJ	(roller_19to56kW_total_fuel_use_gal *mj_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
roller_56to560kW_MJ	(roller_56to560kW_total_fuel_ use_gal *mj_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
sweeper_MJ	(sweeper_total_fuel_use_gal * mj_per_gal_diesel) / tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
tack_coat_tons	(tack_coat_gal /css_1_per_ton)	Value of tack coat used on job in tons
tack_coat_tons_per_ton_aspahlt	tack_coat_tons/tons_of_asphalt	Value of tack coat used on job in tons per ton of asphalt
tack_coat_travel_per_ton_asphalt	(tack_coat_tons *tack_coat_travel_dist_mi)/tons_of_asphalt	Tack coat in (ton-miles) per ton of asphalt. 56.1 derived from
tacktruck_MJ	(tacktruck_total_fuel_use_gal *MJ_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used
truck_travel_ton_miles	ceil(tons_of_asphalt *one_way_trucking_dist_mil)	Approximate number of ton miles that trucks traveled
watertruck_MJ	(watertruck_total_fuel_use_gal *mj_per_gal_diesel) /tons_of_asphalt	Energy consumption in MJ converted from total gallons of diesel used

12 Appendix F: Equipment Summary List

Contract Number	Type	Model	Engine Size (hp)	Engine Size Range (kW)
9954	Backhoe	CAT 420E BACKHOE 4X4 E STICK	93	19 - 56
XE3419	Backhoe	2013 CASE 580 SUPER N	96.6	56 - 560
XE3419	Backhoe	2020 CASE 580SN	95	56 - 560
XE3419	Backhoe	CASE 580CFN	79	56 - 560
XE3419	Backhoe	RENTAL BACKHOE	*not specified	56 - 560
XE3419	Grader	Cat 120H Motor Grader	140	56 - 560
9914	Loader	06 CAT 950G//PL	255	56 - 560
9914	Loader	20 CAT 980M/PF	398	56 - 560
9914	Loader	2017 CAT 259D SKID-STEER LDR	74.3	19 - 56
9914	Loader	16 CAT 972M /PF	299	56 - 560
9914	Loader	07 JD 310SJ/CLK	92	56 - 560
9914	Loader	96 CAT IT-24F /CLK	105	56 - 560
9914	Loader	2019 JD 844 LOADER	417	56 - 560
9954	Loader	CAT 299D2 COMPACT TRACK LOADER	110	56 - 560
9914	Milling Machine	Wirtgen W210i	720	56 - 560
9954	Milling Machine	Milling Machine	*not specified	56 - 560
XE3404	Milling Machine	Wirtgen Cold Milling Machine W 1200 F	700	56 - 560
XE3404	Milling Machine	Wirtgen W100fi	300	56 - 560
XE3419	Milling Machine	Milling Machine	*not specified	56 - 560
9914	MTV	2018 WEILER TRANSFER	250	56 - 560
9954	MTV	ROADTEC SB-2500C SHUTTLE BUGGY	300	56 - 560
XE3404	MTV	Weiler E2850 Transfer Machine	300	56 - 560
XE3419	MTV	Lincoln 660AXL	173	56 - 560
XE3419	MTV	2018 Roadtech SB-2500E Shuttle Buggy	300	56 - 560
XE3419	MTV	Roadtech SB-2500E	300	56 - 560

XE3419	MTV	Kol Cal	*not specified	56 - 560
9914	Paver	2016 VOGELE 10FT PAVER	173	56 - 560
9914	Paver	2017 VOGELE 8FT PAVER	173	56 - 560
9914	Paver	18 WEILER P3858/CLK	120	56 - 560
9954	Paver	CAT AP1055F ASPHALT PAVER	225	56 - 560
XE3404	Paver	Cat 1055E 10Ft Paver	225	56 - 560
XE3419	Paver	2021 Vogele S2000 Paver	250	56 - 560
XE3419	Paver	2022 Vogele Super 2000-3i	250	56 - 560
XE3419	Paver	2021 ROADTECH RP195 1233842	230	56 - 560
XE3419	Paver	2021 VOGELE S1700 PAVER	173	56 - 560
9914	Roller (19-56kW)	13 DYNAPAC CC1200/CLK	35	19 - 56
9914	Roller (19-56kW)	14 DYNAPAC CC-1200/CLK	35	19 - 56
9914	Roller (19-56kW)	2013 DYNAPAC DD1300 ROLLER	29	19 - 56
9954	Roller (19-56kW)	CAT CB24B COMPACTOR	36.2	19 - 56
9954	Roller (19-56kW)	CAT CB224E DD,V ROLLER	32.7	19 - 56
XE3404	Roller (19-56kW)	Dynapac pneumatic roller	75	19 - 56
XE3419	Roller (19-56kW)	Cat 4 Roller	48.2	19 - 56
9914	Roller (56-560kW)	2002 IR DD110 ROLLER	93	56 - 560
9914	Roller (56-560kW)	2017 VOLVO DD120 ROLLER	148	56 - 560
9914	Roller (56-560kW)	13 Caterpillar CB54 Roller	137	56 - 560
9914	Roller (56-560kW)	2019 VOLVO DD105 OS ROLLER	114	56 - 560
9914	Roller (56-560kW)	20 VOLVO PT240/PF	99.8	56 - 560
9914	Roller (56-560kW)	2023 Dynapac Roller	135	56 - 560
9954	Roller (56-560kW)	CAT CB64 ASPHALT COMPACTOR-VERSA VIBE	137	56 - 560
9954	Roller (56-560kW)	CAT CB66B ASPHALT COMPACTOR-5 AMPLITUDE	142	56 - 560
9954	Roller (56-560kW)	I-R DD138HF DD,V ASPH ROLLER	173	56 - 560
9954	Roller (56-560kW)	HAMM HD+90IVO COMPACTOR	114	56 - 560
XE3404	Roller (56-560kW)	Cat CB68B Pave Roller	142	56 - 560
XE3404	Roller (56-560kW)	Cat CB64 Pave Roller	137	56 - 560
XE3419	Roller (56-560kW)	Volvo DD 120 Roller	152	56 - 560

XE3419	Roller (56-560kW)	Volvo DD140 Roller	173	56 - 560
9914	Sweeper (19-56kW)	07 BROCE BROOM	74	19 - 56
XE3419	Sweeper (19-56kW)	2001 Broce Broom RC350	74	19 - 56
XE3419	Sweeper (19-56kW)	2021 BROCE RCT350	74	19 - 56
XE3419	Sweeper (19-56kW)	1994 BROCE HIGHWAY SWEEPER BROOM	74	19 - 56
XE3404	Sweeper (56-560kW)	Elgin Broom Bear Mechanical Sweeper	230	56 - 560
XE3404	Sweeper (56-560kW)	Elgin Regenerative Air Vacuum Sweeper	185	56 - 560
9914	Tack Truck	89 KW ETNYRE DISTR/CLK	*not specified	56 - 560
9954	Tack Truck	PETRB 335 2000GL OIL DIST	260	56 - 560
XE3404	Tack Truck	*not specified	750	56 - 560
XE3419	Tack Truck	Distributor	*not specified	56 - 560
9914	Water Truck	2004 PETERBILT WATER TK	350	56 - 560
9914	Water Truck	2000 STERLING WATER TR	350	56 - 560
9914	Water Truck	1992 FORD F8000 WATER TK	300	56 - 560
9954	Water Truck	INTL 2AX WATER	185	56 - 560

13 References

Ashtiani, M., M. Lewis, B. Waldman, and K. Simonen. 2024a. *CLF Embodied Carbon Toolkit for Roadway Infrastructure Accounting for Embodied Carbon in Roadway Infrastructure*. Seattle.

Ashtiani, M., M. Lewis, B. Waldman, and K. Simonen. 2024b. *CLF Embodied Carbon Toolkit for Roadway Infrastructure Accounting for Embodied Carbon in Roadway Infrastructure*. Seattle.

Ashtiani, M. Z. 2022. "Data-Driven Sustainability Assessment in Roadway Infrastructure Construction." Seattle: University of Washington.

Athena Pavement LCA. 2002. "Pavement LCA Athena Sustainable Materials Institute ." Accessed May 16, 2024. https://www.athenasmi.org/our-software-data/pavement-lca/.

Barbieri, D. M., B. Lou, F. Wang, I. Hoff, S. Wu, J. Li, H. R. Vignisdottir, R. A. Bohne, S. Anastasio, and T. Kristensen. 2021a. "Assessment of carbon dioxide emissions during production, construction and use stages of asphalt pavements." *Transp Res Interdiscip Perspect*, 11. https://doi.org/10.1016/j.trip.2021.100436.

Barbieri, D. M., B. Lou, F. Wang, I. Hoff, S. Wu, J. Li, H. R. Vignisdottir, R. A. Bohne, S. Anastasio, and T. Kristensen. 2021b. "Assessment of carbon dioxide emissions during production, construction and use stages of asphalt pavements." *Transp Res Interdiscip Perspect*, 11. https://doi.org/10.1016/j.trip.2021.100436.

Bjørn, A., M. Owsianiak, C. Molin, and M. Z. Hauschild. 2017. "LCA history." *Life Cycle Assessment: Theory and Practice*, 17–30. Springer International Publishing.

Brown, E. R., and C. E. Bassett. 1990. *Effects of Maximum Aggregate Size on Rutting Potential and Other Properties of Asphalt-Aggregate Mixtures*.

Calvin, K., D. Dasgupta, G. Krinner, A. Mukherji, P. W. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W. W. L. Cheung, S. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, Y.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F. E. L. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D. C. Roberts, J. Roy, A. C. Ruane, J. Skea, P. R. Shukla, R. Slade, A. Slangen, Y. Sokona, A. A. Sörensson, M. Tignor, D. van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, Z. Zommers, J.-C. Hourcade, F. X. Johnson, S. Pachauri, N. P. Simpson, C. Singh, A. Thomas, E. Totin, A. Alegría, K. Armour, B. Bednar-Friedl, K. Blok, G. Cissé, F. Dentener, S. Eriksen, E. Fischer, G. Garner, C. Guivarch, M. Haasnoot, G. Hansen, M. Hauser, E. Hawkins, T. Hermans, R. Kopp, N. Leprince-Ringuet, J. Lewis, D. Ley, C. Ludden, L. Niamir, Z. Nicholls, S. Some, S. Szopa, B. Trewin, K.-I. van der Wijst, G. Winter, M. Witting, A. Birt, and M. Ha. 2023. *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* (P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J. J. Pereira, R. Pichs-Madruga, S. K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürge-Vorsatz, C. Xiao, N. Yassaa, J. Romero, J. Kim, E. F. Haites, Y. Jung, R. Stavins, A. Birt, M. Ha, D. J. A. Orendain, L. Ignon, S. Park, Y. Park, A. Reisinger, D. Cammaramo, A. Fischlin, J. S. Fuglestvedt, G. Hansen, C.

Ludden, V. Masson-Delmotte, J. B. R. Matthews, K. Mintenbeck, A. Pirani, E. Poloczanska, N. Leprince-Ringuet, and C. Péan, eds.).

Frydendal, J., L. E. Hansen, and A. Bonou. 2017. "Environmental labels and declarations." *Life Cycle Assessment: Theory and Practice*, 577–604. Springer International Publishing.

Gettu, N., and W. G. Buttlar. 2024. "Critical Parameters Affecting the Carbon Footprint of Asphalt Mixes." *RILEM Bookseries*, 374–383. Springer Science and Business Media B.V.

Häkkinen, T., and K. Mäkelä. 1996. *Environmental adaption of concrete: Environmental impact of concrete and asphalt pavements*. Espoo: VTT Technical Research Centre of Finland.

Harvey, J. T., J. Meijer, H. Ozer, I. L. Al-Qadi, A. Saboori, and A. Kendall. 2016a. *Pavement Life-Cycle Assessment Framework*. *FHWA*. Washington, D.C.: Federal Highway Administration (FHWA).

Harvey, J. T., J. Meijer, H. Ozer, I. L. Al-Qadi, A. Saboori, and A. Kendall. 2016b. *Pavement Life-Cycle Assessment Framework*. *FHWA*. Washington, D.C.: Federal Highway Administration (FHWA).

Hauschild, M. Z. 2017. "Introduction to LCA methodology." *Life Cycle Assessment: Theory and Practice*, 59–66. Springer International Publishing.

Horvath, A., and C. Hendrickson. 1998. "Comparison of Environmental Implications of Asphalt and Steel-Reinforced Concrete Pavements." *Transportation Research Record: Journal of the Transportation Research Board*, 1626 (1): 105–113. https://doi.org/10.3141/1626-13.

Hoxha, E., H. R. Vignisdottir, D. M. Barbieri, F. Wang, R. A. Bohne, T. Kristensen, and A. Passer. 2021. "Life cycle assessment of roads: Exploring research trends and harmonization challenges." *Science of the Total Environment*, 759: 143506. Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2020.143506.

"International Energy Agency." 2019. *IEA*.

IPCC. 2021. *Headline Statements from the Summary for Policymakers*.

Meijer, J., J. Harvey, A. Butt, C. Kim, P. Ram, K. Smith, and A. Saboori. 2021. *LCA Pave: A Tool to Assess Environmental Impacts of Pavement Material and Design Decisions Underlying Methodology and Assumptions. FHWA-HIF-22-033 Available at: https://www.fhwa.dot.gov/pavement/lcatool/LCA_Pave_Tool_Methodology.pdf*. Washington D.C.

Miller, L., B. Ciavola, and A. Mukherjee. 2024. *EPD BENCHMARK FOR ASPHALT MIXTURES*.

Mukherjee, A. 2022. "Update to the Life Cycle Assessment for Asphalt Mixtures in Support of the Emerald Eco Label Environmental Product Declaration Program." (April).

Mukherjee, A. n.d. *Data Quality Assessment for Background Data*.

National Asphalt Pavement Association. 2022a. *Product Category Rules (PCR) for Asphalt Mixtures*. Greenbelt.

National Asphalt Pavement Association. 2022b. *Product Category Rules (PCR) for Asphalt Mixtures*. Greenbelt.

National Asphalt Pavement Association. 2022c. *Product Category Rules (PCR) for Asphalt Mixtures*. Greenbelt.

Noland, R. B., and C. S. Hanson. 2015. “Life-cycle greenhouse gas emissions associated with a highway reconstruction: A New Jersey case study.” *J Clean Prod*, 107: 731–740. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2015.05.064.

openLCA. 2021. “Tutorial: Explanatio of database elements in openLCA.” Accessed February 25, 2024. https://youtu.be/oSJeYZGH3xs?feature=shared.

PRé Sustainability. 1990. “SimaPro.” *PRé Sustainability*. Accessed May 16, 2024. https://simapro.com/.

Rangelov, M., H. Dylla, A. Mukherjee, and N. Sivaneswaran. 2021a. “Use of environmental product declarations (EPDs) of pavement materials in the United States of America (U.S.A.) to ensure environmental impact reductions.” *J Clean Prod*, 283. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.124619.

Rangelov, M., H. Dylla, A. Mukherjee, and N. Sivaneswaran. 2021b. “Use of environmental product declarations (EPDs) of pavement materials in the United States of America (U.S.A.) to ensure environmental impact reductions.” *J Clean Prod*, 283. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.124619.

RICS. 2023. *Whole Life Carbon Assessment for the Built Environment RICS PROFESSIONAL STANDARD*. London: Royal Institution of Chartered Surveyors.

(SAIC), S. A. I. C. 2006. “Life Cycle Assessment: Principles and Practice Epa/600/R-06/060.” *Global Shadows: Africa in the Neoliberal World Order*, 44 (2): 8–10.

Santero, N., E. Masanet, and A. Horvath. 2010a. “Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research.” *Lawrence Berkeley National Laboratory*, (April): 81. https://doi.org/10.1016/j.resconrec.2011.03.010.

Santero, N., E. Masanet, and A. Horvath. 2010b. “Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research.” *Lawrence Berkeley National Laboratory*, (April): 81. https://doi.org/10.1016/j.resconrec.2011.03.010.

Senseney, C. 2023. *Development of Environmental Product Declarations (EPDs) for Sustainable Pavement Procurement*. Denver, CO.

Shacat, R., J. Willis, and B. Ciavola. 2024. *THE CARBON FOOTPRINT OF ASPHALT PAVEMENTS A REFERENCE DOCUMENT FOR DECARBONIZATION*. Greenbelt.

Sharifi, F., A. G. Birt, C. Gu, J. Shelton, R. Farzaneh, J. Zietsman, A. Fraser, and M. Chester. 2021. “Regional CO2 impact assessment of road infrastructure improvements.” *Transp Res D Transp Environ*, 90 (December 2020): 102638. Elsevier Ltd. https://doi.org/10.1016/j.trd.2020.102638.

Stripple, H. 2001. *Life cycle assessment of road: a pilot study for inventory analysis*. *IVL Swedish Environmental Research Institute Ltd*. Gothenburg, Sweden.

U.S. EPA. 2023. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990-2021 (EPA-420-F-23-016, June 2023)*.

Weiland, C. D., and S. T. Muench. 2010. “Life Cycle Assessment of Portland Cement Concrete Interstate Highway Rehabilitation and Replacement.” (February).

WSDOT. 2024. *Standard Specifications for Road, Bridge, and Municipal Construction*.

Zapata, P., and J. A. Gambatese. 2005. “Energy consumption of asphalt and reinforced concrete pavement materials and construction.” *Journal of Infrastructure Systems*, 11 (1): 9–20. https://doi.org/10.1061/(ASCE)1076-0342(2005)11:1(9).

Zokaei Ashtiani, M. 2022. “Data-Driven Sustainability Assessment in Roadway Infrastructure Construction.” Seattle: University of Washington.

Zokaei Ashtiani, M., and S. Muench. 2024. “Application of Greenroads Rating System and Life Cycle Assessment in Informing the State of the Practice in Sustainable Roadway Construction.” *Transp Res Rec*. SAGE Publications Ltd. https://doi.org/10.1177/03611981241233274.