Greenhouse Gas Emissions Inventory from Construction of Washington State Department of Transportation Roadways

FINAL REPORT

A professional report commissioned by the Washington State Department of Transportation

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Carbon Leadership Forum

COLLEGE OF BUILT ENVIRONMENTS
UNIVERSITY of WASHINGTON

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DISCLAIMER

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The Carbon Leadership Forum (CLF) is a research group at the University of Washington. We are architects, engineers, contractors, product suppliers, building owners, and policymakers who work collaboratively, pioneering research, creating resources, and incubating member-led initiatives for the greatest collective impact. Our goal is to accelerate the transformation of the building sector to radically reduce and ultimately eliminate the embodied carbon in building materials and construction.

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The authors declare no conflict of interest.

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EXECUTIVE SUMMARY

To date, the Washington State Department of Transportation (WSDOT) has not yet conducted a systematic assessment of its upstream construction-related greenhouse gas (GHG) emissions, also known as embodied carbon or upstream [supply chain] Scope 3 emissions (arising from manufacturing, transportation, installation, maintenance, and disposal of construction materials). This research project assesses and analyzes the greenhouse gas emissions of WSDOT's current material practices, and explores opportunities to drive down these embodied carbon emissions. Specifically, this research project aimed to achieve the following objectives:

1. **Establish an embodied carbon baseline**. It was important to estimate WSDOT's current inventory of upstream Scope 3 emissions in order to 1) understand the scope of emissions, and 2) establish a *baseline*, which will be useful for measuring the effects of any carbon reduction strategies in the future.
2. **Develop recommendations**. After analyzing WSDOT's current embodied carbon emissions and learning about its current material practices, the research team developed a list of potential strategies for reducing upstream Scope 3 emissions in WSDOT's standard operating procedures.
3. **Propose decarbonization scenarios**. Use the identified carbon reduction strategies and baseline to perform scenario analysis on potential pathways for WSDOT to achieve significant reductions of its upstream Scope 3 emissions. These scenarios are used to inform the highest priority recommendations for WSDOT.

The impact of this project can be far-ranging. In addition to reducing its own GHG emissions, WSDOT can lead the uptake and regional availability of low-carbon solutions for carbon-intensive construction materials such as asphalt, concrete, and steel by creating a market for lower-carbon materials.

Additionally, state and federal procurement policies, also referred to as Buy Clean, are requiring action from transportation agencies to limit the greenhouse gas emissions of their capital projects. WSDOT can use this research to prepare in advance of future legislation. Getting ahead of anticipated regulations on construction emissions will facilitate future decarbonization efforts, allow WSDOT time to identify the most cost-effective route to adopting lower-carbon material procurement and construction practices, and give WSDOT the opportunity to shape future policy through providing input from lessons learned.

The research team collected a wide variety of data from WSDOT with the assistance of WSDOT staff. This data included pay item lists (unit bid analysis data), HQ Materials Laboratory data (Statistical Analysis of Materials and Record of Materials), Pavement Office data (Pavement Management System), and data from the Washington State Facilities, among others. The main dataset in this study is founded on pay item lists from 609 contracts advertised between 2017 and 2021 (5-years worth of data). The dataset is then modified with the addition of several other data attributes to create a framework for and perform a whole lifecycle assessment (LCA). Lifecycle emission factors for primary construction materials were used to calculate upstream Scope 3 emissions using the LCA framework and received data. Economic emission factors were further developed and used to estimate upstream Scope 3 emissions from projects to provide baseline values.

The following provides a summary of our key findings:

- The 5-year average upstream Scope 3 emissions from roadway construction between 2017 and 2021 is approximately 310 thousand metric tons of CO_2 equivalent (a measure of global warming potential – GWP). Figure ES1 shows a graphical summary of our LCA results broken down by primary material types.
- On average, materials production, transportation, and installation (i.e., construction activities) contribute to 85%, 11%, and 4% of total upstream Scope 3 emissions, respectively.
- Upstream Scope 3 emissions from roadway construction (i.e., excluding emissions produced during the operation of a roadway; for example, fuel usage by vehicles and roadway lighting) are as big of a contributor to WSDOT's greenhouse gas emissions as Scope 1 and 2 emissions (GHG emissions from direct and indirect fuel or energy consumption).
- Pavement construction—hot mix asphalt production in particular—is the biggest contributor to the upstream Scope 3 emissions from WSDOT roadway construction due both to its high consumption and high carbon intensity.

Lastly, this report conducts background research and a literature review on carbon reduction strategies tailored to upstream Scope 3 emissions. Using the dataset created in this study, we performed scenario analyses and provided recommendations on the most impactful strategies that help WSDOT reduce its Scope 3 emissions. Finally, this report proposes carbon reduction targets for WSDOT's roadway construction activities with a proposed decarbonization scenario to achieve near net-zero targets by 2050.

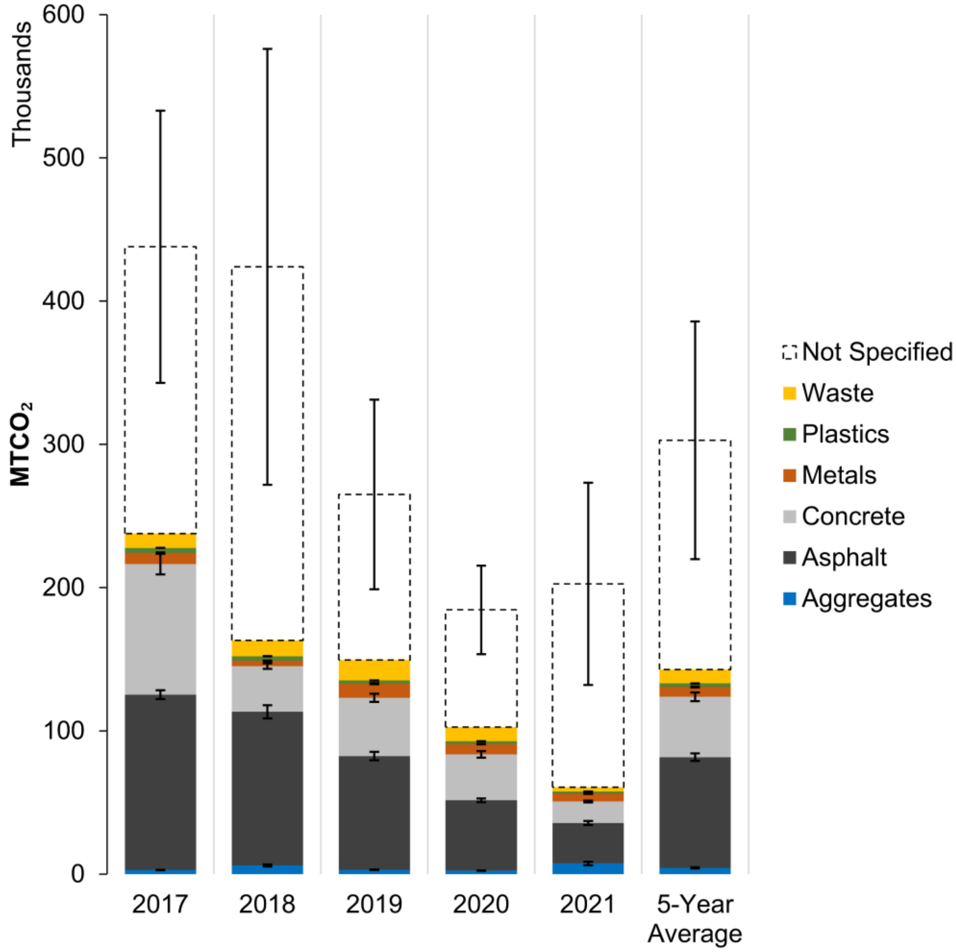

Figure ES1. Total Scope 3 emissions from WSDOT roadway construction projects estimated (dashed boxes) and measured (solid boxes) showing the contribution of each material type to the total annual emissions.

INTRODUCTION AND BACKGROUND

The world is rapidly approaching a tipping point in the climate crisis. Departments of Transportation (DOTs), such as the Washington State Department of Transportation (WSDOT), can help reduce greenhouse gas (GHG) emissions by influencing the uptake and regional availability of low-carbon solutions for carbon-intensive construction materials such as asphalt, concrete, and steel. Due to energy-intensive manufacturing processes, it is difficult to reduce the emissions associated with these materials, but there are readily-available, low-cost solutions to reducing their environmental impacts. DOTs can encourage the adoption of such solutions because they, along with cities, counties and private entities, are responsible for using high volumes of these materials, and can affect demand on a large scale.

Additionally, state and federal procurement policies (e.g., the Federal Buy Clean policy) are requiring action from transportation agencies to limit the greenhouse gas emissions of their capital projects (see the Background section to learn more about the most recent embodied carbon-related policies). WSDOT can prepare for these requirements and possibly shape future pathways by considering agency policies and practices in advance of newer legislation. Getting ahead on anticipated regulations on construction emissions will navigate future decarbonization efforts and allow WSDOT time to identify the most cost-effective route to adopting lower-carbon material procurement and construction practices.

WSDOT has not yet conducted a systematic assessment of its construction-related upstream GHG emissions. In general, GHG emissions from agency operations can be broken down into three categories or scopes:

- **Scope 1 emissions**. This includes direct emissions from sources that are owned or controlled by WSDOT. Emissions from on-site combustion of fuels in boilers, furnaces, vehicles, etc. to generate electricity, heat, or power vehicles.
- **Scope 2 emissions**. This includes indirect emissions from purchased electricity. These emissions physically happen within facilities where electricity is generated. WSDOT can directly control the purchases but cannot control the processes used to generate the electricity from the source.

- **Scope 3 emissions**. This includes all other indirect emissions not captured in Scope 2. Scope 3 emissions are a consequence of WSDOT activities while the emissions are generated by sources not under WSDOT's control. Scope 3 emissions are more difficult to estimate and reduce due to the lack of direct control over the source of emissions. Examples of Scope 3 emissions are employee commute, employee business travel, transmission and distribution (T&D) losses due to electricity purchase, contracted solid waste, contracted wastewater treatment, and emissions due to the production, transportation, and placement of materials (also known as *upstream Scope 3 emissions* or *embodied carbon*).

This report focuses on upstream Scope 3 emissions, including upstream cradle-to-placement GHG emissions from construction materials (see the System boundary section for more detail). These emissions are also referred to as embodied carbon (the GHG emissions arising from manufacturing, transportation, installation, maintenance, and disposal of construction materials). We will be using the term upstream Scope 3 emissions in this report, as this is the term most commonly used by other DOTs (e.g., ICF (2020a) and Good Company (2021a, 2021b)).

This research project assesses and analyzes the greenhouse gas emissions of WSDOT's current material practices, and explores opportunities to drive down these emissions. Specifically, this research project aims to achieve the following objectives:

1. **Establish upstream Scope 3 emission baseline and reduction targets**. It is important to estimate the current greenhouse gas emissions footprint of WSDOT's current construction materials practices in order to establish a *baseline*, which WSDOT can use to measure its future emissions reduction efforts. Once baselines are developed, WSDOT-specific GHG reduction targets can be determined in line with state-wide targets.

2. **Develop recommendations**. After analyzing WSDOT's current Scope 3 emissions footprint and learning about its current material practices, the research team will develop cost-effective, implementable strategies and recommendations for reducing embodied carbon in WSDOT's standard operating procedures. These recommendations will focus on Scope 3 emissions from material production and

construction processes.

3. **Propose decarbonization scenarios**. Apply carbon reduction strategies to the dataset created in this study to perform scenario analyses on the level at which the implementation of each strategy helps mitigate GHG emissions. As a result, a decarbonization roadmap for WSDOT is proposed.

REVIEW OF PREVIOUS WORK

Over one-third of annual emissions from public sector construction in the United States are attributable to highway and street construction.[1] In addition to carbon-intensive materials like asphalt, the transportation infrastructure construction sector relies heavily on cement and steel, the largest sources of industrial carbon emissions (Hasanbeigi et al., 2021). These emissions are "critical to abate" due to the energy-intensive methods required to produce these materials. However, readily-available, low-cost solutions already exist to reduce the environmental impacts of these construction materials. State Departments of Transportation (DOTs) can heavily influence the uptake and regional availability of these low-carbon solutions while reducing their own emissions footprints because DOTs are reliable customers for high volumes of these materials.

Another aspect to consider is policy. Increasingly, state and federal procurement policies are requiring action from transportation agencies to limit the greenhouse gas emissions of their capital projects. For example, California Department of Transportation (Caltrans) projects are required by the Buy Clean California Act (*Buy Clean California Act*, 2018) to use rebar and structural steel materials that are below certain global warming potential (GWP – a measure of GHG emissions) limits, starting in June 2022. Similar bills were passed in Colorado in 2021 (*Global Warming Potential For Public Project Materials*, 2021) and Oregon in 2022 (*Relating to Reductions of Greenhouse Gas Emissions in the State's Transportation System; and Prescribing an Effective Date*, 2022) that will require their state DOTs to implement Buy Clean programs to limit emissions from eligible construction materials. Most recently at the federal level, the General Services Administration (GSA) has published its first standard that sets thresholds on greenhouse gas emissions for asphalt and concrete materials (GSA, 2022) which further showcases the recent interest in cutting down emissions from commonly used construction materials.

Legislators in Washington proposed similar bills in 2018, 2020, and 2021, resulting in two buildings-focused pilot studies of the requirements (Lewis et al., 2021). WSDOT can prepare for these requirements and shape implementation by considering agency policies and practices in advance of newer legislation. Getting ahead on anticipated

[1] Based on US Census Bureau ("Annual Value of Construction Spending Put in Place" for 2008 – 2018) spending data and the US EPA USEEIO v1.1 data for emissions intensity.

regulations on construction emissions will ease future decarbonization efforts and allow time for WSDOT to identify the most cost-effective route to adopting lower-carbon material procurement and construction practices. For more discussions of policies related to upstream Scope 3 emissions refer to the Background section).

The existing literature on a comprehensive agency-wide accounting of embodied carbon for a state DOT is very limited. Oregon Department of Transportation (ODOT) has possibly conducted the most thorough research study on its greenhouse gas emissions of asphalt, concrete, and steel consumption. Although ODOT like many other state DOTs typically has unique mechanisms for data collection and storage practices, its overarching approach to quantifying greenhouse gas emissions can be closely replicated. In the report published by ODOT, it was shown that hot mix asphalt and concrete together contribute to the largest chunk of greenhouse gas emissions stemming from the construction and maintenance of roadways in Oregon (Good Company, 2021a, 2021b).

Like other transportation agencies, WSDOT uses large quantities of concrete, steel, and asphalt in its infrastructure projects. However, WSDOT has not yet conducted a systematic assessment of its construction-related upstream Scope 3 greenhouse gas emissions, also known as embodied carbon (arising from manufacturing, transportation, installation, maintenance, and disposal of construction materials). Thus, this project will assess and analyze the upstream Scope 3 emissions of WSDOT’s current material practices, and explore opportunities to drive down these emissions.

Finally, this study will act as a reference for future development and implementation of environmental product declarations (EPDs) in the procurement of roadway construction projects. EPDs are ready-to-use lifecycle assessment results that facilitate data transparency and validity for emission factors to be used by contractors in order to conform with the soon-to-be standardized specifications limiting the embodied carbon of common construction materials (Mukherjee et al., 2020; Rangelov et al., 2021). Our findings will help provide insights into WSDOT’s readiness to incorporate EPD concepts into its currently operating data management systems while also preparing WSDOT to collaborate with the Federal Highway Administration in its recently funded Climate Challenge project.

RESEARCH APPROACH, DATA COLLECTION, AND METHODS

This chapter introduces the data collection procedure for this research project, including the type and source of data obtained and the interviews conducted to recognize data needs and availabilities, while elaborating on the methodological procedure followed to perform a lifecycle assessment (LCA).

Meetings and Interviews

We conducted a series of interviews mainly with WSDOT staff to become familiar with different data sources and Divisions/Offices responsible for their maintenance throughout the agency. Several bi-monthly virtual meetings have also been held with the WSDOT research panel to discuss questions posed during the interviews, request clarification on certain aspects of the project, and provide updates regarding the research progress. Outside WSDOT, our research team interviewed representatives from the ODOT, the National Asphalt Pavement Association (NAPA), and the Washington Asphalt Pavement Association (WAPA). Table 1 indicates the name of the interviewees, the date of the interviews, and the purpose of our discussion for all the meetings held from the beginning of the project.

Table 1. List of interviews conducted to date and ordered chronologically.

Date	Interviewee(s)	Interview/Meetings Agenda
01/26/2022 02/22/2022 03/30/2022 04/18/2022 05/02/2022 05/16/2022 06/01/2022 06/13/2022 06/27/2022	Project research team at WSDOT: Jon Peterson (research manager) Loc Tran Jonathan Olds Anthony Mizumori Kurt Williams Kim Schofield Jon Deffenbacher Steve Davis	These are the meetings our research team held with the research panel and representatives from WSDOT to discuss the project scope in general and seek assistance regarding data collection and availabilities. Not all interviewees were present during all these meetings and the list only shows the collective presence of those who attended.
04/04/2022	National Asphalt Pavement Association (NAPA): Joseph Shacat Richard Willis Washington Asphalt Pavement Association (WAPA): Dave Gent	Discussed several topics including past DOT experiences with Environmental Product Declarations (EPDs) and carbon baselining efforts, regional availability of asphalt EPDs, LCA tools such as PaveLCA, contractors' views on carbon accounting, roadway infrastructure sustainability and decarbonization pathways, etc.

04/15/2022	Oregon Department of Transportation (ODOT): Zechariah Heck	To date, ODOT has been the only agency that has conducted a similar study to this one. In this interview, we asked about the lessons learned, available resources, and any recommendations to successfully carry out this study.
04/27/2022	WSDOT: Jim Weston	Overview of which WSDOT data sources would be useful for our study. Several WSDOT divisions and contact people were mentioned during this meeting for future follow-up.
05/02/2022	WSDOT: Jianhua Li	Discussed Pavement Management System (PMS) data to form an official request for data. The PMS platform was demonstrated and the extent of available data was explored.
05/03/2022	Washington State Ferries (WSF): Kevin Bartoy	For information regarding the Washington ferry system including the data submitted to the Department of Ecology regarding the carbon inventory of ferry vessels and other fuel usage sources across WSDOT.
05/04/2022	WSDOT: Tomi Hume-Pontius	Questions regarding the use of Unit Bid Analysis data and access to its Pro version.
05/04/2022	WSDOT: Trett Sutter	Introduction to the Highway Activity Tracking System (HATS) and how data collected within that system might help with this project.
05/06/2022	WSDOT: Mark Smith Jim Rodgers	WSDOT-owned facilities including buildings were discussed. Information about electricity usage and other stationary and non-stationary energy sources were sought.
05/11/2022	WSDOT: Steve Holloway	General questions about WSDOT size, its managed inventory (buildings in particular), and requests for data sent to the Department of Ecology for their carbon inventory report.
05/17/2022	WSDOT: Nicole Knudson	Helped collect financial information regarding roadway maintenance activities
05/18/2022	WSDOT: John Henry Waugh	Discussed questions regarding bridge preservation and maintenance at WSDOT.

Data Collection

To understand the full scope of WSDOT’s GHG emissions, the research team endeavored to collect a wide variety of data. In addition to material-related data, the research team also collected information about other sources of emissions in order to understand the relative significance of WSDOT’s Scope 3 emissions. The research team limited the data's temporal range to contracts advertised between January 2017 – December 2021 (5 years). The research team collected this data by either 1) downloading what was publicly available on WSDOT's website, or 2) reaching out to WSDOT staff from various Divisions/Offices, who then provided the requested data. Table 2 shows the specific sources of data sought out by the research team, ranked in order of priority, and the collection results.

Table 2. Sources of data collected from WSDOT.

Priority	Data source	Description	Data collection results
1	Unit bid analysis (UBA)	The UBA database contains cost estimates of bid items from past WSDOT projects. This is the main source of data for material quantity estimates, particularly for items not included in SAM or PMS databases.	The research team downloaded a Standard Bid Item report and a Non-Standard Bid Item report (date range 2017 – 2021) from the website on May 4, 2022.
2	Statistical Analysis of Materials (SAM)	SAM is a computer program in WSDOT's Materials Laboratory that statistically evaluates materials according to the requirements of WSDOT Standard Specifications. SAM mainly contains data on hot mix asphalt and concrete pavements.	WSDOT staff sent export files from SAM to the research team on May 11, 2022. A new request was sent for updated data on June 29, 2022. Data was received July 25, 2022.
3	Highway Activity Tracking System (HATS)	HATS is a software application developed by WSDOT that collects data from maintenance activities (mainly pavement-related) on roadways and bridges.	WSDOT staff sent export files from HATS to the research team on May 22, 2022.
4	Record of Materials (ROM)	ROM is a data repository that contains major construction items provided by WSDOT's Materials Laboratory for each project. The data reflects planned (not put-in-place) material quantities.	WSDOT staff sent data from ROM to the research team on May 11, 2022.
5	Pavement Management System (PMS)	PMS is a database that contains pavement data (e.g., thickness, material type and class, condition, etc.) on all WSDOT roadways.	PMS data was received on June 1, 2022, from the FTP website.
6	Construction equipment data from Unifier	Construction equipment operation hours were received for some contracts awarded after 2019.	Data was received on June 29, 2022.
7	Ferries and	Any data on energy consumption and	WSDOT staff sent data to the

	facilities data	emissions of ferries, buildings, and other stationary and non-stationary energy sources owned by WSDOT.	research team on May 4, 2022.
8	General project construction data	List of contracts awarded between 2017 and 2022 including their general characteristics such as the award date, completion date, location, short description, bid price, final price, etc.	Data was received from the Construction HQ on June 30, 2022.
9	Project plans and specifications	For some contracts, WSDOT's FTP site contains folders that store project-specific information—most importantly, project specifications and plans help inventory material quantities and types.	Data was collected as needed from the contracts listed on the WSDOT's FTP website.

Data Cleaning and Modification

The usefulness of the collected data relied heavily on how well they could be sorted out and prepared for further analysis. None of the received materials were inherently ready-to-use; in that, most data were collected and stored without being structurally suitable for quantitative analysis. For example, SAM contained several repetitions of data rows related to a single lot of a single contract reflecting different properties of the material tested (e.g., binder content, air content, density, voids in mineral aggregate, aggregate size, etc.). Not only does such data structure increase the data size, but it can also make data analysis inefficient. Attempts were made to clean up the data for further analysis. Although the analysis was built upon the bid unit analysis data in this project (we will call the final dataset the *modified pay item list*), the following sections briefly describe the data-cleaning procedures undertaken to reinforce unit bid data with enough information to enable a detailed lifecycle assessment.

Unit bid analysis

Unit bid analysis data (aka pay item list data) was gathered from the publicly available tool through the WSDOT website. Unit bid analysis data comprised the list of items that a project described by its contract number has paid for and was expressed in a short description followed by a unit of measure, planned quantity, unit price, and lowest bid price. Filters were applied to dates to include only contracts advertised after 2017. Both standard and non-standard items were exported. Standard items are those that have been included in the WSDOT Standard Specification Manual with their standard numbers indicated within the unit bid data. Non-standard items are uncommonly used materials that are not still included in the standard specifications. It must be noted that design-build projects were also listed under the non-standard items with a lump sum value representing their bid price which poses serious challenges in terms of material inventory information. Consequently, the majority of design-build projects were left out of the detailed LCA performed based on materials used in a project and were only included in a simulation where greenhouse gases were estimated based on the total project's bid price.

The raw unit bid data exports included several rows summarizing the average bid price for each standard item. This is useful information for contractors in pursuit of bidding for a project. However, such data summaries were not of any use in this research project and were indeed troublesome for data analysis purposes. The raw data further divided pay items by WSDOT regions which caused some difficulties with data sorting and analysis. The raw data were thus cleaned up in a way that bid price summaries for each standard item were removed and the WSDOT regions were included as a separate data column associated with each pay item. This way, a continuous dataset (we call this the *original pay item list dataset*) was obtained including the following columns (i.e., data attributes): ID (an arbitrary number assigned to each row of data to act as a unique identifier), contract number, standard item number, item description, unit of measure, planned quantity, unit price, low bid price, total price of each item (multiplication of unit price by low bid price), project's advertisement date, and WSDOT region.

Material weights

Despite pay item descriptions being self-explanatory in most cases, data sorting and filtering based on those descriptions alone did not satisfy our analysis needs. Our goal in this project was to find out the primary material types that were used by each project as well as an estimate (or actual measurement) of their quantities expressed in conventional units of measure such as weight in tons or pounds. Consequently, five additional data fields were added to the dataset to describe each of the pay items. A top-down approach was taken to describe each pay item with up to five distinct phrase combinations; most of which expressed the main materials used in each of the pay items. For example, a pay item described as "reinforced concrete pavement" was broken down and assigned to three distinct terms: "pavement," "concrete," and "rebar." The top-down approach, in this case, meant that one would only realize this item was a "pavement" before looking closer at its composition. After a closer look at this item, one will understand it is made out of "concrete" and upon further digging into its components, one could understand that it was "reinforced." It is worth noting that pay items measured in the unit of lump sum (L.S.), estimates (EST.), or calculated (CALC.) were most often excluded from our analysis due to complexity. A word cloud of the most repeated items in the unit bid analysis data is depicted in Figure 1 (larger font size indicates more repetition of the term).

Figure 1. Word cloud showing the most repeated items in the unit bid analysis data.

After assigning each pay item to several components that described their composition and functionality, an attempt was made to estimate their density when the unit of measure was neither in tons nor pounds. For example, a "catch basin" is measured in units of "EACH" and one needs to know how much "each catch basin" weighed depending on its type. As another example, one needed to know how much each "linear foot" of curbs and gutters weighed depending on their type to estimate the total quantity of concrete used to build those. For concrete measured in units of volume (e.g., cubic yard or cubic foot), an assumed density of 145 to 150 lbs/ft^3 (or 3,950 to 4,050 lbs/cy) was used to convert to weight. The reasoning behind these conversions is the fact that most lifecycle greenhouse gas emission factors are expressed per unit of weight and without an estimate of the weight for each pay item, an accounting of total greenhouse gas emissions for a project seemed infeasible.

Due to the high volume of data (more than 27,000 data rows), a manual procedure to extract density and weight information for each pay item was impractical. Unit bid price and total price were the only pieces of information available for pay items not measured in either unit of volume (e.g., cubic yard) or weight (e.g., pounds) to help estimate their weights. In this research, we deployed economic-based models to provide estimates of material weights or unit weights for each pay item according to their bid price. A publicly available dataset organized and published by Zokaei Ashtiani & Muench (2022a) that contains detailed pay item lists from 30 roadway construction projects was used to build models that approximate material weights given their price. Several mathematical models were constructed for different material types (see Table 10 in Appendix A). The use of these models was made possible by sorting the unit bid data by the assigned material types explained earlier and applying the models to each row of data. In some cases, material compositions were also extracted from these models when further information was not available from other WSDOT databases.

Material compositions

Each pay item most typically constitutes a mixture of raw materials. For example, a pay item for hot mix asphalt usually consists of three types of materials namely coarse aggregate, fine aggregate, and asphalt binder (aka bitumen). It is, however, worth mentioning that the total price of a pay item includes all expenditures associated with it such as installation, hauling, labor, and any other overhead costs.

To properly indicate the composition of each pay item, we recognized 36 primarily raw materials that can be used to break down composite materials such as [reinforced] cement concrete, hot mix asphalt, manholes, catch basins, bridge superstructures, etc. There were also instances where a pay item consisted of only one type of material that did not require further breakdown (e.g., gravel borrow). For those that were composed of more than one constituent material, we used a variety of resources to find out or estimate material compositions and proportions. Depending on availability, the main resources for that matter were the SAM dataset, ROM dataset, project specifications, and online resources such as standard WSDOT plans or manufacturer's websites.

Material compositions were thus expressed in percentages of the total weight of each pay item. As a result, the actual weight of each constituent material could be calculated by multiplying the total weight by the percentage of those used in a pay item. This would later help perform a lifecycle assessment using emission factors (expressed in units of CO_2eq per weight of the material, for example, metric tons of CO_2 per U.S. short tons). All necessary calculations could then be performed ad hoc.

Material transportation

Transportation of materials from suppliers/producers to the construction job site also emits greenhouse gas emissions and this needed to be accounted for. To estimate emissions due to transportation, three pieces of information were required (added to the unit bid data as three separate columns): 1) material weight, 2) hauling distance, and 3) transportation mode (i.e., type of vehicle). Material weights were estimated from the previous section. For hauling distances, we were unable to find any WSDOT dataset that collected such information. Although ROM provided some information about certain material suppliers, it contained major data gaps that prevented the immediate assignment of transportation distances to particular pay items. The same is true for transportation modes, where no information was found in any of the WSDOT databases. Consequently, the roundtrip transportation distance was assumed to be 25 miles for all pay items with a materialistic nature. A heavy-duty dump truck (HHDVV) was further assumed to be used for hauling materials.

Construction activities

The operation of construction equipment was another source of greenhouse gas emissions. Roadway preparation and earthwork including pavement milling, excavation, removal of structures and obstructions, installation and laydown of paving materials, embankment compaction, etc. were the major construction activities that emit greenhouse gases. Although WSDOT has started acquiring data on construction equipment usage, due to a lack of clarity and missing information, Washington State DOT's *Plans Preparation Manual* (WSDOT, 2020) and Florida DOT's *Construction Project Administration Manual* (FDOT, 2017) were used to estimate production rates and operating hours for each piece of equipment required to deliver a construction activity.

As a result, fourteen extra data columns were added to the unit bid analysis dataset to capture construction activities. In that, one column represented the production rate while another column converted the production rate to operating hours using the quantity or volume of materials involved in that activity. Furthermore, it was assumed that each pay item could be delivered by using up to four distinct construction equipment types (e.g., excavators, rollers, milling machines, dozers, etc.). For each construction equipment, a separate data column was also created to indicate the work efficiency (i.e., down time or idling). And finally, four additional columns were used to assign each construction equipment to an engine size expressed in horsepower. Knowing the rate of fuel consumption for each type of equipment and engine size enabled the calculation of total energy usage and thus total greenhouse gas emissions due to the construction activities related to a pay item. For example, building hot mix asphalt pavements required three main types of equipment: pavers, rollers, and material transfer vehicles. The next chapter elaborates on how greenhouse gas emissions were calculated for construction activities.

Statistical Analysis of Materials (SAM)

The SAM program was developed as a statistical acceptance of materials specifications and is used to calculate pay factors for payment on statistically accepted materials such as aggregate, asphalt and portland cement concrete pavement. SAM data contains information regarding the statistically evaluated materials within a project. SAM mainly pertains to hot mix asphalt and concrete materials used on pavement sections of a project. SAM is most useful to obtain as-built quantities since it includes information on the quantities tested for statistical conformance with specifications. SAM further includes several other data attributes related to material properties and mix designs (i.e., material compositions). Once added up per contract, the total quantity of asphalt or concrete materials used in a project can also be calculated.

Data cleaning for SAM started with eliminating data fields with NULL values to reduce data size. The data structure was also modified to reduce memory size and facilitate data analysis. The original SAM data for HMA contained a column that specified the measured property for each lot and sub-lot of a project. This was an inefficient way of storing data in that several rows of data with similar information except for one column needed to be stored. Alternatively, information related to each lot and sub-lot of a contract were listed as separate columns in the dataset with their measured quantities listed under the appropriate column header. As a result, the number of data rows decreased by about

80%. A similar procedure was followed for concrete SAM data in order to reduce its file size. As a result, the total HMA and concrete tonnages recorded in SAM were found to be around 4 million and 800 thousand tons, respectively.

SAM data is typically collected for each lot in a project while indicating slightly different material properties (i.e., mix designs). Since information regarding different lots and sub-lots is absent from the unit bid analysis data (e.g., all hot mix asphalt used in a project is most often clustered into one single pay item even though it may represent different mix designs), the weighted average of mix designs used in a project (described by its contract number) was taken to represent an average mix design for a single pay item. The same procedure was followed for concrete materials. The weighted average was calculated as:

$$W_{m,c} = \frac{\sum_{i=1}^{n} w_{i|m,c} X_{i|m,c}}{\sum_{i=1}^{n} w_{i|m,c}} \tag{1}$$

where,

$W_{m,c}$	=	the weighted average of material property *m* in contract *c*,
n	=	the number of terms to be averaged,
$w_{i\|m,c}$	=	the weight of material *m* for lot/sub-lot *i* of contract *c*, and
$X_{i\|m,c}$	=	the property of material *m* for lot/sub-lot *i* of contract *c* (for example, percent asphalt binder, or percent cement).

Using the contract number as the unique common data attribute between the unit bid analysis data and SAM data, material properties were assigned to their associated pay item (in place of the material compositions explained earlier). However, there were several cases of missing contract numbers within the SAM dataset. For those cases, an average mix design was calculated based on what was obtained directly from the SAM dataset (such a procedure is formally called data imputation).

Highway Activity Tracking System (HATS)

The main goal of using HATS in this project was to estimate material quantities used for pavement maintenance, which mostly included patching pavements and bridge decks with asphalt and concrete, sealing cracks and joints, and in some cases overlaying out-of-service pavements. Similar to several other data pieces, HATS did not keep track of material quantities directly. What was reported through HATS was mainly the repair area and repair (or patching) depth.

Similar to how SAM data is structured, HATS also uses several duplicate rows of data for a certain activity to store information such as repair area, patching depth, being part of the P1 program, maintenance activity involving subgrade replacement, etc. To reduce the overall file size and prepare the data for further analysis, the data structure was transformed in a way to avoid duplicate rows and store information in separate columns. Finally, material quantities were estimated by multiplying repair areas by average patching [or sealing] depths and then factoring in an assumed density of 145 to 150 lbs/ft^3 for asphalt and concrete. As a result, the total quantity of materials was found to be around 340 thousand tons (for both asphalt and concrete with asphalt being responsible for more than 90% of the total). We believe this is a rough estimate of quantities, and other resources would be required to verify the order of magnitudes. Accordingly, HATS data was largely excluded from further analysis.

Record of Materials (ROM)

ROM lists the type and quantity of all materials used in a project that requires quality control. It relies on plan quantities and is not an exhaustive list of [standard and non-standard] items that do not require acceptance and verification.

The received ROM data went through extensive elimination of rows and columns that indicated NULL values. Moreover, several contracts that were initially selected for inclusion in our analysis based on unit bid analysis data were missing information in ROM. In addition to missing the required information, the ROM data received by our project team was found to be messy and structurally flawed. This could have been due to a faulty query of the original data. Nevertheless, we believed that ROM data was most useful to track material supplier information to estimate transportation distances for project supplies. However, we were so far unable to develop an algorithm to link supplier data to pay item lists and relied on assumptions for transportation distances as explained earlier.

Pavement Management System (PMS)

As the name suggests, PMS data only includes information regarding the pavement sections of projects. The data we received showed a summary of hot mix asphalt quantities used in each project which matched closely with the planned quantities obtained from pay item lists. However, PMS data was most useful for design-build projects where pay item lists lacked any quantity estimates. As a result, the pay item list data was reinforced with information from the PMS data to include a few line items for design bid projects depicting the tonnage of hot mix asphalt.

Another aspect of the PMS data that was found useful was the information regarding maintenance and preservation projects not included under the pay item lists. The challenge, however, was that no material quantity estimates were provided for any of those projects. PMS data only specified the total lane miles treated as part of the preservation or maintenance activities and rough assumptions needed to be made to estimate material quantities. And it was not still clear whether all preservation projects were excluded from the pay item lists since we found project PINs that were assigned to a contract number already existed in the pay item lists. Upon further investigation, pay item lists for the missing contracts from the unit bid analysis dataset were found in either the ROM dataset or projects' plans and specifications. Lastly, we concluded that PMS data did not offer any additional information beyond material quantities for a few contracts that were not included in the original unit bid analysis query. PMS data was most useful in estimating material quantities for HMA used in design-build projects.

<u>Construction equipment data from Unifier</u>

We also attempted to obtain data for construction equipment fuel usage and their associated emissions. After several meetings with the Construction division at WSDOT, we found out that operating hours of equipment for contracts completed after 2019 might be available. After several inquiries, we obtained some data that captured the type and operating hours of equipment used in a project. Emission factors and typical engine sizes were extracted from the existing literature such as the Federal Highway Administration (FHWA)'s Infrastructure Carbon Estimator (ICF, 2020b) and the Environmental Protection Agency (EPA)'s MOtor Vehicle Emission Simulator (MOVES) (US EPA, 2015). Although equipment data was not available for all contracts under study, even a subset of projects could be evaluated to inspect the contribution of fuel usage by equipment in the overall Scope 3 emissions attributed to projects.

However, the inspection of Unifier data revealed several challenges including the lack of engine size information for equipment, a wide variety of equipment makes and models, which made immediate data analysis infeasible, and missing data for several contracts. As a result, a decision was made to independently (not based on collected data) assign equipment types and operating hours to pay items that involved construction activities. Major sources to extract equipment production rates were the Washington State DOT's Plans Preparation Manual (WSDOT, 2020) and Florida DOT's Construction Project Administration Manual (FDOT, 2017). See the Construction activities section for more information.

Stationary and non-stationary fuel usage

Scope 1 and 2 greenhouse gas emissions due to direct and indirect energy consumption are well-captured by WSDOT. This mainly includes fossil fuels used for mobile vehicles and ferry vessels, electricity usage by WSDOT-owned buildings, and other stationary usages of fuels such as natural gas and propane for heating purposes. Washington State Department of Ecology reports these emissions as part of their biennial inventory of state-wide greenhouse gas emissions (Washington State Department of Ecology, 2021). This data is widely available across WSDOT and we received a summary of data submitted to the Department of Ecology. This data required minimal manipulation and modifications. However, the report excluded estimates of emissions for the year 2021. The approach taken to estimate the previous year’s emissions was closely followed to replicate the results for the year 2021 to meet the scope of our analysis period. This data was very useful in putting numbers into perspective and running a pairwise comparison between Scope 1 and 2 emissions and Scope 3 emissions to be found as part of this present study.

General project construction data

We obtained a dataset from the Construction division summarizing all construction projects awarded and completed within the analysis period of 2017 to 2021. This dataset provided a brief description of the projects and their geographic location and acted as a supplement to the unit bid analysis data. Additionally, this dataset was useful in that final project prices were included. It was also helpful to verify that all contracts obtained from unit bid analysis data were in line with the Construction division records of the projects. It was observed that a few contract numbers were missing from our unit bid analysis query and we ended up updating the pay item lists with the missing contact information.

Roadway maintenance financials

Roadway maintenance projects were treated differently than the construction projects at WSDOT in that no contract numbers were assigned to maintenance work. Although the HATS database contained some material-related information as they related to roadway maintenance, there were several other aspects of roadway maintenance that were not necessarily related to the structural retrofit of the roadway. For example, signal repair, roadway sanding, winter preparation, guardrail replacement, traffic sign upgrades, etc. were some items that were not well-documented in terms of material inventory. However, we were able to get a hold of the WSDOT staff in charge of financial recording for maintenance activities and run some analysis on how expenditures compared with construction projects. We adopted most of the terminologies from the WSDOT's *Maintenance Accountability Process Manual* (WSDOT, 2022b). A formal LCA for maintenance activities was, however, left out of the scope of this study due to the lack of sufficient information.

Whole Roadway Lifecycle Assessment (LCA) Framework

This research used an internally developed LCA method that follows standardized procedures outlined in ISO14040 and 14044 and adheres to other conventions seen in several published reports or journal articles (for example, Chen and Wang 2018; Harvey et al. 2016; Jiang and Wu 2019; Amlan Mukherjee, Stawowy, and Cass 2013; Liu, Wang, and Li 2017). Our choice to include the entire roadway construction scope of work (i.e., all items on the pay item list) necessitated a new, internally developed LCA framework. Existing vetted roadway LCA tools are typically limited to pavement structure only or were not based on editable pay item lists. The following sections describe our whole roadway LCA framework and its execution. For a full description of the LCA dataset structure, refer to Appendix A.

Goal and Scope Definition

The goals of our whole roadway LCA are to 1) quantify the embodied carbon of an entire roadway construction project as defined by its contract specification, 2) investigate the correlation between LCA results and bid price, 3) establish carbon baselines for future roadway construction projects, and 4) provide a method, if possible, for others to estimate embodied carbon based on construction price alone.

Declared unit

Although a variety of declared units are defined for roadway or pavement LCAs (e.g., a lane-mile of pavement construction, square foot or square meter of construction, etc.), we define a declared unit as "constructing a roadway project that meets specifications." This definition is well aligned with our use of pay item lists to build the LCA framework on. In that, all pay items in a contract need to be delivered to complete the project. We further normalize results by project bid price because this allows for projects of different types (e.g., bridge projects, pavement overlays, intersections, highways, rural roads, etc.) to be compared. More traditional pavement functional units (based on lane-miles and/or area, and structural design requirements) would not allow for this comparison. Notably, our declared unit does not include a design life.

System boundary

Our LCA is cradle-to-construction (see Figure 2) meaning that it includes 1) raw material extraction and processing, 2) electricity and fuel consumption at each stage, 3) upstream (from plants to suppliers) and downstream (from suppliers to construction sites) transportation of materials, and 4) on-site construction activities. The cut-off criteria are set to exclude pay items that contribute less than 0.1% of each project’s bid price. Furthermore, processes within a pay item that contribute to less than 0.5% of a pay item’s total GHG emissions were excluded from the system boundary. Additionally, items bid as lump sums (e.g., lump sum traffic control), electrical and mechanical systems (e.g., signals, traffic control cabinets, irrigation systems), and equipment mobilization are mostly excluded because our data do not contain enough information to meaningfully include them. Table 3 provides more details of the pay items included and excluded from the system boundary.

Allocation procedure

An open-loop approach was implemented where recycled materials were to be used. In that, it was assumed that the by-products are available through the [local] plants/suppliers as raw material. To close the loop, unit processes (i.e., "the smallest -

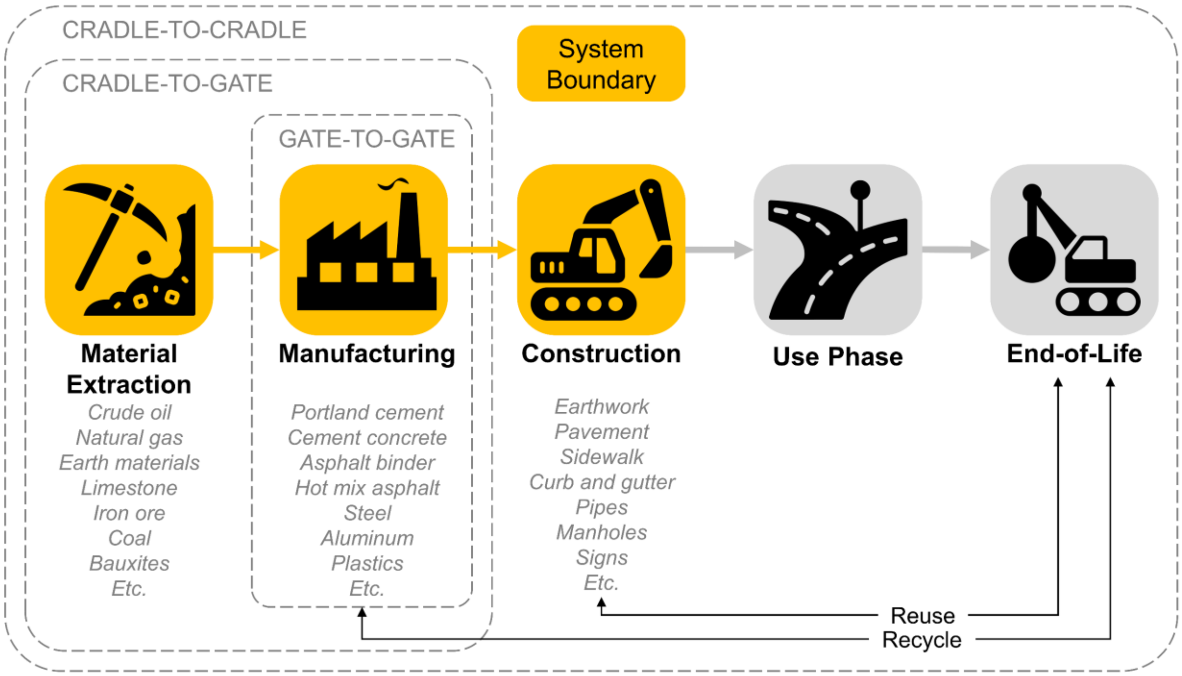

Figure 2. System boundary for the lifecycle assessment in this project.

Table 3. Examples of items included and excluded from the system boundary of the LCA framework.

Example Items Included in the LCA	Example Items Excluded from the LCA
Aggregate borrows; Anchor cables; Asphalt mixes (HMA/WMA/Porous); Beam guardrails and anchors; Bridge deck repairs; Catch basins; Cement concrete pavements/driveways; Chain link fences; Column jacketing; Column retrofit; Concrete barriers; Concrete girders; Concrete used in structures; Construction equipment activities for paving and earthwork; Crack sealing; Crushed surfacing base course; Culverts; Curbs and gutters; Ductile iron pipes; Earthwork and embankment preparation; Emulsified asphalt; Excavations; Geotextiles; Gravel backfills; HDPE pipes; High visibility fences; Inlets; Junction boxes; Manholes; Mast arms; Material transportations; Noise barrier walls; Pavement markings; Pavement planing; Pavement/bridge deck removals; Plant transportation; PVC pipes; Quarry spalls; Sawcutting; Shafts; Sign bridges/structures; Soldier piles; Steel casings; Steel reinforcements; Steel superstructures; Storm/water pipes; Streambed cobbles; Structural steel (when data available); Topsoils; Underdrain pipes; Waterproof membranes	Abandoning structures; Adjustments of water management elements; Administrative items; Bark or wood chip mulch; Barrier delineator; Bridge deck preparation; Bridge railing; Buildings; Cleaning and painting bridges; Clearing and grubbing; Compost; Conduit systems; Design-build projects (except for asphalt and concrete pavements); Dewatering systems; Electrical systems; Erosion/water control systems; Expansion joints; Force account items; Induction loops; Intelligent Transportation Systems; Irrigation systems; Large woody materials (LWMs); Mobilization; Modifications and repairs; Potholing; Raised pavement markers; Removal of structures; Replacement of elements; Root barriers; Rumble strips; Seeding and fertilizing; Sewer cleanout; Shoring; Soil amendments; Surveying; Temporary structures; Timber structures; Traffic control; Traffic signals and cabinets; Training; Ventilation systems; Video detection systems; Weed and pest control; Wood products; Work access

element considered in the lifecycle inventory analysis for which input and output data are quantified" (ISO 14040)) were considered for removal/demolition, processing, and transportation of the by-products. For example, reclaimed asphalt pavement (RAP) was assumed to be a “free” material to obtain for the project using it. However, the environmental burden of obtaining RAP when a project undergoes pavement milling operations was considered to be a project-related burden. In addition, asphalt plant adjustments to include RAP in the mix (additional heat to dry RAP particles, RAP crushing and processing, etc.) were also considered within our system boundary and as a burden on projects. It is worth noting that, to date, WSDOT does not inventory recycled material usage in projects and our analysis was based on assumptions and projections on recycled material contents.

Impact categories

Our LCA considered global warming potential (GWP; also referred to as carbon footprint or embodied carbon) as the main impact category which is measured in metric tons of CO_2eq. The majority of input lifecycle emission impact data were collected from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET 2020) (Wang et al., 2020), United States Environmental Protection Agency (EPA) AP-42 report (RTI International, 2004), EPA Motor Vehicle Emission Simulator (MOVES) 2014b (US EPA, 2015), and the Embodied Carbon in Construction Calculator (EC3) tool. This LCA used environmental impact characterization factors from the individualistic perspective (20-year GWP) according to ReCiPe (Huijbregts et al., 2017) when data was not available in units of CO_2eq.

<u>Lifecycle Inventory Analysis (LCIA)</u>

The lifecycle data sources consist of two components: the reference flows and the lifecycle emission factors. Reference flow data contain information about the weight, type, and composition of materials produced, the transportation mode used, the hauling distance for those materials, and the construction activities required to install/place them. Lifecycle emission factor data includes environmental impact multipliers (i.e., global warming potentials measured in units of CO_2eq) of items described in the reference flows.

Reference flow data sources

The main data source used to inventory materials used in a project was the unit bid analysis data (or pay item lists) collected from WSDOT. This dataset was then modified and reinforced with several other WSDOT databases such as SAM, ROM, PMS, project plans and specifications, and other general project information. For more information about data sources, refer to the Data Collection and Data Cleaning and Modification sections. It must be noted that nearly all material properties data collected from WSDOT resources do not report the percentage of recycled materials (especially for asphalt and concrete mix designs). Therefore, our baseline analysis considers the use of all virgin materials unless the emission factor data for a particular material already considers the use of recycled materials (steel production, for example).

Lifecycle emission factors

Lifecycle emission factors (expressed as GWP or [greenhouse gas] emission factors and measured in units of CO_2 equivalents) were used to calculate embodied carbon for each pay item using the reference flow dataset (the modified pay item list) as an input. Table 4 shows average greenhouse gas emission factors and their sources used for different material types, Table 5 does the same for transportation, and Table 6 for construction equipment. The sensitivity of LCA results to variations in materials' lifecycle emission factors will be later explored in this report.

Lifecycle inventory solution

The final step in performing an LCA involved some algebraic operations. A computational approach similar to the one outlined in Heijungs & Suh (2002) was followed to solve the inventory problem. The computational algorithm here followed a vector multiplication. In that, a sum product of primary material weights and their associated emission factors for each pay item would result in the total embodied carbon. Similarly, embodied carbon from transportation and construction activities was computed by multiplying emission factors either by the product of weight and distance or operation hours of each piece of equipment, respectively. Microsoft Excel was used to lay out the computational mechanism while taking advantage of *index* functions to link reference flow and lifecycle emission factor data when needed. The following equations summarize the inventory problem solution:

Table 4. Average lifecycle GHG emission factors for primary materials.

Material Type	CO_2eq (kg / US ton)	Source
Aggregate Base	2.6	(McEwen, 2017)
Aluminum	7,259.5	(GREET, 2020)
Average Plastic	4,336.9	(GREET, 2020)
Bedding	2.1	(McEwen, 2017)
Bitumen	668.1	(Wildnauer et al., 2019)
Bitumen + Ground Tire Rubber (GTR)	649.9	(Wildnauer et al., 2019)
Bitumen + Styrene-Butadiene-Styrene (SBS)	800.6	(Wildnauer et al., 2019)
Coarse Aggregate in Asphalt	3.4	(McEwen, 2017)
Coarse Aggregate in Concrete	2.7	(McEwen, 2017)
Cement	730.9	EC3 – Average for North America
Cold Steel	898.3	(GREET, 2020) – Adjusted using EC3
Copper	3,044.2	(GREET, 2020)
Fine Aggregate for Asphalt	3.6	(McEwen, 2017)
Fine Aggregate for Concrete	2.8	(McEwen, 2017)
Galvanized Steel	963.8	(GREET, 2020) – Adjusted using EC3
High-density polyethylene (HDPE)	3,778.5	(GREET, 2020)
Hot Mix Asphalt (HMA)	30.1	Energy: IVL; Emission: EPA AP-42 Table 11-1.3&7&8, Table 4-19,20 AP-42 fabric filter, natural gas.
Hot Steel	779.2	EC3 – Average for North America
Iron	814.6	(GREET, 2020)
Lime	1,200.7	(GREET, 2020)
Polyethylene	3,798.9	(GREET, 2020)
Polypropylene	3,350.6	(GREET, 2020)
Polyvinyl chloride (PVC)	3,130.8	(GREET, 2020)
Reclaimed Asphalt Pavement (RAP)	1.6	(Mukherjee, 2022), (Mukherjee & Dylla, 2017), (Miliutenko et al., 2013), (Yang et al., 2014).
Recycled Aluminum	1,575.9	(GREET, 2020)
Recycled Steel	425.7	(GREET, 2020) – Adjusted using EC3
Riprap	1.6	(McEwen, 2017)
Rocks	2.2	(McEwen, 2017)
Soil	1.4	(McEwen, 2017)
Stainless Steel	585.8	(GREET, 2020) – Adjusted using EC3
Pavement Marking	1,018,0	DOW Coating Materials Presentation
Wall Backfill	2.1	(McEwen, 2017)
Warm Mix Asphalt (WMA)	28.6	Assume 5% less Carbon/Energy than HMA

Table 5. Average lifecycle GHG emission factors for the most common transportation vehicles.

Vehicle Type	Abbreviation	Image	Load Capacity (tons)	CO_2eq (grams / US ton-miles)	Source
Diesel Heavy-Duty Pick-Up Truck	DHDPUT		0.9	65.0	(GREET, 2020)
Light Heavy-Duty Vocational Vehicle	LHDVV		2.1	57.7	(GREET, 2020)
Medium Heavy-Duty Vocational Vehicle	MHDVV		4.1	35.0	(GREET, 2020)
Heavy Heavy-Duty Vocational Vehicle	HHDVV		12.7	9.1	(GREET, 2020)
Combination Short-Haul Truck	CSHT		14.7	10.4	(GREET, 2020)
Combination Long-Haul Truck	CLHT		18.6	10.2	(GREET, 2020)
Barge	Barge		>1000	4.1	(GREET, 2020)
Diesel Rail	DR		>1000	2.6	(GREET, 2020)
Electric Rail	ER		>1000	0.9	(GREET, 2020)
Ocean Tanker	OT		>1000	1.0	(GREET, 2020)

Table 6. Average lifecycle GHG emission factors for the most common construction equipment.

Source: (US EPA, 2015).

Equipment	Default Engine Power (HP)	CO_2eq (kg/hr)
Backhoe	300	26.3
Bore/Drill Rigs	300	54.6
Cement & Mortar Mixers	40	8.3
Chain Saws < 6 HP (Gasoline)	3	1.8
Chippers/Stump Grinders (Diesel)	50	12.0
Chippers/Stump Grinders (Gasoline)	25	17.3
Cranes	300	54.3
Crawler Tractor/Dozers	300	74.6
Crushing Equipment	300	55.1
Dumpers/Tenders	50	7.1
Excavator	300	73.9
Grader	175	44.6
Industrial / Concrete Saw	50	15.2
Loader	175	43.2
Milling Machine	600	156.1
Miscellaneous Equipment	11~1200	29.7
Material Transfer Vehicle (MTV)	300	73.0
Off-Highway Tractors	1000	287.6
Off-highway Trucks	2000	566.4
Other Lawn & Garden Equipment (Diesel)	50	12.0
Other Lawn & Garden Equipment (Gasoline)	25	13.9
Paver	175	42.7
Plate Compactor	11	2.2
Roller	175	41.9
Rough Terrain Forklifts	50	15.9
Scrapers	300	78.3
Shredders < 6 HP (Gasoline)	6	5.1
Signal Boards/Light Plants	40	7.7
Skid Steer Loaders	16	2.3
Sweepers/Scrubbers	40	8.9
Trenchers	300	79.4

$$GWP_i = GWP_i^{PM} + GWP_i^{TV} + GWP_i^{CE} \quad (2)$$

$$GWP_i^{PM} = \sum_i (W_i)(PMP_{i,j})(GWP_j^{PM}) \quad (3)$$

$$GWP_i^{TV} = \sum_t (W_i)(D_i)(GWP_t^{TV}) \quad (4)$$

$$GWP_i^{CE} = \sum_e (OH_i)(WE_{i,e})(GWP_e^{CE}) \quad (5)$$

Where,

GWP_i = Total global warming potential (i.e., embodied carbon) associated with the i^{th} pay item in metric tons of CO_2eq,

GWP_i^{PM} = Total global warming potential of the primary material production for the i^{th} pay item in metric tons of CO_2eq,

GWP_i^{TV} = Total global warming potential of transporting the i^{th} pay item in metric tons of CO_2eq,

GWP_i^{CE} = Total global warming potential of constructing the i^{th} pay item in metric tons of CO_2eq,

W_i = Total weight of the i^{th} pay item in tons, $W_i = (Q_i)(UW_i)/2000$,

Q_i = Quantity of the i^{th} pay item according to the unit of measure,

UW_i = Unit weight of the i^{th} pay item in pounds per unit of measure,

$PMP_{i,j}$ = j^{th} primary material proportion of the i^{th} pay item expressed in percentages,

GWP_j^{PM} = Per unit global warming potential of the j^{th} primary material in metric tons of CO_2eq/US tons,

D_i = Transportation distance of the i^{th} pay item in miles,

GWP_t^{TV} = Per unit global warming potential of the t^{th} transportation vehicle in metric tons of CO_2eq /US ton-miles,

OH_i = Operation hours of the i^{th} pay item, $OH_i = 8\times(Q_i)/(PR_i)$,

PR_i = Production rate of the i^{th} pay item in the unit of measure per day (assuming 8-hour workdays),

$WE_{i,e}$ = Working efficiency of the e^{th} construction equipment to place or install the i^{th} pay item, and

GWP_e^{CE} = Per unit global warming potential of the e^{th} construction equipment in metric tons of CO_2eq /hours of operation.

Lifecycle emission factors uncertainty analysis

Lifecycle emission factors are inherently uncertain and the use of average values can raise questions about the reliability of deterministic approaches to performing LCA. Temporal and geographical technology variations, regional supply chain variability, differences in electricity grid mix, variable raw material properties and production processes, among other factors, are the main sources of uncertainty. To better capture the variability in input parameters, we used Monte Carlo simulations to investigate the impacts of uncertainty on final LCA outcomes. In this research, we assumed that lifecycle emission factors followed a normal distribution with a standard deviation equal to 20% of the average emission factors to investigate sensitivity. We then generated thousands of randomly selected numbers following the assumed statistical distributions. Specifically, the uncertainty analysis algorithm followed the steps below:

1. Generate normal distributions for the lifecycle emission factors of primary materials using the average values listed in Table 4 and an assumed standard deviation equal to 20% of the average values. Figure 3 illustrates the distribution of emission factors per primary material type.
2. Based on the assumed emission factor distributions, extract 5000 randomly generated numbers.
3. Randomly assign one emission factor from the generated distribution to a pay item that uses a particular type of material(s) and multiply that by the weight of the associated material.
4. Sum up greenhouse gas emissions from different materials that constitute any given pay item.
5. Repeat Steps 3 and 4 for 1000 times and take the average and standard deviation of the result.

Microsoft Excel was used as the main platform for the random generation of numbers. Microsoft Excel VBA space was used to code the Monte Carlo simulations and other quantitative calculations.

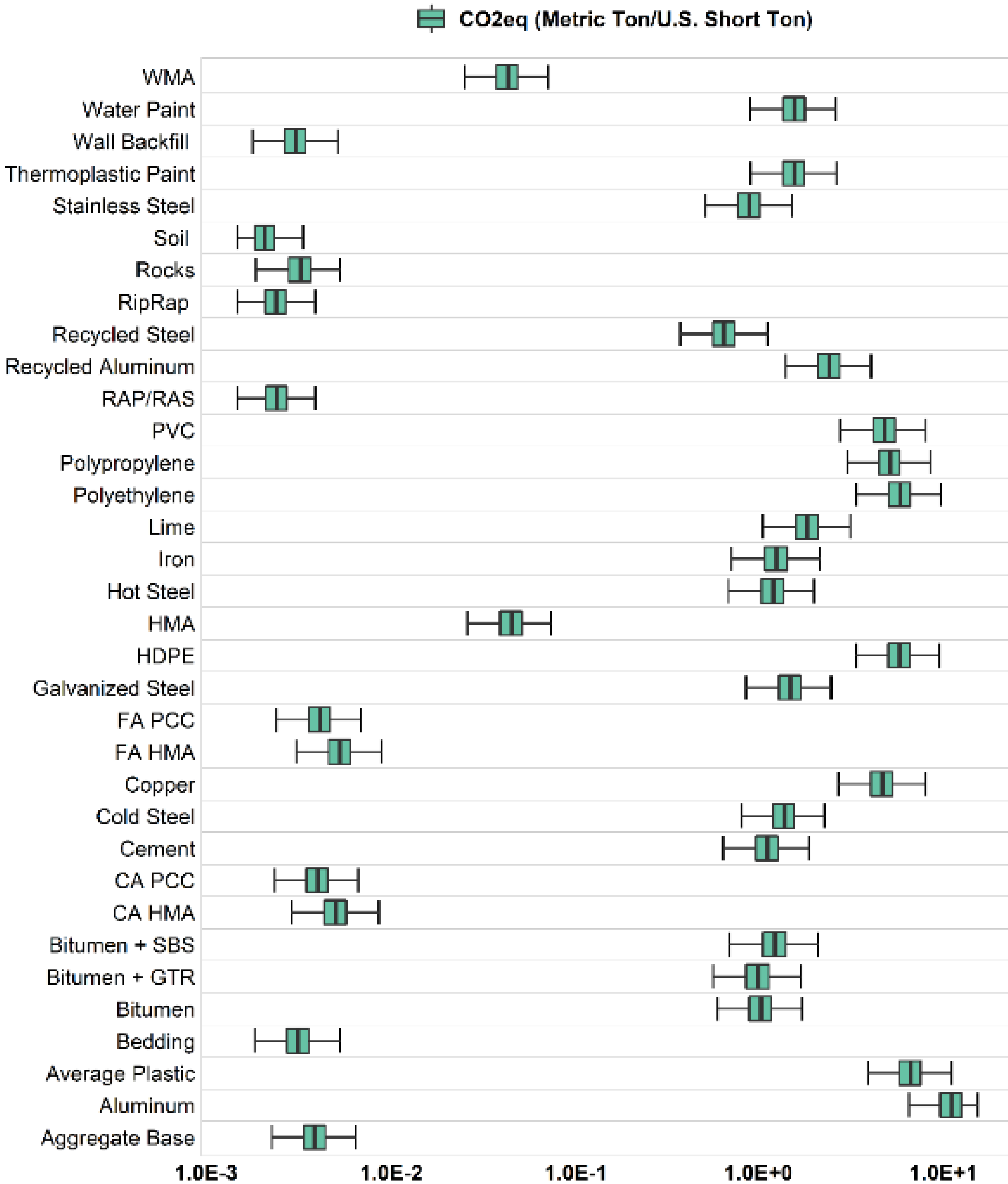

Figure 3. Normally distributed lifecycle emission factors of materials generated for uncertainty analysis.

FINDINGS AND DISCUSSIONS

What follows starts with our findings regarding financial accounting of maintenance and construction projects which will then be followed by some of our estimates of greenhouse gas emissions stemming from the production and placement of materials used in WSDOT construction projects. We use two different approaches to estimate GHG emissions. First, we use lifecycle emission factors for construction materials and processes to calculate upstream Scope 3 emissions from material inventory data (i.e., modified pay item list data). Second, we develop economic (spend-based) emission factors to estimate the overall GHG emissions of projects from their bid price values. Lastly, a pairwise comparison will be made between Scope 1 and 2 emissions and upstream Scope 3 emissions to signify the implications of this research.

Note: Our findings from Progress Report 1 were presented at the International Symposium on Sustainable Systems and Technology (ISSST) on June 21st, 2022, in Pittsburgh, PA.

Financial Backgrounds

Figure 4 and Figure 5 show the amount of money put into roadway maintenance and construction, respectively. In Figure 4, roadway maintenance expenditures are broken down into 10 categories according to WSDOT's Maintenance Accountability Process (MAP) manual. Despite year-by-year fluctuations, the top categories where most of the spending is allocated are snow and ice control, traffic control maintenance and operation, and roadway maintenance and operation (e.g., chip sealing and patching pavements).

The financial footprint of construction projects is solely based on the bid price of contracts obtained from the unit bid analysis data. Figure 5 breaks down construction values into design-bid-build and design-build delivery methods as these two dominate the contract types which in fact split the WSDOT budgets almost equally. One immediate observation from the total value of construction projects during the past five years is that the impact of the global pandemic due to the spread of the COVID-19 virus started to show up after 2019. We speculate that this is because of the supply chain disruptions in the construction materials market, lack of funding, and staff shortage.

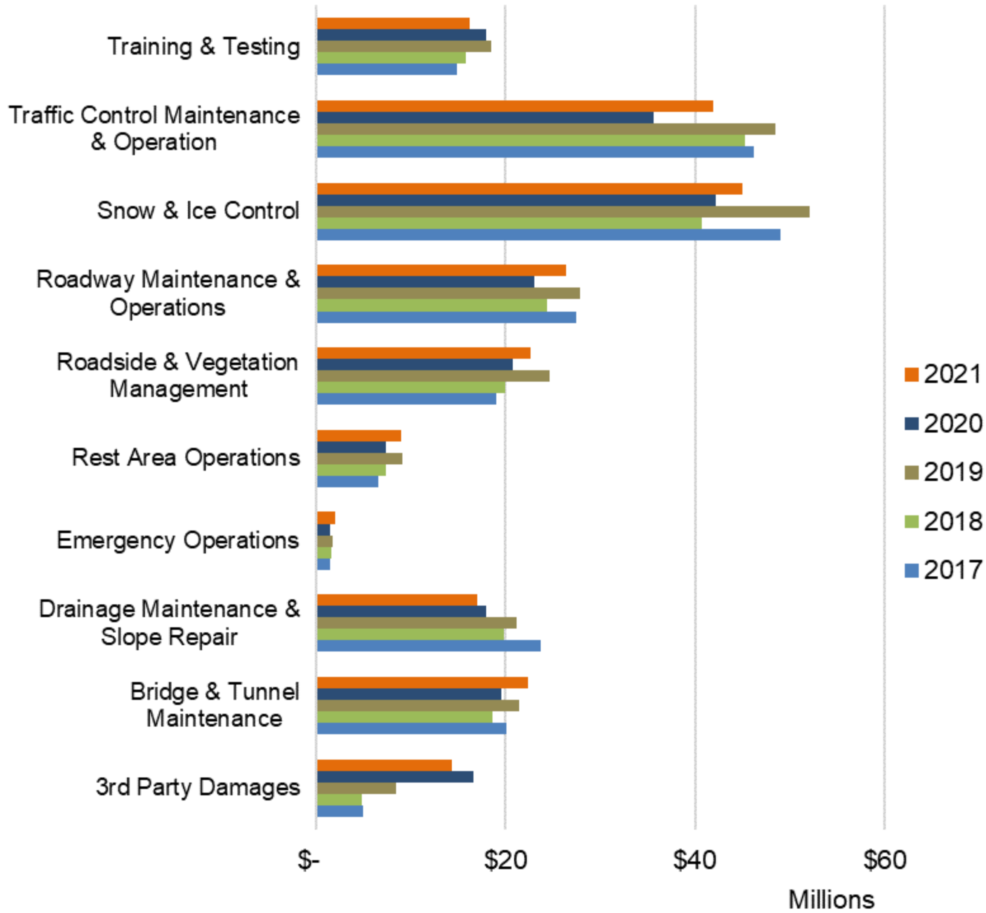

Figure 4. Financial footprint of roadway maintenance activities.

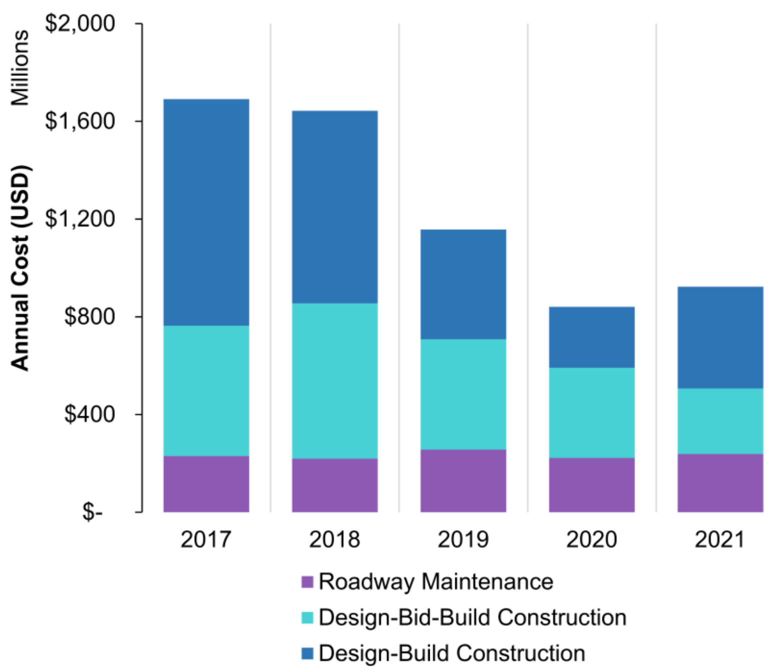

Figure 5. Financial footprint of roadway construction projects compared to maintenance.

Collectively, expenditures on roadway maintenance have remained relatively stable during the past five years despite the challenges resulting from the global pandemic. However, the share of spending on maintenance changed throughout the years since less money was put into construction from 2019 to 2021. In general, WSDOT seems to allocate around 10 to 15 percent of its roadway-related budget to maintenance with the rest being spent on construction, except for the years impacted by the global pandemic.

Scope 1 and 2 Emissions

The report to the Department of Ecology had some interesting insights into how much fuel and energy is used within WSDOT territory and how much greenhouse gas emissions are emitted as a result. This can be broadly categorized as Scope 1 and 2 emissions since WSDOT either directly consumed those sources of energy (Scope 1) or indirectly purchased that energy from other entities such as electricity from the grid (Scope 2). This will be greatly helpful to put numbers into perspective and gain a better understanding of the significance of Scope 3 emissions estimated in this study. It is worth noting that Scope 1 and 2 emissions described here are not related to WSDOT construction activities by any measure. For example, the ferry fuel usage has nothing to do with how much emissions are resulted from purchasing hot mix asphalt despite WSDOT being the entity that is responsible for managing the greenhouse gas emissions from both sources.

Figure 6 illustrates the GHG emissions from three main consumption sources of stationary (e.g., fuels used by WSDOT including natural gas, diesel, fuel oil, and propane largely for air and water heating at WSDOT facilities and as fuel for electric generators), mobile (e.g., gasoline and ethanol blends, diesel, biodiesel, and renewable diesel blends, compressed natural gas, and propane used in a variety of equipment – these emissions are typically referred to as tailpipe emissions), and ferry (e.g., diesel and biodiesel blends). Figure 6 supports the fact that more renewable energy sources result in lower greenhouse gas emissions with a drop in total emissions starting from the year 2020. However, lower ferry ridership could have also contributed to this trend.

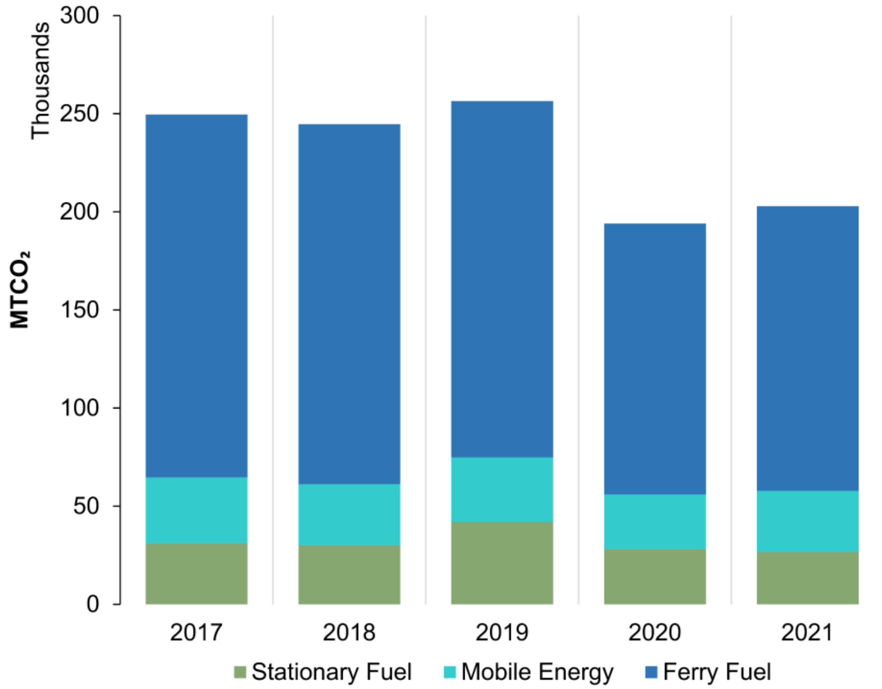

Figure 6. Scope 1 and 2 greenhouse gas emissions due to WSDOT operations.

Upstream Scope 3 Emissions

Since the main objective of this research is to provide estimates of greenhouse gas emissions produced during the production and placement of construction materials in roadway infrastructure, this section is attributed to our findings from the LCA methodology explained earlier. In particular, this section also summarizes the results from the uncertainty analysis described in previous sections to estimate upstream Scope 3 emissions from contracts advertised from 2017 to 2021. There are numerous ways data summaries could be presented, but this report focuses on six areas: 1) summary of material weights, 2) summary of calculated embodied carbon from primary construction material categories, 3) correlation analysis between a project's monetary value and overall greenhouse gas emissions, 4) estimation of a project's total greenhouse gas emissions based on economic emission factors, 5) contribution of construction categories to overall upstream Scope 3 emissions, and 6) pairwise comparison of upstream Scope 3 emissions found here with Scope 1 and 2 emissions. The following sections elaborate on each topic.

<u>Material weight contribution</u>

We define the following six primary material type categories to summarize data:

- Asphalt: Hot, warm, or cold bituminous mixtures used in pavement applications and asphalt cement used for sealing and coating compounds.
- Concrete: Cement concrete used in horizontal surfaces (e.g., concrete pavements and sidewalks) and structures (e.g., walls and bridges, pipes, catch basins, etc.).
- Metals: All metals used including steel, cast iron, aluminum, copper, and more. Steel, which is most prevalent, is used as a stand-alone structural element (e.g., bridge girders), as rebar in concrete structures, as dowel bars, tie bars, and rebar in concrete pavement, or in other roadside features (e.g., poles, guardrail). Other metals are typically used in roadside features/signs (e.g., aluminum), pipes (e.g., cast iron), and electrical systems (e.g., copper).
- Plastics: Polyvinyl chloride (PVC) and high-density polyethylene (HDPE) are used for pipes and geotextiles, polyethylene (PE) for coverings or moisture barriers, thermoplastic paint for pavement markings, and other plastic products such as traffic cones, trash cans, and other appurtenances.
- Aggregates: Crushed stone, sand, and gravel that are commonly used as fill material, pavement sub-layers, pipe beddings, wall backfills, landscaping, etc. Aggregate as a constituent of HMA or cement concrete is included in the asphalt or concrete category instead of this category.
- Wastes: Materials removed from the construction site for landfilling, recycling offsite, or reuse within the project boundaries. The largest contributors are clearing and grubbing, demolition, and earthwork activities.

Figure 7 shows the weight breakdown of the six primary material categories used to build roadways and expresses the total weights per year. The weight of materials is dominated by the waste category, followed by aggregates, asphalt, concrete, metals, and plastics. This order in material weights, however, was somewhat expected. The majority of roadway projects involve earthwork operations either in the form of imported materials (e.g., gravel borrow, embankments, wall backfills, pipe beddings, pavement sublayers, etc.) or exported materials (e.g., pavement milling, several instances of excavations for roadways, bridges, and water infrastructure, removal and disposal of roadway obstructions, etc.). Furthermore, these categories of materials most often have high densities.

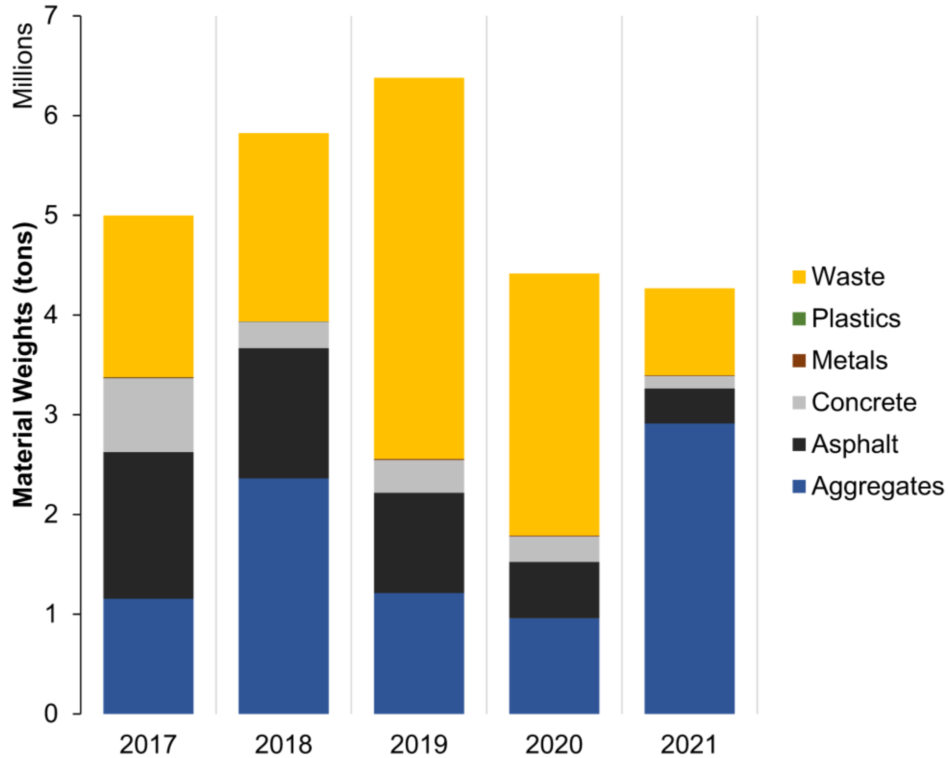

Figure 7. Total material weights used to deliver roadway projects that are included in LCA.

<u>Upstream Scope 3 emissions from materials</u>

Upstream Scope 3 emissions from WSDOT construction are illustrated in Figure 8. It must be mentioned that the results in this figure only pertain to the pay items that we were able to perform LCA on and do not necessarily provide an accurate estimate of the total emissions produced each year as several pay items were not included in the analysis. Since reference flow data could not be found for all materials and activities on the projects, only a portion of the materials were included in the LCA. This portion is represented by the price of these materials as a percentage of the overall bid price. The median project bid price included in our LCA is 55% (we calculated this metric in five steps: 1) find the total bid price of a project, 2) identify pay items that an LCA was conducted for, 3) sum the total price of each pay item that LCA was conducted for, 4) divide (3) by (1) to find the percentage of a project's bid price included in the LCA, 5) take the median of (4) for all projects.) Also, the error bars in this graph denote standard deviations due to the variation of lifecycle emission factors used to run LCA. Although the total annual emissions seemed to have dropped in 2019, this does not necessarily mean that more sustainable materials and practices have been implemented during those times. Rather, this is just reflecting the impact of COVID-19 on the material supply chain and construction market in general.

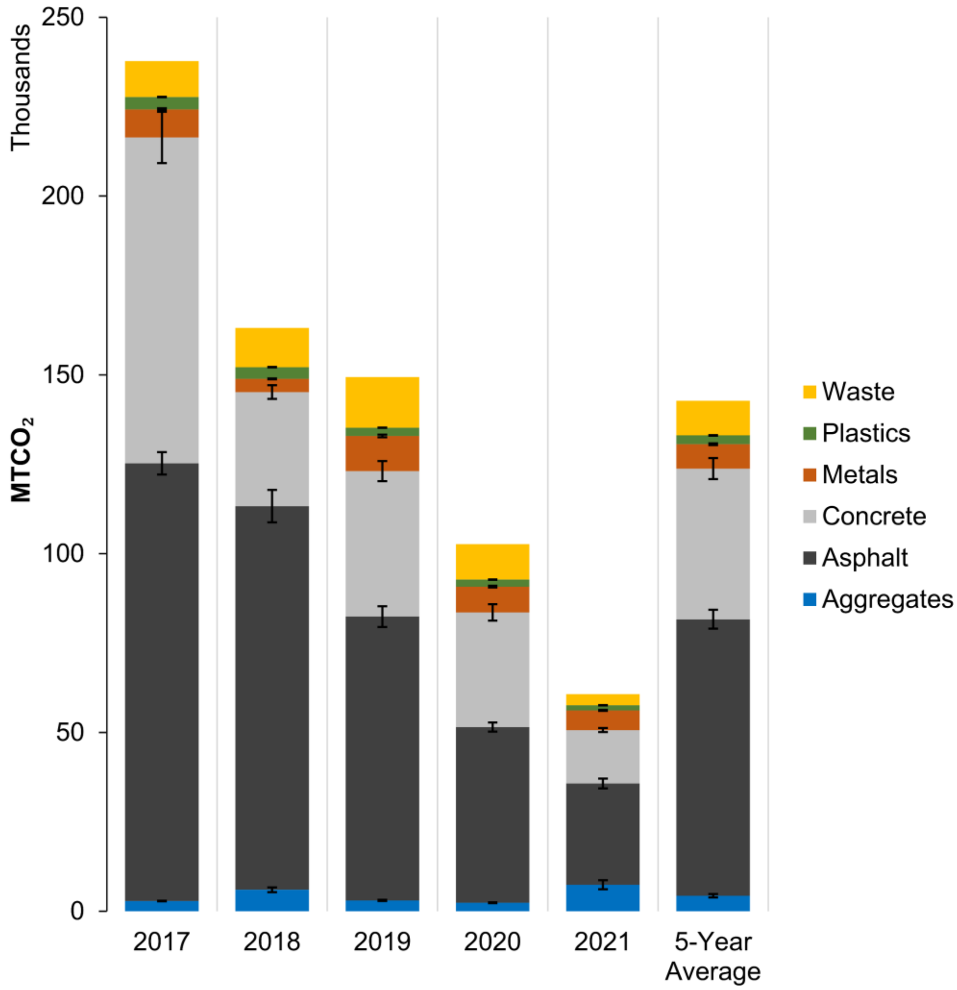

Figure 8. Upstream Scope 3 emissions from WSDOT roadway construction with error bars denoting standard deviations. This graph represents the emissions calculated from the LCA on the pay item lists and does not necessarily reflect all potentially emitting processes.

Figure 9 further illustrates the contribution of each primary material category to the overall GHG emissions. As this figure shows, the asphalt category (including all bituminous materials) dominates all other categories by around 50% average contribution. However, it must be restated that Figure 9 (similar to Figure 8) only represents the LCA results for the pay items included in the analysis (see System boundary). Therefore, the results depicted in these figures should be interpreted with some caveats. For example, the actual contribution of asphalt materials to total GHG emissions is most probably lower than 50% since our analysis excludes several items that can drive up total GHG emissions. In later sections, we provide estimates of GHG emissions from items that are excluded from our analysis by using project-based economic emission factors.

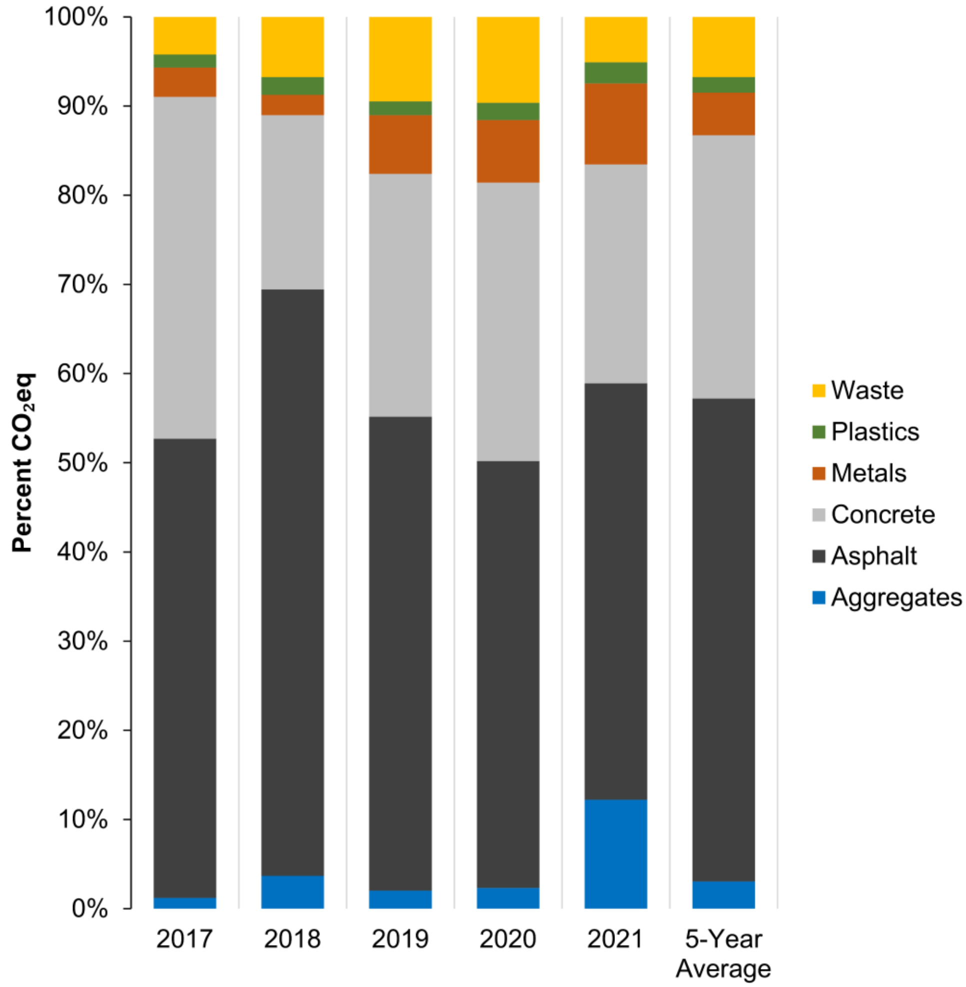

Figure 9. The share of each primary material category to the upstream Scope 3 emissions. This graph only shows the results for the pay items included in the LCA of this study (~55% of the total projects' bid price).

<u>Correlation analysis</u>

Another value of building the LCA structure on a pay item list dataset is in the fact that financial footprints (i.e., bid price) of projects can be associated and correlated with their embodied carbon. Figure 10 illustrates the results of a combined LCA and pay item list analysis and the correlation between the itemized bid prices and embodied carbon calculated per contract. The use of a log-log scatterplot and power functions to regress bid prices to embodied carbon quantities seems more appropriate due to the high variability of material weights (and hence footprints and prices) that exists within our data.

As expected, larger projects use larger quantities of materials and thus result in higher footprints. Figure 10 and its regressed power line can serve as a reference for future roadway construction projects to estimate their embodied carbon based on the total bid price. With a majority of project bid prices falling between $1 to $10 million, the trendline is most accurate for medium-sized road maintenance and reconstruction projects. To exemplify, a $10 million roadway construction project emits about 3 thousand metric tons of CO_2eq. Also shown in Figure 10 is the percentage of project bid prices included in the LCA; in that, larger circles show a higher proportion of a project's bid price included in the analysis. On average, 47% (55% on a median basis) of projects' bid prices were captured in this LCA.

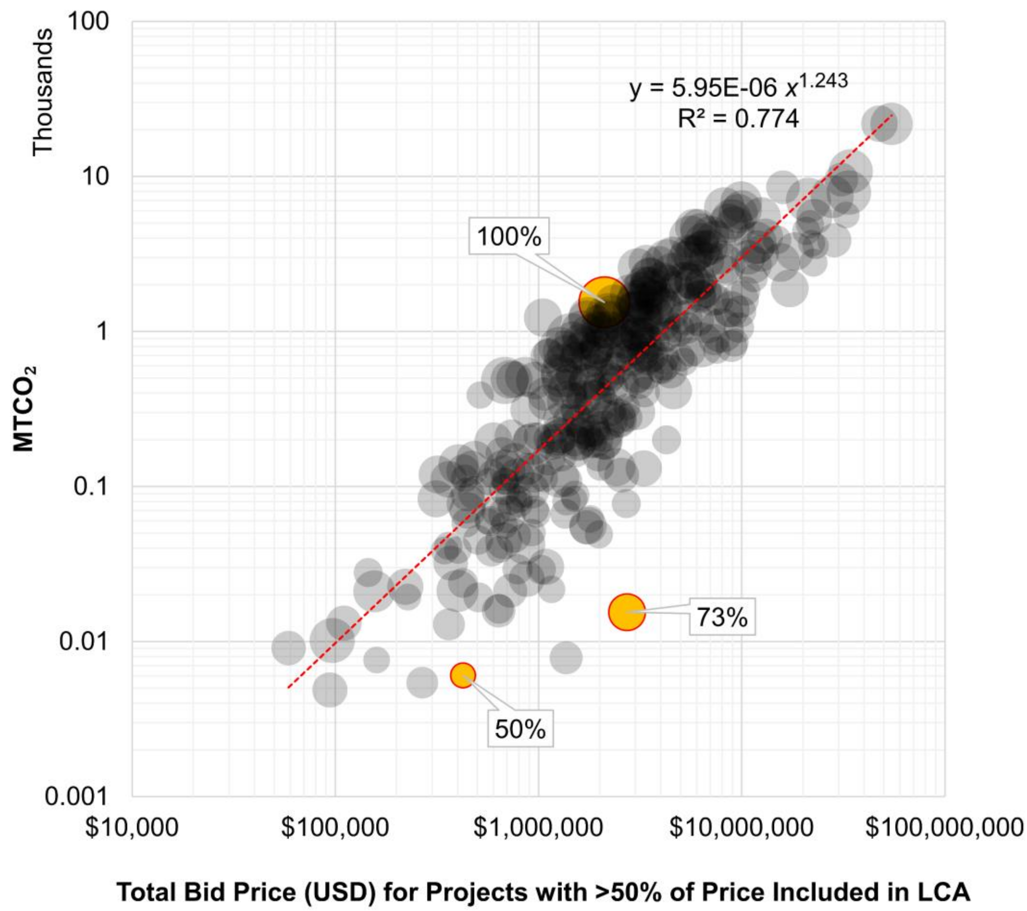

Figure 10. Regression analysis of projects' bid price and upstream Scope 3 emissions using a power line. The size of circles in this scatterplot denotes the fraction of each project's bid price included in the LCA of this research. Of note, this graph only includes contracts that had at least 50% of their bid price calculated by the LCA.

<u>Estimating the total upstream Scope 3 emissions of projects</u>

Results from the previous section are of great value; in that, the regression analysis results can be used to estimate total upstream Scope 3 emissions from projects only knowing their bid price. This modeling technique has similarities with the so-called economic input-output (EIO) LCA models that use material's monetary values to estimate

GHG emissions. As stated earlier, the LCA framework constructed in this research was able to estimate a median of about 55% of a project's total bid price. Other than the fact that some pay items in a roadway project are inherently non-materialistic and a meaningful LCA cannot be performed on those items, there were several data gaps in the dataset especially related to projects with a design-build delivery method. Therefore, this section attempts to use the previous section's LCA results and mathematical simulations to estimate embodied carbon for projects that did not provide accurate material inventory information.

To simplify the analysis, we first developed a series of greenhouse gas emission factors for projects based on their total bid price (i.e., economic emission factors). In that, the total embodied carbon for each project illustrated in Figure 10 is first divided by the total bid price of that particular project. To produce more reliable factors, only projects with more than 50% of their bid price included as part of the LCA (totaling 356 contracts) were considered. That results in a distribution of emission factors depicted in Figure 11. The analysis would then take a similar Monte Carlo simulation approach to what was described as part of the Lifecycle emission factors uncertainty analysis section where emission factors are randomly selected from the distribution of Figure 11 and assigned to each contract number. The simulation then repeats this process for 1,000 iterations, sums up emissions per year, and calculates statistical summaries (e.g., average, median, standard deviation, etc.) for the sum of emissions per year.

Figure 12 in the form of box plots summarizes the estimated total embodied carbon from the construction of all WSDOT roadway contracts advertised between 2017 and 2021. To reiterate, this figure only represents an estimation of total embodied carbon quantities based on the economic emission factors developed in this section using the project's bid price. In that essence, the results are different from what was shown as part of Figure 8 where the annual embodied carbon quantities were calculated directly from the available pay item lists and the consequent LCA framework developed in line with that.

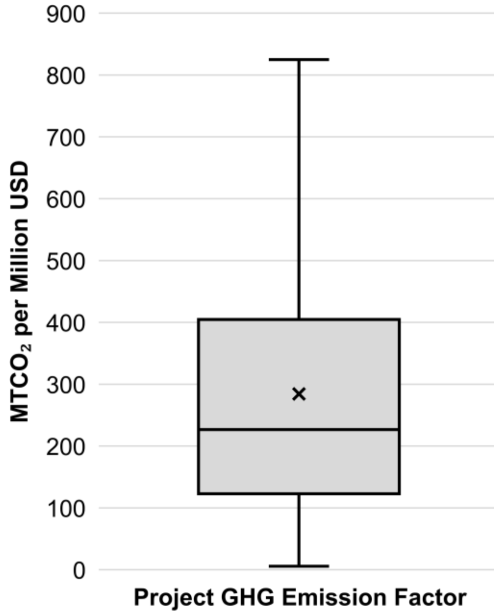

Figure 11. The distribution of economic greenhouse gas emission factors based on a project's total bid price obtained from projects included in the initial LCA. Only projects with more than 50% of the bid price covered by the LCA are included in this distribution (356 contracts).

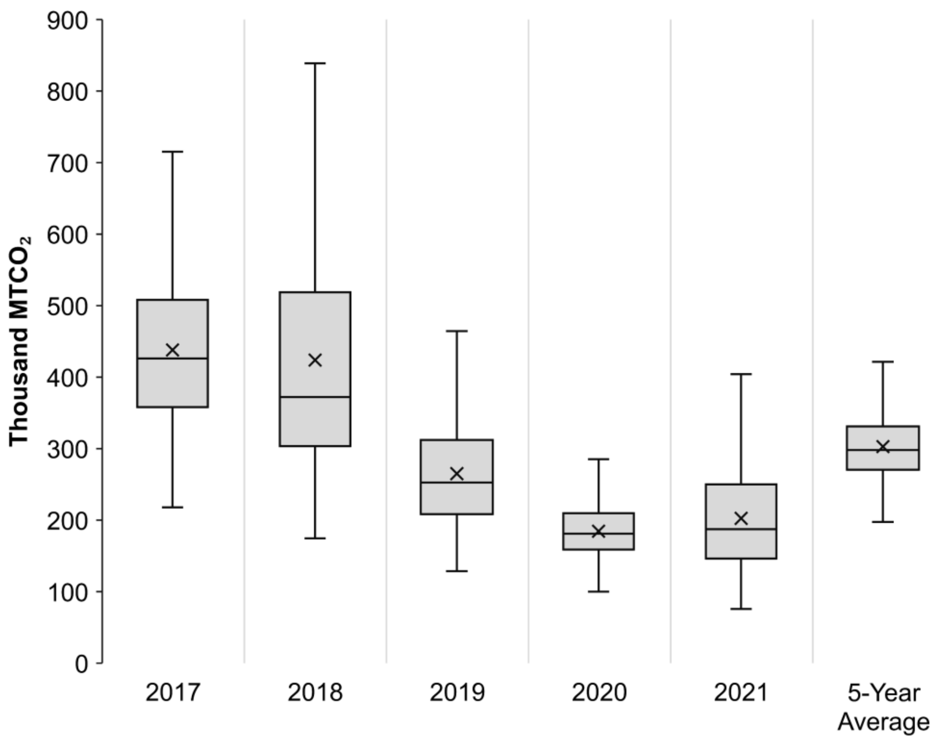

Figure 12. The distribution of estimated annual upstream Scope 3 emissions due to the construction of all WSDOT roadway projects advertised between 2017 and 2021. The cross signs (x) indicate averages and the horizontal lines in the middle of each box represent medians.

Finally, merging the estimated embodied carbon results (Figure 12) with the LCA outcomes of the modified pay item list analysis (Figure 8 and Figure 9) would reveal some interesting findings. In producing Figure 13, the total upstream Scope 3 emissions estimated from Figure 12 are subtracted from those measured as part of Figure 8. This would result in some amount of emissions that are not calculated (labeled as "Not Specified") as part of the developed pay-item-based LCA framework of this research.

The "Not Specified" category may contain emissions stemming from a variety of sources such as material production, construction activities, and direct or indirect fuel consumption (such as petroleum or gasoline for transportation purposes) that fall outside of our LCA's system boundary. At this point, we are unable to provide any more insights into the types of materials that constitute the Not Specified category in Figure 13; however, we can speculate that asphalt, concrete, and steel would still make up for a large fraction of pay items not available in our original dataset. In particular, the Not Specified category includes emissions from large design-build projects that do not provide pay item lists because of their method of delivery.

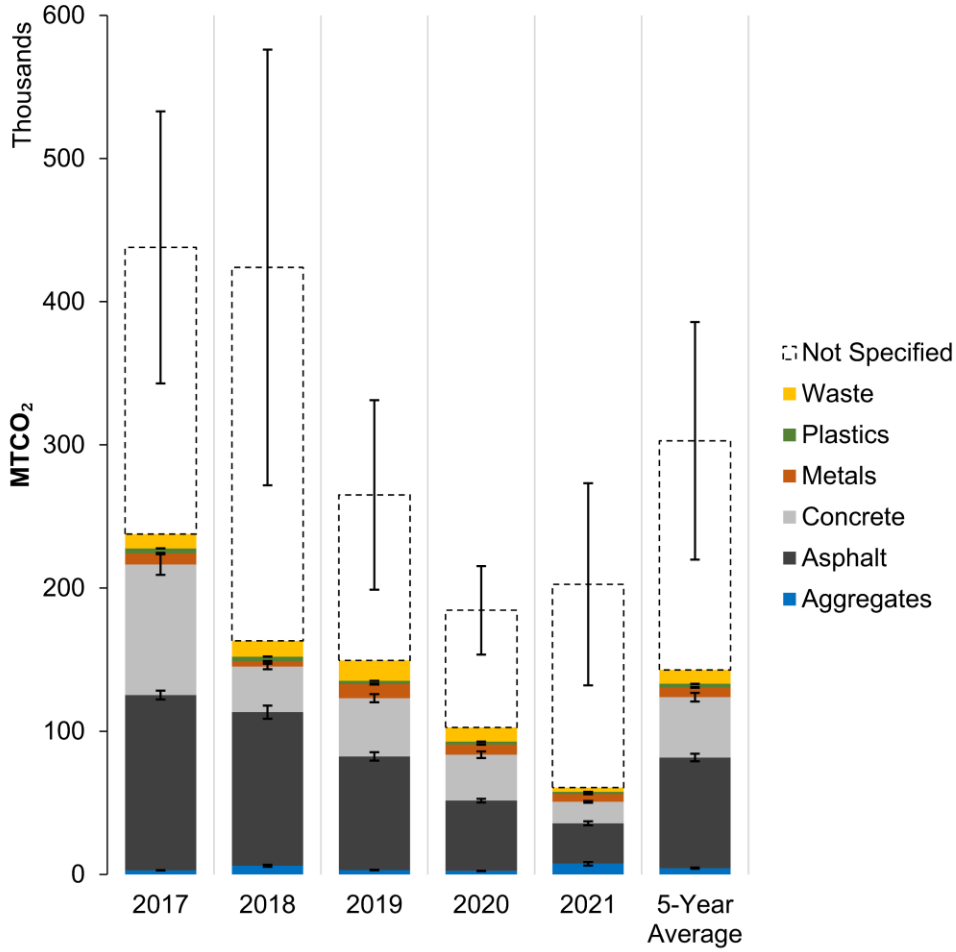

Figure 13. Total upstream Scope 3 emissions from WSDOT roadway construction projects estimated (dashed boxes) and measured (solid boxes) showing the contribution of each material type to the total annual emissions.

Furthermore, Figure 14 (similar to Figure 9) depicts the contribution of primary material categories to the overall Scope 3 emissions. We believe this would give a better understanding of the true share of material categories since it considers the estimated total emissions. However, this graph should be used with caution since the Not Specified category may be constituted of any fraction of the primary material categories identified in this research. Nevertheless, Figure 14 suggests that, on an average basis, aggregates, asphalt, concrete, metals, plastics, and wastes contribute to at least 1.7%, 25.9%, 14.3%, 2.7%, 0.9%, and 2.3% of total Scope 3 emissions, respectively, while an estimated average of 52.3% of emissions remain uncategorized. A big takeaway from this observation is that asphalt and concrete production, transportation, and laydown alone are responsible for *at least* 40% of the total Scope 3 emissions from WSDOT roadway construction projects.

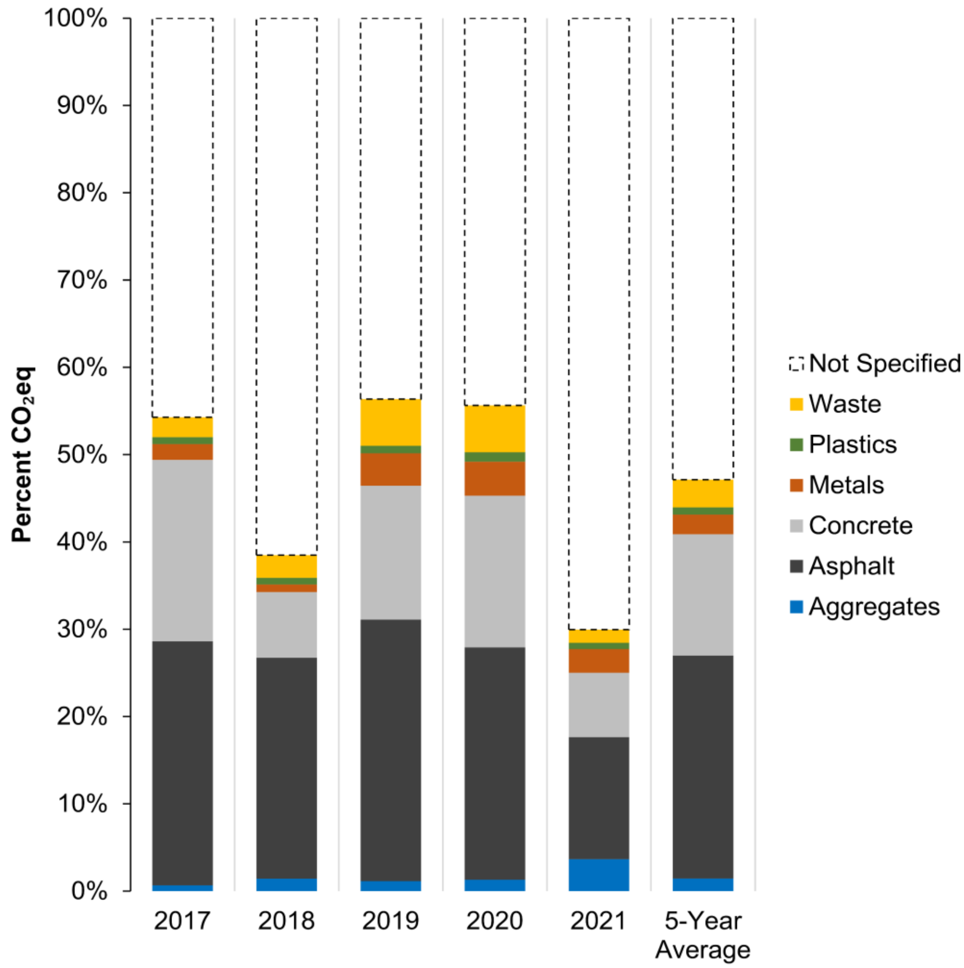

Figure 14. The share of each primary material category to the total measured and estimated upstream Scope 3 emissions. This graph shows the results for both the pay items included in the LCA of this study and the estimated emissions (the Not Specified category) based on the projects' bid price. It is worth mentioning that the Not Specified category may contain any fraction of the primary material categories depicted in this figure.

Contribution of construction categories to upstream Scope 3 emissions

GHG emissions can further be organized into thematic categories. Here, we use two themes to categorize GHG emissions. First, it is very common to group LCA results into categories of materials production (upstream emissions from the extraction until the production of all construction materials), transportation (emissions associated with hauling materials from/to job sites), and construction (emissions from the consumption of energy sources in the job site to install roadway elements). Figure 15 shows that on average, materials production dominates the overall upstream Scope 3 emissions by 85%, followed by 11% from material transportation, and 4% from construction activities. Our finding is highly consistent with previous studies (Lokesh et al., 2022).

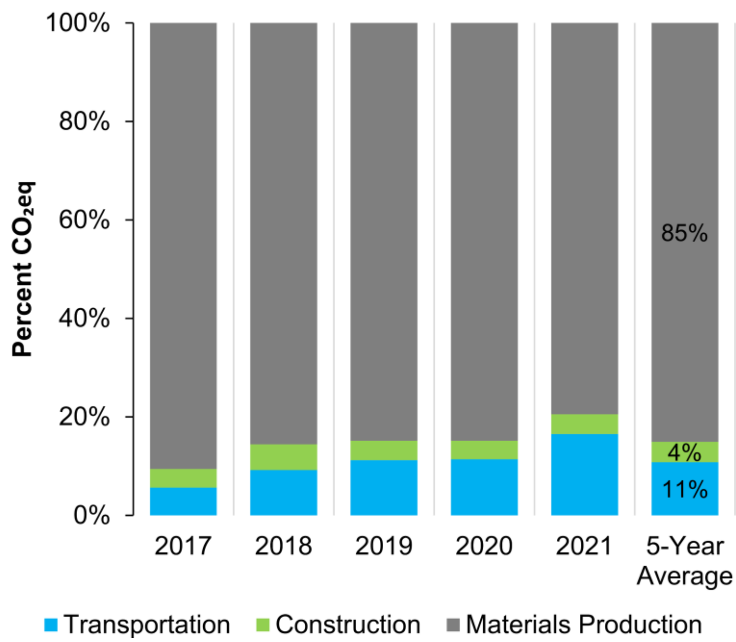

Figure 15. Upstream Scope 3 emissions breakdown by the three main categories of upstream material production emissions, emissions from transportation of materials to/from job site, and construction activities during the installation of roadway elements.

GHG emissions can further be organized into certain construction categories that repeat in major roadway construction projects. In this study, we introduce 11 construction categories and evaluate the contribution of each to the total upstream Scope 3 emissions. Figure 16 shows the results of upstream Scope 3 emissions assignments to construction categories. Pavement structures dominate the emissions by around 53% followed by the preparation and earthwork at 13%, and roadway structures (primarily bridges and walls) at 11%. This finding highlights why paving materials and LCA tool developments related to pavement structures are the focus of the existing body of knowledge.

It is also worth noting that the categories with no emissions contributed to them are those that are left out of the LCA boundaries defined in this study. In that, the items that were not included in the project LCAs are those that typically belong to one of the categories of admin (administrative processes to deliver a project such as scheduling and training), building (construction of WSDOT buildings), traffic control (e.g., hiring police officers, labor, determining detour plans, etc.), intelligent transport systems (ITS), electrical, and lighting features (which constitute more sophisticated mixes of electronics). Running a comprehensive LCA that encompasses all elements used in a roadway requires several more data pieces such as material quantity takeoffs from design-build projects and lump sum pay items that are not currently available in the existing WSDOT databases.

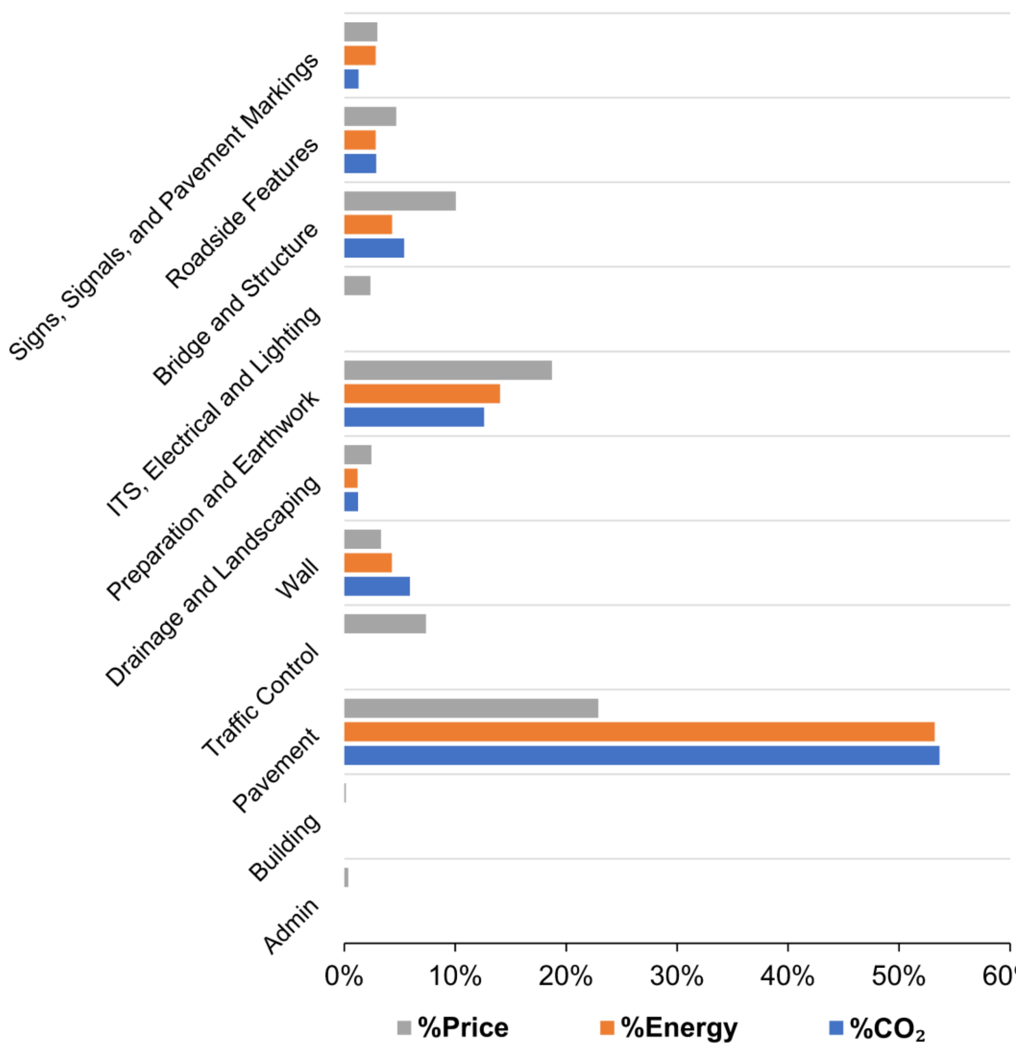

Figure 16. Contribution of major construction categories to the total upstream Scope 3 emissions, energy consumption, and bid price.

Pairwise comparison of upstream Scope 3 emissions with Scope 1 and 2 emissions

Finally, a pairwise comparison between Scope 1 and 2 emissions and upstream Scope 3 emissions estimated above concludes this section. We believe findings from Figure 17 are significant because 1) on an average basis, upstream Scope 3 emissions seem to outweigh Scope 1 and 2 emissions, 2) Scope 1 and 2 emissions in WSDOT might be among the highest in the nation since the Washington ferry system owns the largest vessel fleet in the U.S. and is the biggest contributor to Scope 1 and 2 emissions (Washington State Ferries, 2019), 3) upstream Scope 3 emissions are not well understood and accounted for within DOT environments, and our findings can help support environmental product declarations (EPDs) requirements for high-impact construction materials so that we can get project-specific material data and work to identify low carbon material solutions, 4) the newly proposed (i.e., Buy Clean and Buy Fair Washington) and passed (California, Colorado, and Oregon Buy Clean Acts) legislations that target reductions in Scope 3 emissions could impact WSDOT significantly.

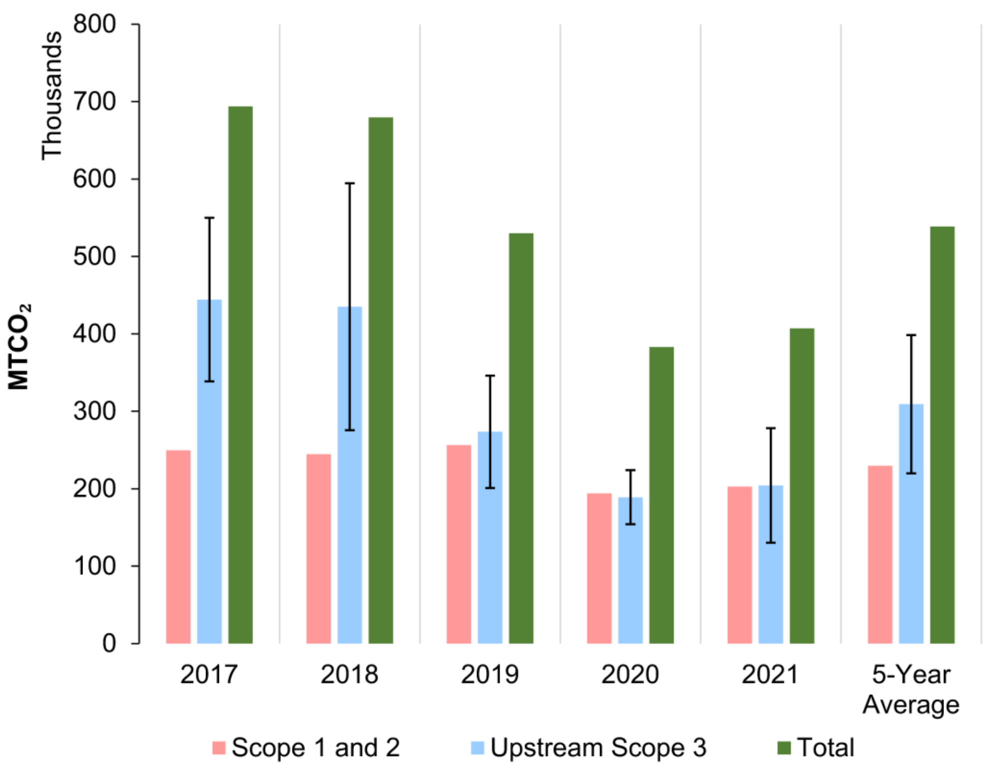

Figure 17. Comparison of Scope 1 and 2 emissions with upstream Scope 3 emissions for WSDOT as an agency.

RECOMMENDATIONS AND IMPLEMENTATION

This report so far provided estimates of upstream Scope 3 greenhouse gas (GHG) emissions from the procurement and installation of construction materials used to build roadways owned and operated by WSDOT. Reports from the Washington Department of Ecology on Scope 1 and 2 greenhouse gas emissions (i.e., WSDOT's direct and indirect energy use) were also included to put the estimated upstream Scope 3 emissions (i.e., supply chain emissions from materials production, transportation, and installation; also referred to as *embodied carbon*) into perspective. We found that upstream Scope 3 emissions outweighed Scope 1 and 2 based on available data; thus, calling for strategies to better quantify and subsequently track progress towards reducing those emissions.

To this end, this section starts with a review of existing work around emerging policies, best practices, and strategies to reduce greenhouse gas emissions for Departments of Transportation with an emphasis on upstream Scope 3 emissions from material production supply chains. We then perform scenario analyses using the data collected in this study to showcase how different strategies would lead to GHG reductions. Finally, based on the literature review and data analysis results, this report provides recommendations for WSDOT on best practices to progress toward decarbonization.

Background

Many states have considered GHG emission reduction targets to tackle climate change impacts. A reduction target is a way to focus mitigation actions and provide foundations for tracking progress toward that goal. These reduction targets can be set for different emission scopes per agency or can adhere to statewide goals. Nevertheless, setting reduction targets is the first step to establishing a carbon reduction plan. Most of these targets envision a [near] net-zero GHG emissions by the year 2050. In Washington for example, the revised RCW 70A.50 lists the following targets:

- 15% GHG reduction below 2005 levels by 2020
- 45% GHG reduction below 2005 levels by 2030
- 70% GHG reduction below 2005 levels by 2040
- 95% GHG reduction below 2005 levels by 2050

WSDOT has a role to play in reducing two critical sectors of GHG emissions:

transportation and industrial emissions. These sectors are of growing importance as the urgency to reduce GHG emissions shifts the global focus from just power generation to include other critical sectors in emerging policies, legislations, initiatives, and task forces targeting federal, state, and local governments. The transportation sector is responsible for around 36% of greenhouse gas emissions in the U.S. (U.S. DOE, 2022) mainly in the form of fossil fuel consumption. The industrial sector accounts for about 28% of global greenhouse gas emissions with chemicals, cement, and steel production representing 70% of emissions from this sector (iea, 2021). This report focuses on strategies related to industrial sector GHG emissions that occur due to construction activities from WSDOT and potentially to other transportation agencies.

Buy Clean

The federal government through the Bipartisan Infrastructure Law and the Inflation Reduction Act has secured historic investments to upgrade nationwide infrastructure while growing the clean energy economy (The White House, 2022b). In particular, the Federal Buy Clean Initiative and Task Force has recently secured $4.5 billion in funding for the General Services Administration (GSA), Department of Transportation (DOT), and Environmental Protection Agency (EPA) to usher in the manufacturing of construction materials with substantially lower GHG emissions (The White House, 2022a). "Buy Clean" refers to a policy that promotes the procurement of construction materials with lower carbon footprints while taking into account the upstream emissions embodied in their production (The White House, 2021). The Buy Clean initiatives also support the new Carbon Reduction Program (CRP) announced in early 2022 that unlocks funding for state and local governments to develop carbon reduction strategies (The White House, 2022b).

There are four areas in which the Federal Buy Clean is intended to impact (The White House, 2022a): 1) prioritize and incentivize the purchase of cleaner steel, concrete, asphalt, and flat glass for the Federal Government's purchases of these materials, 2) support the use of lower-carbon construction materials in federally-funded projects such as those administered by the DOT ($120 billion in infrastructure spending in the fiscal year 2022), 3) jumpstarting a new partnership between state governments and federal partners to align statewide Buy Clean policies with federal incentives, and 4) expand the transparency, reliability, and utilization of EPDs.

This federal effort is in line with similar initiatives and policies at the state level such as the Buy Clean Colorado, Buy Clean California, and Buy Clean and Buy Fair Washington, and at the local level such as the Port Authority of New York and New Jersey and the City of Portland (Tracy, 2015). It can be expected that more states and cities would participate in the development of carbon reduction strategies with the injection of recent federal funding and increased awareness around EPDs and embodied carbon of materials.

Departments of Transportation

The quantification of upstream Scope 3 emissions using lifecycle assessment approaches currently requires extensive effort and has rarely been conducted for a DOT inventory (ICF, 2020a). This is partly why most DOTs include only Scope 1 and 2 emissions in their greenhouse gas inventory (ICF, 2020a). As a result, carbon reduction strategies that target the production of construction materials (mainly asphalt, concrete, aggregates, and steel) are undergoing research, and studies such as this one are believed to help inform policies to track and reduce embodied carbon.

California department of transportation (Caltrans) is one of the state DOTs that has done more extensive research on the greenhouse gas inventory of its operation and construction. In 2020, for example, Scope 1 and 2 emissions from Caltrans internal operations (i.e., vehicles and equipment operation, buildings, highway lighting, and other facilities) were roughly estimated at 120 thousand metric tons (ICF, 2020a). The same study followed an LCA approach using the annual Caltrans Contract Cost Data reports (similar to the Unit Bid Analysis data from WSDOT) to report 2.5 million metric tons attributed to upstream Scope 3 emissions from material production.

Oregon Department of Transportation (ODOT) has possibly performed the most comprehensive agency-wide greenhouse gas inventory analysis. For ODOT, Scope 1 and 2 emissions are reported to account for roughly 50 thousand metric tons while Scope 3 emissions are estimated at around 130 thousand metric tons (Good Company, 2021a). Table 7 provides a summary of GHG emissions from three state DOTs (including the results of this study for WSDOT). ODOT has also published a report summarizing best practices and recommendations for reducing its owned greenhouse gas emissions while providing estimates of their quantitative impacts on the agency’s GHG inventory (Good Company, 2021b).

Table 7. Comparing Scope 1 and 2 and upstream Scope 3 emissions among different DOTs.

Department of Transportation	Scope 1 and 2 emissions (thousand metric tons)	Upstream Scope 3 emissions (thousand metric tons)
California (Caltrans)	120	2,500
Oregon (ODOT)	50	130
Washington (WSDOT)	220	310 (estimated)

WSDOT, like most other state DOTs, has a strong focus on multimodal transportation solutions and does not currently fully track GHG emissions from its operation and infrastructure construction (National Academies of Sciences; Engineering; and Medicine, 2022). To date, Washington State Ferries (WSF) as part of its sustainability action plan (WSF, 2021a) has been the only WSDOT division that produced a decarbonization roadmap with the main focus on fuel transition and modernization for its ferry fleet (WSF, 2021b). With about 180 thousand metric tons, ferry vessels are claimed to represent 73% of the GHG emissions for WSDOT (WSF, 2021a); such high contribution is primarily a result of neglecting Scope 3 emissions in their accounting. The present study refers the reader to the strategies and GHG estimates established from the WSF study while uses the GHG inventory analysis performed here to draw a more complete roadmap to decarbonization for WSDOT as an agency.

Carbon Reduction Strategies

In this section, we explore opportunities to reduce upstream Scope 3 GHG emissions based on the baseline emissions analysis conducted for WSDOT. The main focus of this research is on WSDOT operations related to roadway construction and upstream Scope 3 emissions from material production. Although these emissions are shared between WSDOT and contractors building the roadways, there are still several avenues for WSDOT to influence cleaner material purchases, modify or establish specifications to allow more aggressive sustainable solutions, and inform research-based decision-making strategies. In the next section, we perform quantitative analyses on the impact of implementing these strategies according to the data collected in this study. Finally, we offer decarbonization scenarios for WSDOT according to the existing and projected technologies to better understand the challenges in achieving the carbon reduction targets.

In general, a carbon reduction strategy involves five main steps (Tracy, 2015):

1) **Inventory GHG emissions**. Determining a baseline of greenhouse gas emissions is the first step in laying out a carbon reduction strategy. Without such baselines, setting reduction goals and tracking progress toward carbon reduction strategies would not be possible. To date, WSDOT did not offer a GHG baseline for its operations. This study, however, can be considered a first estimate of upstream Scope 3 emissions from WSDOT construction operations.

2) **Establish reduction targets**. Upstream Scope 3 GHG emission baselines determined in the previous step would help devise reasonable, agency-specific, reduction targets. Although it may be possible to set reduction goals that are aligned with existing statewide targets (for example, RCW 70A.50 targets), the establishment of locally developed targets is often more politically popular and more grounded in DOT activities. This study provides decarbonization scenario analyses that may be helpful in identifying meaningful reduction targets for WSDOT.

3) **Revise climate action plans to include Scope 3 emissions**. This includes a series of recommendations and strategies that detail how the reduction targets set in the previous step will be achieved. Although WSDOT currently has existing climate action plans in place, they do not directly entail carbon reduction strategies for Scope 3 emissions. Our work can help develop inventories and provide recommendations for reducing emissions from materials production that is currently missing from most climate action plans.

4) **Implement policies and measures**. Successful implementation of climate action plans relies heavily on policies to help balance stakeholders' expectations and the builders' constraints. This step is possibly the most challenging to accomplish because 1) it may require substantial adjustments in technical specifications as well as the attitudes of project managers, engineers, and stakeholders, and 2) the literature on this topic is relatively nascent and does not provide a wealth of information compared to more technical aspects of decarbonization.

5) **Monitor and verify results**. A carbon reduction strategy is an iterative process. That means once policies are implemented according to the action plans, the

entire process needs to be revisited: periodically update the GHG inventory to track progress towards reaching the previously established targets and modifying those targets based on the implementation of reduction strategies. This way, agencies can identify gaps and address shortcomings within each step.

Creating a carbon reduction strategy framework in the form of a climate action or sustainability plan is beyond the scope of this study. Nevertheless, this research attempts to highlight the breadth of strategies available for WSDOT to reduce its upstream Scope 3 GHG emissions.

Upstream Scope 3 emissions reduction opportunities

This section summarizes opportunities to reduce upstream Scope 3 emissions for WSDOT as an agency. In this research, we narrowed down Scope 3 emissions to only include upstream supply chain emissions due to the construction of WSDOT roadways as defined in our LCA system boundary. In a nutshell, that includes cradle-to-construction emissions from material production, transportation of materials from/to job sites, and construction activities taking place to deliver a project (see Table 3). Consequently, the following sections delve into opportunities to reduce upstream Scope 3 emissions from three primary construction materials identified in this study that contribute the most to overall emissions (i.e., asphalt, cement concrete, and steel), material transportation, and construction activities. There are also some generic strategies to reduce Scope 3 emissions that we outline under a separate category.

Asphalt materials

Asphalt mixtures are the primary material used to pave roadways. Asphalt binder production from refining crude oil and hot mix asphalt production in plants are the two major sources of GHG emissions for asphalt materials. Therefore, strategies to reduce emissions from asphalt materials typically emphasize material and mix production-related emissions (Shacat et al., 2022). Our analysis further suggested that asphalt materials are the major contributor to upstream Scope 3 emissions per year. Therefore, we support the claim that strategies to reduce emissions from asphalt production and placement present the highest potential to decrease upstream Scope 3 emissions. The following bullet points, in the order of technology availability and actionability, provide a list of carbon reduction strategies, their carbon reduction potential, the state of the practice, and challenges in implementation:

- **Reclaimed asphalt pavement (RAP)**. RAP is obtained from post-processing the removed out-of-service asphalt pavements. The use of RAP in hot mix asphalt production offers the most readily available solution to reduce emissions.
    - *Reduction potential*. The use of RAP following current allowable contents is reported to offer a 6.8% to about 20% emissions reduction (Morse, 2021, Shacat et al., 2022, N. Liu et al., 2022). It is also reported that 90% of avoided emissions from asphalt production are resulted from using RAP (Shacat et al., 2022).
    - *State of practice*. While an average asphalt mixture contains around 20% RAP (Williams et al., 2020), WSDOT does not currently track RAP usage in any of its datasets. WSDOT currently limits asphalt binder replacement content to 40% (WSDOT, 2022a). However, studies have shown that up to 50% RAP can be incorporated in asphalt mixtures following best plant production practices (West & Copeland, 2015). The use of recycled engine bottom oils and other chemicals as rejuvenating admixtures to soften RAP binder is a common practice to help with mixture long-term performance issues (Good Company, 2021b).
    - *Challenges*. A limiting factor in the use of high RAP content is the concern about its adverse effects on pavement longevity. This concern is somewhat reflected in many of the current nationwide DOT specifications limiting maximum allowable RAP content and requiring supplementary material testing for mixes with higher than 20-25% RAP. Another policy-related barrier to using RAP is the practice that some agencies retain the ownership of RAP instead of transferring ownership to the contractor which can limit contractors' ability to use RAP (Shacat et al., 2022). Issues with RAP supply, mixture quality control, RAP processing, and plant modification are other factors that prevent high RAP content production (Muench et al., 2015).

- **Recycled asphalt shingles (RAS)**. RAS is a waste product from shingles manufacturers and is available in two forms: manufacturer waste scrap shingles (MWSS) and tear-off scrap shingles (TOSS).
    - *Reduction potential*. Depending on the type of RAS and its mixture properties, a hot mix asphalt mix made with 5% RAS can have an equal carbon reduction potential to 15% RAP.
    - *State of practice.* Although the use of RAS in asphalt production is ruled out by some DOTs, research shows that 5% RAS in HMA production can be used safely without compromising long-term performance (Ashtiani et al., 2018). When used in hot mix asphalt production, MWSS is the preferable RAS type because of its lower PG binder grading (compared to TOSS) and consistency.
    - *Challenges*. The highly aged asphalt binder in RAS is believed to negatively affect the performance of pavements made with it. In particular, due to years of being in service, TOSS can contain several types of debris and, with older shingles, the possibility of asbestos materials that make its recycling more prohibitive. Concerns with the degree of blending between the aged binder from RAS and virgin asphalt binders pose challenges in the manufacturing of HMA with RAS.
- **Warm mix asphalt (WMA)**. WMA refers to technologies and chemical additives incorporated during hot mix asphalt production that help reduce mixing temperatures. The plant foaming technique is the most prevalent method of WMA production (Muench et al., 2015).
    - *Reduction potential*. Although the use of WMA technology was believed to significantly contribute to emission reductions, new studies suggest that WMA is mainly used as a compaction aid without remarkably reducing the mixing temperature (Good Company, 2021b). Nevertheless, WMA is reported to reduce emissions by 6-15% (Gallivan et al., 2010, Woodall, 2021).
    - *State of practice*. In 2019, WMA was used in the production of 19% of asphalt mixtures in the U.S. to reduce the mixing temperature by at least 10^{o}F (Shacat et al., 2022). For WSDOT, it is reported that 66% of all hot

mix asphalt production in 2010 used WMA technology (Muench et al., 2015). Currently, WSDOT does not track the use of WMA in any of its datasets. Using WMA as a compaction aid component can still offer long-term performance benefits; especially when combined with RAP.

- *Challenges*. When using WMA additives, there is a need to completely dry aggregates to ensure proper adhesion of asphalt binder to aggregates. As a result, the benefits of a lower mixing temperature can be offset by a higher burner temperature required to dry out aggregates. Moreover, upstream emissions associated with the production of WMA additives are not well studied and may decrease its perceived overall benefits. Another challenge could be some of the WMA additives that can lead to longer-term cracking in the pavement.

- **Cleaner fuel/electricity**. Hot mix asphalt production requires a significant amount of heat to liquefy asphalt binder and create bonds with hot aggregates. Asphalt plant operations account for more than one-quarter of the entire cradle-to-gate GHG emissions for hot mix asphalt. Hence, many believe that hot mix asphalt decarbonization should rely heavily on substituting the source of heating energy with cleaner, less-emitting, sources. Biomass, renewable natural gas (RNG), renewable propane for mobile asphalt plants, biodiesel, renewable diesel, and renewable hydrogen are among the highly cited substitutions for asphalt plant burner fuel (Shacat et al., 2022, Swanson, 2022a, Good Company, 2021b). As another alternative, full electrification of asphalt plant operations given a renewable-based electricity grid offers equal carbon reduction opportunities.
  - *Reduction potential*. Compared with coal-fired asphalt plants, renewable natural gas offers carbon reductions of 10-15% to produce one ton of hot mix asphalt (N. Liu et al., 2022). Ultimately, the use of renewable fuels or full electrification can offer savings of up to 40%.
  - *State of practice.* Most asphalt plants currently use residual fuel oil (mobile plants) or natural gas (fixed plants) to fuel their burner (national average natural gas consumption is 69%). A full transition to natural gas is the first step toward the use of cleaner energy sources for asphalt plant

burner and dryer operations. Some plants also participate in the EPA's EnergyStar Challenge which sets a 10% reduction goal over five years.

- *Challenges*. Plant equipment upgrades and technology scaling, significant capital costs, limited domestic supply of renewable fuels, and proximity to local fuel producers are among the most challenging aspects of the transition to cleaner energy consumption at asphalt plants.

- **Stockpile management**. Stockpile management consists of housekeeping practices within asphalt plants that help manage aggregate and RAP/RAS stockpiles while providing opportunities to become more sustainable. Aggregate moisture content control, RAP fractioning into stockpiles with different sizes, and reforestation of aggregate quarries are among the best stockpile management practices.
  - *Reduction potential*. The evaporation of aggregate moisture accounts for more than 40% of burner fuel consumption (Shacat et al., 2022). Reducing aggregate moisture content by 1% can result in a 10% reduction in burner energy use, a 10-20% increase in production speed, and a 14% reduction in fan volume required for a drum plant (Good Company, 2021b, Shacat et al., 2022).
  - *State of practice.* Covering aggregate and RAP stockpiles (using a structure or plastic fabrics), sloping the grade under stockpiles, paving the medium underneath stockpiles, collecting aggregates from the tip of stockpiles with lower moisture contents, and decreasing the number of small piles are among the practices to help reduce the moisture content of stockpiles. RAP fractionating can also help maximize the use of RAP in mixtures and to help plant operators meet volumetric specifications (Swanson, 2022b). Reforestation of open land within aggregate quarries continues to be a core element of sustainability best practices within the aggregate industry (NSSGA, 2021). The emission reduction potential of the latter two strategies requires more research.
  - *Challenges*. Most of the strategies outlined above are only applicable to fixed plants. These strategies further incur additional costs for asphalt plants. Additionally, the high number of asphalt mixtures specified by

WSDOT [similar to other state DOTs] requires plants to store several stockpiles with specific aggregate sizes. Reducing the number of stockpiles as a result of limiting the number of mixes being requested by WSDOT can help asphalt plants better manage their stockpiles (Good Company, 2021b).

- **Cold mix asphalt (cold recycling)**. Refers to a category of asphalt mixtures made with emulsified asphalt binders, which are in a liquid state above freezing temperatures. Cold mix asphalt eliminates the need for heating raw materials to build pavements and thus has a lower carbon footprint. Most cold mix asphalts use recycled materials like RAP or reclaimed base materials. Cold mix recycling technologies can be classified into three categories: cold in-place recycling (CIR), cold central-plant recycling (CCPR), and full-depth reclamation (FDR) (Xiao et al., 2018). All three categories can potentially use 100% of reclaimed materials in place or in a plant.
    - *Reduction potential*. Since around 40% of emissions from hot mix asphalt production are attributed to the energy needs for heating up aggregates and asphalt binder, cold mix asphalt can potentially reduce cradle-to-gate GHG emissions by 40%. However, emissions due to longer road closure times and the need for larger engine equipment on-site need to be considered when using in-place recycling methods. Moreover, when using additives (such as cement stabilization) to strengthen pavement layers, the embodied carbon of cold recycling can increase.
    - *State of practice.* Some state DOTs have included cold mixes (especially FDR) in their standard specifications. WSDOT currently allows for the use of cold mix asphalt technologies with one CIR project done in 2022. The lack of superior performance of cold mix asphalt pavements can be among the reasons why cold mixes are less popular in roads managed by DOTs.
    - *Challenges*. Lower performance properties (both permanent deformation and cracking), the need for long road closures due to equipment operation (for in-place recycling methods) and longer curing times than conventional HMA, and difficulty in quality control due to aggregate gradation

alternation during in-place recycling are among the challenges in cold mix asphalt pavement construction.

- **Polymer-modified asphalt binder**. Styrene-butadiene-styrene (SBS) and ground tire rubber (GTR) are two primary polymer-based additives used in asphalt binder production. The dosage at which these additives are used is typically less than 10% of the weight of asphalt binder or less than 1% of the total asphalt mixture (Shacat et al., 2022).
    - *Reduction potential*. Although the use of SBS-modified asphalt binder is reported to increase cradle-to-gate emissions of asphalt mixtures by 9% (Shacat et al., 2022), the use of SBS has been shown to improve pavement long-term performance. At 8% application, GTR can potentially reduce overall asphalt mixture emissions by less than 1% (Wildnauer et al., 2019).
    - *State of practice.* 3.5% SBS and 8% GTR per weight of asphalt binder are the typical dosages used in practice. Caltrans requires a minimum of about 11% GTR in asphalt binders (ICF, 2020a).
    - *Challenges*. The long-term effects of using asphalt binder modifiers are not well understood.
- **Recycled aggregates**. Although the use of reclaimed aggregates in hot mix asphalt production offers fewer advantages, they can be used in other applications such as in pavement base, subbase, and sublayers. Recycled concrete materials and steel slag can also fall under this category.
    - *Reduction potential*. After accounting for the modifications of recycled aggregates to be suitable for use, they offer carbon reductions of about 5 to 8% compared to virgin aggregates (Lokesh et al., 2022).
    - *State of practice.* WSDOT allows the use of up to 100% recycled concrete aggregates in some applications (e.g., coarse aggregate for commercial concrete and concrete pavements, backfill for foundations, walls, pipe zone bedding, gravel/select borrow, etc.)). The use of steel slag is limited to 20% replacement of aggregates for hot mix asphalt production and other aggregate products. From 2016 to 2022, the majority of recycled concrete aggregates were used in crushed surfacing, gravel backfill for pipe bedding, and common borrow in WSDOT applications.

  - *Challenges*. Aggregate gradation control requires additional procedures which makes the use of recycled aggregates less popular in hot mix asphalt and cement concrete production.
- **Bio-binder**. A new generation of carbon-sequestering bio-component asphalt binders is undergoing research and development (Shacat et al., 2022).
  - *Reduction potential*. The bio-based binder produced by Shell Oil Company is advertised to reduce 0.227 metric tons of CO_2eq per ton of asphalt (Shell, 2022). More research is needed to validate such claims.
  - *State of practice.* Shell Oil Company presented its first bio-based binder called CarbonSink and used it on a small paving project in the U.K. (Shell, 2022).
  - *Challenges*. The primary concern with the use of bio-binders from an engineering perspective is the uncertainty of their impact on the performance of pavements (Shacat et al., 2022). Other potential concerns are about the cost and large-scale supply of bio-binders.
- **Carbon capture, utilization, and storage (CCUS)**. CCUS refers to technologies that capture carbon dioxide emissions immediately upon release into the atmosphere. The captured carbon can be either stored permanently or utilized in processes that require carbon. GHG emissions associated with asphalt binder production can be significantly reduced when the CCUS technology expands to oil refineries.
  - *Reduction potential*. CCUS offers significant carbon reduction potential. 100% of direct carbon emissions can be technically captured; however, the technology is not yet available for large-scale applications.
  - *State of practice.* Although some cement manufacturers have begun plans to integrate CCUS at select plant locations, there are no known asphalt production plants that currently use this technology in the U.S.
  - *Challenges*. CCUS technologies incur significant amounts of capital expenditures, and their application remains cost prohibitive until fully developed and incentivized (Shacat et al., 2022).
- **Balanced mix design (BMD)**. Most DOTs currently use volumetric methods to design asphalt mixtures. Recently, research has been done on the addition of

several types of mechanical performance tests to either reinforce or replace the existing mix design approaches. A BMD approach takes the rutting and fatigue resistance of asphalt mixtures into consideration and is believed to pave the way for the incorporation of more controversial materials such as RAP, RAS, GTR, etc. into asphalt mixtures (Shacat et al., 2022).

  - *Reduction potential*. BMD does not directly cause carbon reduction. However, BMD may allow the use of higher dosages of recycled materials while improving the long-term performance characteristics of asphalt pavements.
  - *State of practice.* Some DOTs (including WSDOT) require mixes to undergo performance tests such as the Hamburg wheel tracking test (HWTT) to measure rutting resistance and moisture susceptibility and the indirect tensile strength test (IDT) to measure cracking resistance. However, a BMD approach is technically a mix design procedure and has not yet been explicitly introduced in WSDOT standard specifications.
  - *Challenges*. Taking a BMD approach to mix design requires significant changes to standard specifications and how asphalt mixtures are verified.

- **Use phase and lifecycle optimization**. Although the scope of this research does not consider the whole lifecycle impacts of roadways, GHG emissions associated with the operation of vehicles and their interaction with pavements can be as significant as cradle-to-construction emissions. In particular, pavement smoothness, density, and durability are among the key factors contributing to the whole lifecycle GHG emissions of pavements (Good Company, 2021b). This is in part reflected in WSDOT specifications where smoother, denser, and more durable pavements are incentivized with pay factors calculated from field test measures. Carbon reduction potentials from optimized pavement design require further research beyond the scope of the present study.
- **Synthetic aggregates**. These are produced by combining waste carbon dioxide with calcium which is also typically sourced from waste products. The primary type is synthetic limestone aggregate.

- *Reduction potential*. Blue Planet, the company known for its synthetic limestone aggregate products, claims that these aggregates can sequester carbon at about 40% of the weight of aggregates.
- *State of practice.* Large-scale production and application of synthetic aggregates are undergoing research.
- *Challenges*. The technology is mostly advertised for use in cement concrete and is still highly cost-prohibitive.

- **Recycled plastic**. The use of hard-to-recycle plastics (such as HDPE, LDPE, and PP) in asphalt binder production is currently undergoing research. Recycled plastics can be incorporated either directly into an asphalt binder as a blend (the wet method) or in a dry state like an additive (the dry method) (Swanson, 2022b).
- **Improve asphalt plant operation**. This includes activities to enhance productivity in asphalt plant operations. For example, controlling exhaust gas temperatures by continually adjusting the dryer drum speed and using silo storages to enable plant operators to run continuously and with higher production rates. Silo storage can potentially enable higher RAP content incorporation into asphalt mixes.

Cement concrete materials

Superstructures and substructures of bridges, bridge decks, retaining walls, pavements, sidewalks, pipes, curbs and gutters, catch basins, manhole structures, among others are examples of applications where concrete is used. The building sector is more mature in research on carbon reduction strategies for concrete. Thus, in this study, we may refer to several strategies that are more commonly used for building construction. However, decarbonization scenarios for concrete in buildings should resemble those for roadways, perhaps with some differences in how they should be prioritized for a DOT (Azari Jafari, 2021).

The majority of GHG emissions for concrete come from clinker production which consequently is ground into powder to create cement. To produce clinker, a source of naturally occurring rock (typically limestone; or calcium carbonate) is mixed with other ingredients such as clay at very high temperatures (above 2,700^{o}F) (Woodall, 2021). As a result, GHG emissions are released from burning the fuels used to generate that high degree of heat (around 40% of GHG emissions) with the remaining emissions (about 60%) attributed to the production-related calcination process where a significant amount of CO_2 is released due to the chemical reaction between raw ingredients at high temperatures (Good Company, 2021b). Therefore, the majority of carbon reduction strategies for PCC are centered around clinker production and technologies to make the process less carbon-intensive. The following bullet points, in the order of technology availability and actionability, provide a list of concrete carbon reduction strategies, their carbon reduction potential, the state of the practice, and challenges in implementation:

- **Alternative and supplementary cementitious materials**. This is a broad category of materials used to replace portland cement. While SCMs reduce the need for portland cement production, they can further enhance concrete properties. However, some supplementary cementitious materials cannot fully replace portland cement (e.g., pozzolans). Fly ash (a by-product of coal combustion), microsilica and silica fume (by-products of silicon metal), ground granulated blast furnace slag (GGBFS; a by-product of iron production), pozzolans (e.g., volcanic ash and glass), portland limestone cement (PLC or Type IL cement), and limestone calcinated clay cement (LC3) are among the most commonly used and cited cement alternatives or substitutes.
    - *Reduction potential*. Together, SCMs used at current rates can potentially reduce GHG emissions from cement production by 36% (Azari Jafari, 2021, King & Gross, 2022). According to one source, fly ash and GGBFS can reduce CO_2 emissions by 894 kg and 763 kg, respectively; this is roughly equivalent to their content in portland cement (i.e., 1% fly ash reduces emissions from cement by 1%) (Morse, 2021). 15% Type IL limestone cement substitute can offer about 10 to 15% GHG emissions reduction (Good Company, 2021b).
    - *State of practice.* In general, alternative cement constituted 15 to 25% of the weight of cement in 2021 (Azari Jafari, 2021). Fly ash is the most commonly used SCM. WSDOT mixes contained an average of 20% fly ash in 2010 while specifications allow for up to 35% (percentages are by weight of cement) (Muench et al., 2015). Seattle Department of

Transportation (SDOT) requires all sidewalks to use 25% SCMs (Tracy, 2015). Caltrans currently requires the use of at least 25% SCMs and allows up to 50% replacement (ICF, 2020a). ODOT allows 30% fly ash and 50% slag. The Slag Cement Association suggests that up to 80% of slag can be used in specific applications. Slag is used in 25% of all cementitious materials in WSDOT (Muench et al., 2015). Silica fume is typically used at a 5% replacement rate (Good Company, 2021b). Portland cement specifications allow up to 5% replacement of limestone, while PLCs limit limestone content to 15% (PCA, 2021). Ground glass used as a pozzolanic material comes in three main types of container glass, plate glass, and e-glass (a by-product of fiberglass production). The substitution rate of ground glass products can vary from 10 to 40%.

   - *Challenges*. Local availability of SCMs can limit their use, especially when transportation distances increase and less environmentally friendly transportation modes are required to ship these materials. The future supply of some SCMs can also become a limitation; for example, coal fire plants across the country and in Washington are shutting down which in turn cuts the supply of fly ash. Other challenges can include longer curing times for mixes made with SCMs (i.e., early-age performance issues), and other environmental issues with alternative cements such as toxicity, increased risk of salt scaling, among others. There are also some policy-related challenges in using SCMs such as liability transfer from contractors to specifying agencies if minimum dosages are required.

- **Optimized design**. Structural design optimization typically refers to designs that reduce the total amount of concrete required while delivering similar durability and strength properties (King & Gross, 2022). Mix design optimization similarly focuses on decreasing cement content without compromising its performance, typically by improving the particle packing (PCA, 2021).
   - *Reduction potential*. For concrete pavements, it is postulated that a 19% reduction in concrete consumption per area is achievable with optimized design with a decrease in cement content by 50% targeted by the year 2050 (Azari Jafari, 2021). Portland cement association (PCA) also proposes that

a 26% GHG emissions reduction is possible by the year 2050 following mix design optimization. It is also suggested that structural design and mix design optimization can potentially reduce GHG emissions by 12% and 19%, respectively (Azari Jafari, 2021).

- **Avoiding overdesign**. Currently, more than 5% of concrete is returned from construction sites. The underutilized concrete which is in an unhardened state is referred to as returned plastic concrete (RPC) and is suitable for recycling and reuse (ICF, 2020a). Other than GHG reduction, the benefits associated with reduced RPC include a reduction in energy consumption, landfill areas, disposal costs, and hauling costs.
    - *Reduction potential*. Through more precise design and construction practices, the returned concrete can be reduced to 2.5% by the year 2050 (PCA, 2021).
- **Concrete recycling and reuse**. Mainly referred to as recycled concrete materials (RCM), out-of-service concrete can be collected and post-processed for use in other applications. In the U.S., over 140 million tons of concrete are recycled annually (ICF, 2020a). Recycled concrete is primarily used as a virgin aggregate substitute for base and sub-layers and not much so in asphalt or concrete production.
    - *Reduction potential*. The benefits of using RCMs are typically due to the avoidance of virgin aggregate use. Reusing 10% of recycled concrete by the year 2050 is estimated to cut GHG emissions by 6% (Azari Jafari, 2021). On-site recycling may offer additional benefits. Substituting 1 ton of materials with RCMs would offer about a 7 kg reduction in CO_2 (Gallivan et al., 2010). Furthermore, some research suggest that recycled concrete can potentially sequester carbon (referred to as carbon uptake or cement carbonation) from the atmosphere during a longer time horizon (Xi et al., 2016). Evaluation of the potential carbon reduction of this theory is beyond the scope of this research.
    - *State of practice*. WSDOT currently allows for the use of coarse RCMs in new concrete pavements, commercial concrete, and class 3000 concrete by up to 100%. RCM is not allowed in asphalt mixtures. However, up to

100% recycling is allowed for the substitution of ballast, base, backfill, borrow, foundations, etc. RCMs are mainly used to substitute crushed surfacing materials, gravel and common borrow, and as foundation material Class A and B.

  - *Challenges*. Altered gradation and aggregate physical properties (e.g., high moisture absorption, irregular and angled particle shapes) limit RCM usage in new concrete and asphalt mixes. Long transportation distances from the job site to processing plants and vice versa can reduce or even cancel out the benefits of using RCMs.

- **Carbon capture, storage, and utilization (CCSU)**. As explained previously, CCSU technologies can help capture process emissions resulting from [cement] production from a facility's exhaust gas before they are released into the atmosphere. Carbon capture processes are undergoing research and include a variety of technologies such as amine scrubbing, calcium looping, oxycombustion, algae capture, etc. (PCA, 2021, Woodall, 2021). Using synthetic materials with stored CO_2 (i.e., carbon mineralization) such as synthetic aggregates can align well with CCSU technologies.
  - *Reduction potential*. It is difficult to predict the carbon reduction potential using CCSU technologies. EIA projects a 2 to 38% reduction by the year 2050. Others postulated a reduction of 32% to 100% at cement clinker plants (N. Liu et al., 2022, Woodall, 2021). In another study, the overall reduction potential for concrete after the employment of CCSU technologies is reported to vary between 10% to 16% (Azari Jafari, 2021). Moreover, 12% of GHG emissions can be potentially reduced using synthetic aggregates (Woodall, 2021).
  - *State of practice.* Current technologies emit between 0.1 to 0.72 kg CO_2 per kWh of electricity usage. Once operating with a fully renewable energy supply, CCSU technologies would emit 0.02 kg CO_2 per kWh. There is no known usage of CCSU currently at any cement production plant.
  - *Challenges*. Employment of CCSU technologies requires significant scale-up effort and there are serious cost uncertainties associated with

them. Furthermore, to fully benefit from CCSU, a clean electricity supply is necessary.

- **Fuel switching and energy efficiency improvement**. Clinker production requires high temperatures to activate the chemical reactions between limestone and other materials. The heat is typically generated using fossil fuels like coal and petcoke. The use of low-carbon alternative fuels such as natural gas and biomass would help reduce GHG emissions. In addition, through modernization, upgrades, machine learning, and artificial intelligence, the efficiency of cement plants can be improved. Concrete manufacturing and transportation also contribute to 5% and 6% of total GHG emissions, respectively. Bio-based cement plant fuel, using waste as cement plant fuel, and plant electrification are example strategies that we included here.
    - *Reduction potential*. The use of natural gas is believed to cut CO_2 emissions due to combustion by about 24% in the near-term (PCA, 2021). Bio-based cement plants, the use of waste as plant fuel, and plant electrification would respectively reduce emissions by 28%, 20%, and 54% (N. Liu et al., 2022). Energy efficiency improvements within cement plant operations are believed to reduce emissions from cement production by 25% in the long run (PCA, 2021). Shifting to renewable energy sources for concrete manufacturing and transportation can potentially reduce GHG emissions to 0% and 3% by the year 2050 (PCA, 2021).
- **Carbon uptake**. It has just recently been argued that the calcination process during clinker production is reversible (Xi et al., 2016). During its lifecycle, the curation of concrete (given sufficient humidity and above-freezing temperatures) absorbs CO_2 in the atmosphere by reacting with the calcium hydroxide ($Ca(OH)_2$) to produce calcium carbonate ($CaCO_3$). This process is conventionally termed carbon uptake of concrete.
    - *Reduction potential*. There is no consensus about how much CO_2 can potentially be sequestered by concrete during the use phase. PCA states that 20% of CO_2 emitted during the calcination process can be permanently sequestered during concrete's lifecycle (Azari Jafari, 2021,

PCA, 2021). Others reported that 1% of overall concrete GHG emissions can be potentially sequestered (Azari Jafari, 2021).

- *State of practice.* There are some approaches to increase the potential of carbon uptake by concrete. For example, spreading RCM over the land to maximize interaction with the ambient atmosphere is believed to increase the CO_2 sequestration rate. Research on carbon uptake is ongoing and methods to practically maximize carbon sequestration do not exist.
- *Challenges*. Carbon uptake is a purely theoretical concept at this point. Proposed methods (e.g., spreading RCM) are not proven to effectively help lower overall GHG emissions of concrete.

Steel materials

The third largest contributor to GHG emissions from road construction is steel. Structural and reinforcing steel are the two most common applications of steel in roadways (e.g., bridge girders, mast arms, reinforced concrete pavement, etc.). Around 85% of GHG emission savings in steel production come from technologies that are currently on the market and it is believed to continue until the year 2030 (iea, 2021). Technologies under development will deliver the bulk of GHG emission reductions after 2030. Therefore, carbon reduction strategies for steel are majorly limited to its supply chain and not much is delivered through construction practices.

The primary pathways to reduce embodied carbon of steel include:

- **Procurement policies** (see Holistic approaches below for further discussion). Unlike concrete and asphalt, there is no change in the technical specifications for steel when requesting lower embodied carbon products. There are strategies for steel manufacturers to reduce emissions. For this reason, collecting product-specific and facility-specific data to differentiate suppliers that have adopted carbon reduction best practices is particularly critical for steel materials.
- **Fuel switching and plant energy efficiency improvement**. The use of biobased integrated steel plant fuels, biobased secondary steel heating oven fuel, biobased steel metallurgy fuel, shift to low emission electricity, iron ore electrolysis, electrification of ancillary equipment (e.g., electrification of re-heat furnaces), plasma smelting reduction, smart manufacturing and the application of the

internet of things to increase plant energy productivity, and the use of hydrogen in blast furnaces are among the technological advancements that can cut GHG emissions from steel production (iea, 2021, U.S. DOE, 2022). An increase in scarp-based electric arc furnace steel production, which requires about one-tenth of the energy required for primary steel production, drives most of the GHG emission reductions within the next decade (iea, 2021). Currently, the Nucor steel plant can be considered one of the cleanest steel production plants across the country due to the high content of scrap steel usage in their electric arc furnaces (EAF) in addition to the hydropower-based energy grid in Washington. EPDs for rebar produced at this plant suggest about 11% below industry average emissions.

- **Hydrogen as steel reduction agent.** In traditional steelmaking processes, carbon-based reducing agents, such as coal and coke, are used to remove the oxygen from iron ore and produce molten iron. However, the use of hydrogen as a reducing agent has been proposed as a more environmentally friendly alternative, as it does not produce carbon dioxide emissions. Instead, the reaction between hydrogen and iron ore results in the production of water as the only byproduct. Using hydrogen as a reducing agent in steel production is still in the developmental stage, but it has the potential to significantly reduce GHG emissions from steel manufacturing.
- **Carbon capture, storage, and utilization (CCSU).** As previously explained in the case of asphalt and cement manufacturing, CCSU in steel manufacturing refers to a set of processes that involve capturing the carbon dioxide emissions produced during steel production, storing it, and then utilizing it for other industrial applications. The objective of CCSU is to reduce the carbon footprint of the steel industry and mitigate its impact on the environment. The captured CO_2 can be compressed, transported and stored in underground geological formations, or used for enhanced oil recovery. It can also be utilized in other industrial applications such as producing chemicals, fuels, and minerals. Implementing CCSU in steel production is still in its early stages, but it holds promise for reducing carbon emissions from the sector in the future.

- **Top gas recycling.** Top gas recycling in steel production refers to the process of capturing and reusing the waste gases generated during the production of iron and steel. The waste gases, commonly known as top gas, are generated during the production of iron and steel in blast furnaces, basic oxygen furnaces, and electric arc furnaces. Top gas contains valuable gases such as carbon monoxide and hydrogen which can be recovered and used as fuel in the production process, reducing the need for external fuel sources and reducing emissions. The recovered gases can also be used as feedstocks in chemical synthesis, helping to reduce the GHG emissions from steel manufacturing.
- **Recycled reinforcement steel.** Recycled reinforcement steel refers to steel that is collected from demolition sites, scrap yards, or end-of-life products and reused as reinforcement in concrete structures. Recycling steel requires significantly less energy compared to producing it from raw materials. This reduction in energy consumption reduces greenhouse gas emissions. Reusing recycled steel instead of producing it from raw materials conserves resources and reduces the demand for new iron ore, coal, and other materials used in the production of steel. Furthermore, transporting steel from mines to production facilities and then to construction sites is a major source of greenhouse gas emissions. Recycling steel locally further reduces transportation distances and the associated emissions.
- **Structural optimization.** The main application of steel in roadways which offers opportunities for structural optimization is in bridge construction. The goal of structural optimization is to minimize material usage, reduce the weight of the structure, and increase its strength and stiffness while ensuring that it meets all necessary performance requirements and safety standards. Structural optimization considers various factors such as loading conditions, material properties, geometries, and constraints to determine the optimal design of the bridge structure. By reducing material usage, energy consumption, and waste, structural optimization can play a significant role in reducing GHG emissions associated with steel production and use.

Material transportation and equipment operation

Transporting materials from/to job sites and the operation of construction equipment to deliver products in roadway projects together account for about 15% of total GHG emissions (Lokesh et al., 2022). Our analysis also conforms with the existing literature on the order of magnitude for GHG emission contributions from these two broad categories. For material transportation and construction activities, carbon reduction strategies typically include:

- **Reduced hauling distance** by purchasing locally available materials and the use of alternative fuels such as biofuels, renewable diesel, hydrogen fuel cells, and battery electric heavy-duty vehicles for truck operations (Shacat et al., 2022). For example, it has been shown that the environmental benefits of using RAP may be offset when the hauling distance exceeds 50 miles (Ashtiani & Muench, 2020).
- **Reduce on-site fossil fuel usage** through the use of alternative fuel sources for construction equipment (e.g., biofuels, hybrid-electric equipment, or battery-electric equipment) and other construction best practices such as the employment of anti-idling regulations and technologies deliver the majority of carbon reductions.

Holistic approaches

Despite this section's focus on carbon reduction strategies for materials, there are several other approaches that help reduce GHG emissions from roadway construction projects. These approaches are typically administrative and do not directly cause a reduction in GHG emissions. In that, they mainly help drive and implement carbon reduction strategies by establishing policy language to embed GHG emissions into project procurement and delivery. Providing a quantitative measure of the carbon reduction potential from the adoption of these general strategies is difficult and we only provide examples with references to external documents.

- **Green procurement policies**. The establishment of green procurement policies, often referred to as Buy Clean, is an important tool for influencing WSDOT's construction materials as well as the practices of its contractors and suppliers. These policies can include several components:

- *Reporting of GHG emissions environmental product declarations (EPDs)*. Not only do EPDs help collect GHG emissions data for products, but they are also great tools to track progress toward sustainable solutions and promote the production of less carbon-intensive materials. EPDs are easy to understand by manufacturers and help them pay attention to the environmental aspects of their products (Butt & Harvey, 2021). EPDs can be collected and reviewed alongside other product data submittals. Several jurisdictions across the U.S. such as the City of Portland, Caltrans, Sound Transit, Colorado DOT, and Port Authority of New York and New Jersey (PANYNJ), among others, have started programs to require EPDs to be submitted with material delivery.
- *Reporting of project lifecycle emissions*. In addition to reporting EPDs, DOTs may encourage the use of pavement and other LCA tools to assess the GHG emissions of the project as a whole, rather than only of the materials. Buy Clean Oregon requires this approach for ODOT. Project LCAs can help assess design alternatives according to their environmental impacts. Requiring a project LCA is more time-intensive than collecting EPDs for different materials and may be most appropriate for a small set of more complex projects.
- *GHG emissions targets*. Over time, agencies like WSDOT may be able to set GHG emission thresholds on specific materials according to their historical track of EPDs. As a result, technology advancements and innovations offered by manufacturers can be recognized, quantified, promoted, incentivized, and finally implemented in a broader array of projects (Adams, 2021). EPDs are used to verify that a contractor procured materials meeting the targets set out in a specification, also referred to as a maximum allowable global warming potential (GWP). GWP limits are required by Buy Clean California and Buy Clean Colorado for DOT projects.
- *Performance incentives*. Similar to the way that contractors are provided financial incentives related to project schedule and construction quality, DOTs can consider the use of performance incentives to encourage

procurement practices and the use of lower-carbon material transportation and on-site construction practices.

- **Sustainability rating systems**. Another approach to promoting sustainable design and delivery of construction projects is to either require or incentivize the acquisition of certification from agreed-upon sustainability rating systems. Similar to how the LEED rating system has evolved from a voluntary certification to a requirement for some buildings in several jurisdictions, roadway rating systems such as Greenroads and INVEST can help build more sustainable roads. Not only do these rating systems provide a list of sustainable best practices, but when implemented early during the design phase can help deliver more environmentally friendly products. Carbon reduction assessment of projects that accomplish sustainable practices offered and certified by such programs is still a challenging undertaking; however, they offer several other benefits than carbon reduction such as increased pervious surfaces, more access to public transport, better data collection habits, etc. (Zokaei Ashtiani & Muench, 2022b). There are also guidebooks available to contractors to implement particular practices that are believed to deliver a more sustainable roadway project (Muench et al., 2019).

Barriers to implementing carbon reduction strategies

In the previous subsection, we described material-specific challenges to carbon reduction. This section briefly summarizes high-level challenges in implementing carbon reduction strategies from materials. These challenges are difficult to overcome, especially for the embodied carbon in the materials which is referred to as ‘stubborn’ or ‘critical to abate’. The following bullet points list some of the barriers that explain the slower pace of emissions reductions in heavy industries (iea, 2021; Karlsson, Rootzén, & Johnsson, 2020; cefc, 2021; Lokesh et al., 2022):

- **Competitive markets**. Many industrial materials including cement, steel, and asphalt are traded globally which leaves little room to absorb additional costs from adopting technology transfer actions that reduce energy consumption and carbon emissions. Therefore, it may take time to develop global cooperation frameworks and solutions to pave the way for these technologies. As reliable purchasers of high volumes of industrial materials, DOTs may be able to lead the way by creating markets for material suppliers and contractors that are early adopters of best practices.

- **Capital-intensive equipment**. Most industrial equipment have relatively long lifecycles which causes a slowdown in the innovation of low-carbon technologies. Furthermore, technology transfer comes with high upfront costs to producers. A good example is the CCSU technologies which are critical for reaching net-zero for industrial products but require substantial capital investments (iea, 2021).
- **Procurement barriers**. At the end of the day, most carbon reduction potentials are to be implemented by the contractors who build roadways. Attempting less carbon-intensive practices may expose contractors and suppliers to actual or perceived increased risk (uncommon practices are less understood). Also, construction projects do not typically last for a long time and that limits the engagement of contractors with the supply chain for low-carbon alternatives. Furthermore, contractors mainly focus on cost and optimize practices for minimal expenditures. In such a low-bid environment, additional costs to contractors without providing appropriate incentives can simply mean a failure in winning a project. And finally, current specifications do not incentivize contractors to collect environmental data from EPDs or to implement environmental assessment approaches such as LCA to inform decision-making.
- **Technical barriers**. The availability of standards, design guides, and tools to assess embodied carbon of materials is limited (e.g., shortage of specialist skills with LCA within industry professionals and limited EPD availabilities for a wide range of materials and suppliers). The performance of innovative materials with lower embodied carbon is largely unproven within roadways which in turn increases the risk for contractors. The local unavailability of many of the low-carbon manufacturing technologies further limits the options on the table. We recommend additional testing and pilot studies to overcome some of these technical barriers and support the uptake of carbon reduction strategies proposed earlier.

- **Governance barriers**. Although this is expected to change in the next few years with the emergence of federal Buy Clean initiatives, the regulations and regulatory support for implementing low-carbon strategies do not fully exist. The Inflation Reduction Act (IRA) and other aligned recent policies and funding include over $2 billion towards developing data and methods (including supporting of EPD creation) that should significantly ameliorate current challenges.

<u>Summary of potential carbon reduction strategies and measures</u>

Based on the strategies and opportunities explained previously, this section provides a summary of carbon reduction measures associated with pursuing each strategy (see Table 8). It is worth noting that this report intends to apply these measures to the data at hand and thus may not represent the entirety of all proposed strategies in this study and elsewhere.

Table 8. Summary of carbon reduction strategies, including the type of action required and whether pilots or additional testing may support uptake.

Strategy	Type of Potential Action			Recommend Pilot/Testing or Tracking
	Supplier/ Facility Action	*WSDOT Specification*	*Contractor/ Mix Design*	
Asphalt materials				
Reclaimed asphalt pavement (RAP)*		x	x	x
Recycled asphalt shingles (RAS)		x	x	x
Warm mix asphalt (WMA)*		x	x	x
Renewable fuel (bio-based) /electricity	x			
Stockpile management	x			
Plant energy efficiency	x			x
Cold mix asphalt (cold recycling)		x	x	
Polymer-modified asphalt binder		x	x	
Bio-binder		x	x	x
Carbon capture, utilization, and storage (CCUS)	x			
Recycled plastic		x	x	x
Synthetic aggregates		x	x	x
Balanced mix design (BMD)			x	
Use phase and lifecycle optimization		x	x	
Downcycled/recycled aggregates		x	x	x

Cement concrete materials				
Alternative and supplementary cementitious materials:				
*Fly ash, slag, microsilica**		x	x	
Type 1L, LC3		x	x	x
Advanced cement clinker substitutes (e.g., PLC)		x	x	x
Optimize concrete structural and mix design		x	x	
Avoiding overdesign			x	
Concrete recycling/reuse*		x	x	
CCSU at cement plant	x			
Fuel switching and plant energy efficiency improvement:				
Bio-based cement plant fuel	x			
Waste as cement plant fuel	x			
Cement plant electrification	x			
Cement plant energy efficiency	x			
Carbon uptake				*Not proven*
Steel materials				
Fuel switching and plant energy efficiency improvement:				
Biobased integrated steel plant fuel	x			
Low emissions electricity for production	x			
Plant energy efficiency	x			
Biobased secondary steel heating oven fuel	x			
Biobased steel metallurgy fuel	x			
CCSU at steel plant	x			
Top gas recycling	x			
Hydrogen as steel reduction agent	x			
Recycled reinforcement steel		x	x	
Structural optimization			x	
Material transportation and equipment operation				
Shift to biofuel (transport and site)			x	
Hybridization (transport and site)			x	
Fuel-celled/plug-in hybrid trucks (transport and site)			x	
Local material purchase		x	x	
Electrified equipment			x	
Optimized equipment use			x	
Electric rock crushing plant			x	
Recycled aggregate base layers		x	x	
Holistic approaches				
GPP: EPD Requirements		x	x	
GPP: GWP Reduction Targets		x	x	

GPP: Performance incentives	x	x	
Sustainability rating systems	x	x	

**Indicated strategies are used by WSDOT but not tracked.*

Pilot opportunities identify strategies that (1) have concerns related to performance that may be removed from additional testing/pilots or (2) are relatively new strategies or materials that would benefit from pilots before broader use.

Figure 18 illustrates the range of potential GHG emission reductions due to the adoption of technologies and practices categorized into the primary materials and processes used in roadway construction. A collection of sources from the literature and research reports is used to produce this figure (Karlsson, Rootzén, & Johnsson, 2020, Y. Liu et al., 2021, Shacat et al., 2022, WSF, 2021b). Figure 18 does not consider the magnitude of technology adoption per strategy (the temporal aspect of technology advancement is not considered). For example, GHG emission reduction in HMA production due to the use of RAP highly depends on its content in the mix design. Therefore, the variability in carbon reduction captures the variability in the extent of technology adoption and the variability in the reported reduction potentials. The next section proposes scenarios where we make assumptions about the technology adoption rates and assess their impacts.

WSDOT Decarbonization Strategies

Based on the carbon reduction strategies explained previously, this section attempts to 1) propose a decarbonization roadmap that fits best to WSDOT's context and 2) perform scenario analyses by applying the roadmap to the GHG emission inventory developed as part of this research. Both objectives rely heavily on the available data used to inventory Scope 3 emissions reported in this study. The impetus of such an effort can be highlighted by restating the consensus in reaching net-zero by the year 2050. However, this report does not necessarily propose a complete roadmap to reach net-zero for WSDOT as an agency. In that, the strategies explained prior to this section only pertain to the narrower scope of roadway construction projects managed by WSDOT.

Decarbonization scenario analysis

This section introduces five scenarios. In each scenario, a series of strategies are assumed to be effective. Scenario 1 relies on the most conservative assumptions and tries to capture the business as usual (sometimes referred to as best available technologies – BAT) and the state of the practice as of the time of this writing. The subsequent scenarios

2 thru 5 become more progressive, successively, with scenario 5 being the most progressive that somehow mimics the high ends of the carbon reduction potentials due to a higher level of technology implementation per strategy according to Figure 18. The goal of this analysis is to assess the role of different carbon reduction strategies for decarbonizing WSDOT's practices and to provide support for identifying meaningful carbon reduction targets for WSDOT.

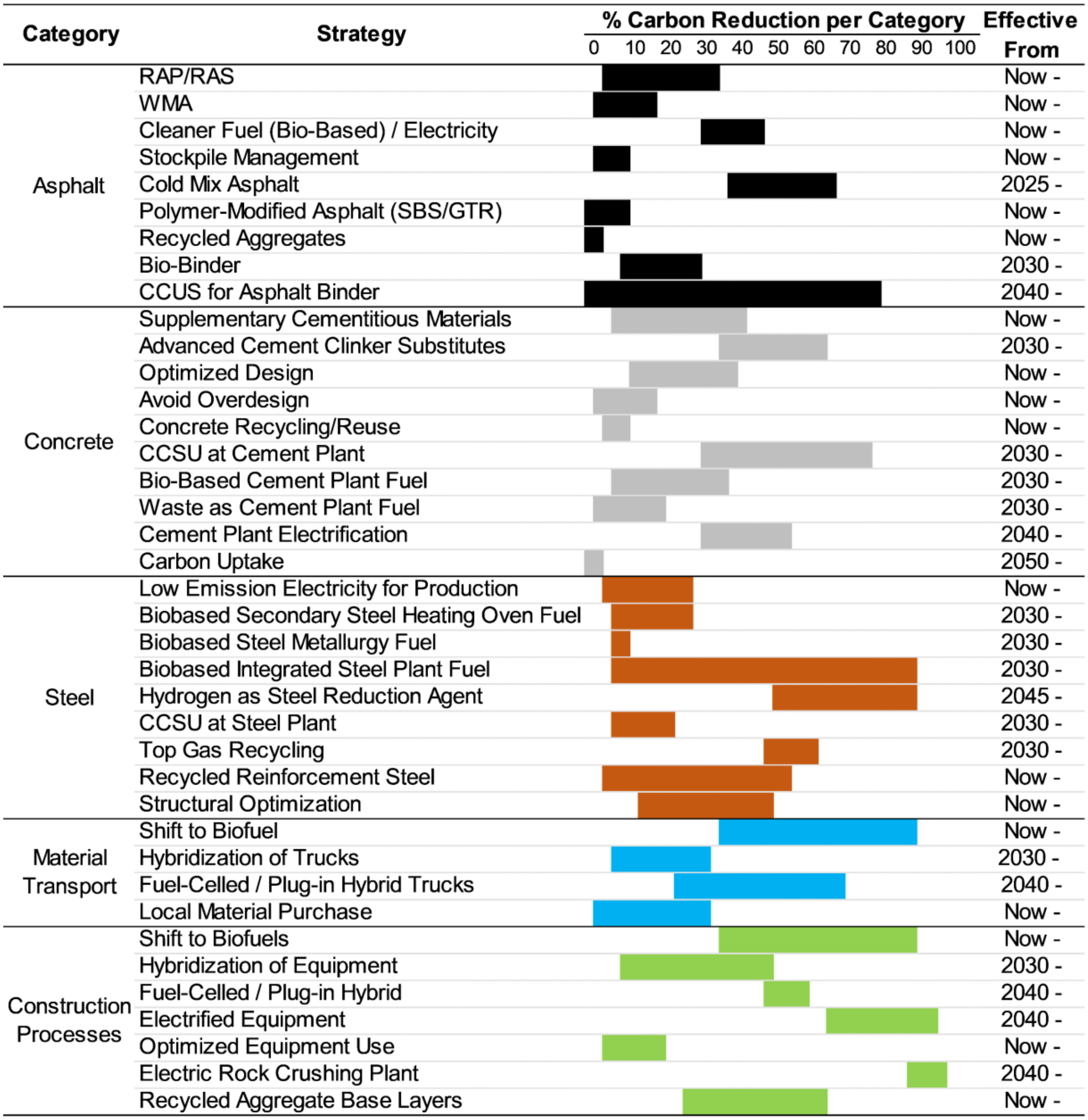

Figure 18. GHG emission reduction potentials per category and strategy.

Table 9 presents the carbon reduction pathways assessed in the five scenarios developed here. Numbers in this table are primarily adopted from existing resources that previously developed similar roadmaps (Azari Jafari, 2021; iea, 2020, 2021; Karlsson, Rootzén, & Johnsson, 2020; Karlsson, Rootzén, Toktarova, et al., 2020). However, this table includes more strategies than explained previously and excludes some strategies that we are not able to numerically assess. Scenarios in Table 9 can also be interpreted as projected technology developments and their level of implementation in the future years. For example, Scenario 1 more closely represents the technologies and levels of implementation in the year 2020 and Scenario 5 does the same for the year 2050. The intention of proposing such roadmaps is to perform a scenario analysis and investigate the impact of each strategy in reducing overall upstream Scope 3 GHG emissions for WSDOT. The results would help present recommendations to WSDOT about the effectiveness of carbon reduction strategies.

Scenario analysis

This section presents a quantitative approach to evaluate the impact of carbon reduction strategies per decarbonization roadmaps developed in the previous section. We use the baseline GHG values from Figure 8 to perform scenario analyses. In that, we avoid using the estimated GHG emissions from the economic GHG emission factors and only rely on the results directly driven by analyzing existing data using material-specific emission factors. To simplify analyses, average emission factor values will be used to perform LCA and the sensitivity of analysis on input values is not considered.

The implementation of each strategy listed under Table 9 is applied to the modified pay item list dataset created in this research. For example, lifecycle emission factor data are modified according to the assumptions made in Table 9 to depict a series of strategies (e.g., adoption of WMA technologies, CCSU, use of alternative energy sources to fuel plants, etc.). As another example, asphalt and concrete mix designs are modified according to the strategies that suggest a change in the mix designs (e.g., changes in cement content, RAP content, use of SCMs, etc.). As a result, the amount of which adoption of each strategy and its level of implementation per scenario help reduce overall emissions can be quantified. To further simplify the analysis, we use the 5-year average values (from 2017 to 2021) to summarize, illustrate, and interpret results.

Table 9. Five hypothetical decarbonization scenarios suggesting the level of technology/strategy implementation per material or process category. Scenario 1 more closely represents the business as usual (the year 2020) and is the most conservative. Scenario 5 is the most progressive and represents the highest carbon reduction potential per strategy (the year 2050).

Category	Strategy	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Unit of measure
Asphalt	RAP/RAS	20%	30%	40%	50%	60%	Percent in mix design
	WMA	60%	70%	80%	90%	100%	Percent of mixtures
	Natural gas in plant	70%	75%	85%	90%	95%	Percent of fossil fuel
	Bio-fuel plant / Electrification	0%	5%	15%	25%	40%	Percent of energy use
	Stockpile management	0%	0.5%	1.0%	1.5%	2%	Percent of moisture reduction
	Plant energy efficiency	0%	5%	10%	15%	20%	Percent improvement
	Cold mix asphalt	5%	10%	15%	20%	25%	Percent of mixtures
	SBS modified asphalt binder	3.5%	4%	5%	6%	7%	Percent of asphalt binder
	GTR modified asphalt binder	8%	10%	12%	14%	20%	Percent of asphalt binder
	Bio-binder	0%	5%	10%	15%	20%	Percent of asphalt binder
	CCUS for asphalt binder	0%	5%	10%	15%	20%	Percent of captured carbon
Concrete	Fly ash	10%	15%	21%	21%	20%	Percent of cement content
	GGBFS	10%	14%	18%	23%	28%	Percent of cement content
	Microsilica	0.1%	0.2%	0.5%	0.8%	1.3%	Percent of cement content
	PLC	0.1%	0.5%	2.5%	5.0%	10.0%	Percent of cement content
	Container glass or plate glass	0%	0.1%	0.5%	1.0%	1.5%	Percent of cement content
	E-glass	0%	0.1%	0.3%	0.5%	1.0%	Percent of cement content
	SCMs (all strategies)	20%	30%	40%	50%	60%	Percent of cement content
	Optimized design	0.0%	2.5%	5.0%	7.5%	10.0%	Percent reduction of concrete volume
	Improved particle packing	0%	5%	10%	15%	20%	Percent reduction of cement content
	Avoid overdesign	0%	0.5%	1.0%	1.5%	2.0%	Percent reduction of concrete volume
	Concrete reuse	0%	2.5%	5.0%	7.5%	10.0%	Percent of reused content
	Concrete recycling	0%	20%	40%	60%	80%	Percent of RCM in concrete
	CCSU at cement plant	0%	5%	10%	15%	20%	Percent of captured carbon
	Plant energy efficiency improvement	0%	5%	10%	15%	20%	Percent of plant energy reduction
	Renewable energy for plant operation	0%	10%	20%	30%	40%	Percent of plant energy reduction
	Carbon mineralization	0%	1%	2%	3%	4%	Percent of carbon reduction in cement
Steel	Energy efficiency	0%	5%	10%	15%	20%	Percent of energy reduction
	CCSU at steel plant	0%	5%	10%	15%	20%	Percent of captured carbon
	Electrification and biofuels	0%	15%	30%	45%	60%	Percent increase
Material Transport	Shift to biofuels	0%	10%	20%	30%	40%	Percent of average biofuel content
	Hybridization of trucks	0%	5%	10%	15%	20%	Percent of fleet
	Fuel-cell / plug-in hybrid trucks	0%	0%	5%	15%	25%	Percent of fleet
	Electric trucks	0%	5%	10%	15%	20%	Percent of fleet
	Local material purchase	0	2	4	6	8	Reduction in travel distance (miles)
Construction Processes	Shift to biofuels	0%	10%	20%	30%	40%	Percent of average biofuel content
	Hybridization of Equipment	0%	5%	10%	15%	20%	Percent of equipment
	Fuel-cell / plug-in hybrid equipment	0%	0%	5%	10%	15%	Percent of equipment
	Electrified equipment	0%	0%	10%	15%	20%	Percent of equipment
	Optimized equipment usage	0%	5%	10%	15%	20%	Percent reduction in operating hours
	Electric rock crushing plant	0%	20%	40%	60%	80%	Percent energy from electricity

Assumptions

Several assumptions have been made to perform scenario analyses. A major assumption in all analyses is that the models used in this research do not predict or consider material supply chains in the future. Furthermore, the analysis does not consider changes in the electricity grid, traffic levels, number of projects to be contracted in the future, and product availability. Refinement of these assumptions should be based on input from the industry and experts in various disciplines and we would recommend future research on the legitimacy and accuracy of these assumptions. The following lists the other primary assumptions in the order of strategies presented in Table 9:

- RAP and RAS contain 5% and 20% asphalt binder, respectively. All the aged binders from RAP and RAS contribute to the mix design. RAP processing is considered a separate unit process when running LCA.
- WMA consumes 5% less energy in HMA production.
- A 1% increase in natural gas usage decreases HMA production emissions by 0.5%.
- A 100% bio-fueled/electrified plant reduces HMA production emissions by 100%.
- A 1% reduction in aggregate moisture content reduces HMA production energy use by 5%.
- 100% improvement in plant efficiency decreases HMA production emissions by 20%.
- 100% cold mix reduces HMA production emissions by 100%.
- Asphalt Institutes lifecycle emission factors values are used to model SBS and GTR usage.
- 100% bio-binder reduces emissions by 0.227 metric tons per U.S. ton.
- 100% CCUS adoption would reduce asphalt binder emissions by 50%.
- 1% cement substitution reduces emissions by 0.9%.
- Constant relative ratio holds between mix components when the overall concrete volume is decreased. The avoided transportation burden is considered when material weights change.
- 1% reuse decreases concrete volume requirement by 1%.
- 1% carbon captured from cement carbonation decreases total cement emissions by 0.85%.
- 1% efficiency improvement in cement production decreases emissions by 0.33%.
- A 1% increase in renewable energy consumption decreases cement emissions by 0.33%.

- RCM replaces 70% of coarse and 30% of fine aggregates. RCM processing is not considered.
- 1% carbon mineralization decreases cement emissions by 0.6%.
- Carbon uptake from concrete materials is not considered.
- A 1% increase in energy efficiency decreases steel production emissions by 1%.
- 1% application of CCSU in steel plants decreases emissions by 0.6%.
- A 1% increase in electrification or biofuel consumption decreases total steel production emissions by 0.5%.
- 1% biofuel content decreases emissions from equipment/truck operations by 1%
- Hybrid equipment emit 50% less emissions.
- Fuel-cell / plug-in hybrid equipment emit 50% less emissions.
- Electric equipment emit no tailpipe emissions.
- 1% biofuel content decreases GHG emissions by 1%.
- Hybrid equipment emit 50% less emissions.
- Fuel-cell / plug-in hybrid equipment emit 50% less emissions.
- Electric equipment emit no tailpipe emissions.
- Emissions from rock-crushing plant operations constitute 50% of total emissions.

Results

Figure 19 shows the percent of GHG reductions per carbon reduction scenario from the baseline value. The baseline value represents the average upstream Scope 3 emissions from WSDOT construction activities from 2017 to 2021 (a 5-year average). To simplify the interpretation of the effectiveness of each scenario, values are normalized to the baseline GHG value (154 thousand $MTCO_2eq$) and are represented in percentages. Adoption of Scenarios 1 thru 5 results in carbon reductions of 10%, 29%, 50%, 70%, and 91%, respectively. As stated previously, these scenarios can be in effect in the future years; for example, Scenario 1 best depicts the business as usual in the year 2020 and Scenarios 2 thru 5 can represent the years 2030, 2035, 2040, and 2050, respectively.

Our analyses suggest that carbon reduction strategies related to asphalt and concrete materials dominate the more conservative scenarios (short-term strategies as in Scenarios 2 and 3). Shift to cleaner fuels drives the majority of carbon reductions in the construction and transportation categories which are expected to happen in the farther future (Scenarios 4 and 5). Scenario 5, in particular, can be regarded as the pathway to net-zero in 2050. Although full adoption of strategies from Scenario 5 can decrease GHG emissions by 91%, the remaining 9% is from other processes and materials not considered in scenario analyses. For example, the use of recycled plastics and the adoption of waste management practices can reduce GHG emissions from these categories of materials not considered in the scenario analysis (see Figure 8).

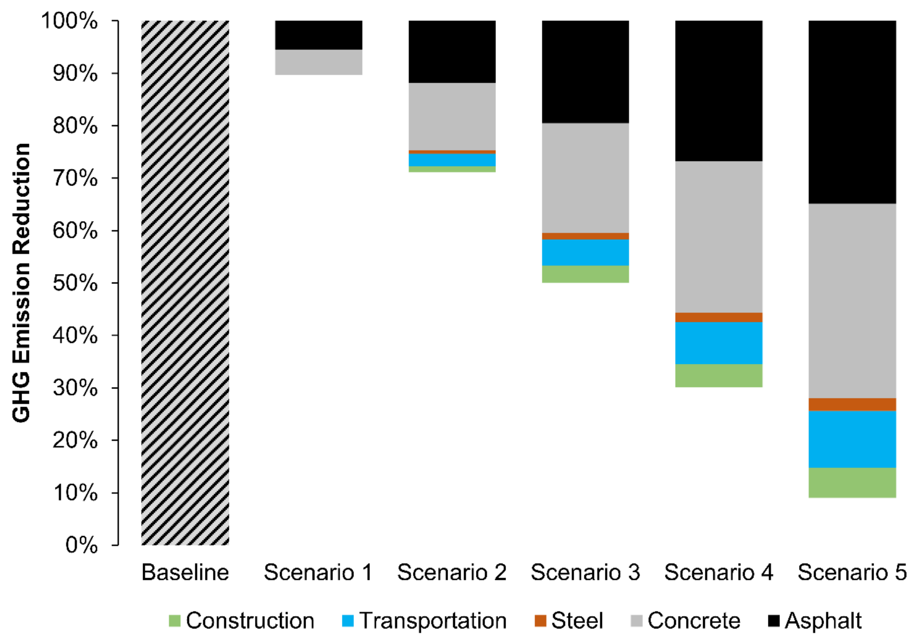

Figure 19. Scenario analysis results showing the percent GHG reduction due to the adoption of carbon reduction strategies under each scenario.

Figure 20 illustrates the GHG emission reduction of each carbon reduction strategy under Scenario 5. This figure can be considered a net-zero decarbonization scenario for WSDOT given the strategies listed in Table 9. Figure 20 shows the relative effectiveness of strategies for each category of asphalt, concrete, steel, transportation, and construction. In summary, the use of RAP/RAS in asphalt mixes, the use of cleaner energy sources to operate asphalt plants, the use of SCMs in concrete mixes, cement content reduction approaches, and the shift to bio-fuels and electrification of construction equipment and transportation fleet are the major contributors to GHG emission reductions. Accordingly, the adoption of decarbonization strategies can be prioritized for WSDOT based on their carbon reduction potentials. However, it is worth mentioning that the challenges in the adoption of each carbon reduction strategy are not considered here.

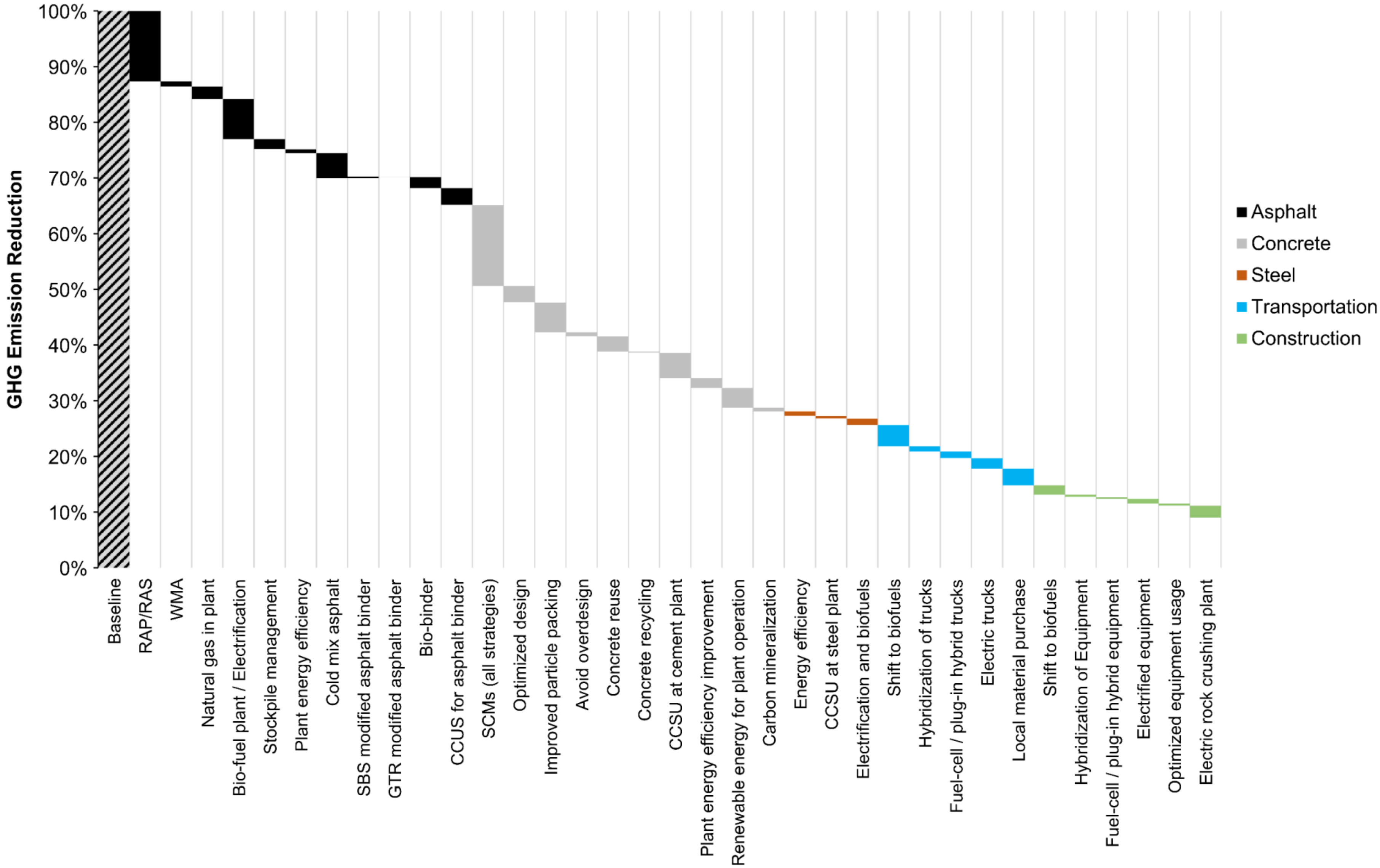

Figure 20. WSDOT decarbonization scenario broken down by carbon reduction strategies under Scenario 5.

Recommendations to WSDOT

This section identifies materials used by WSDOT that have the highest GHG emissions and greatest potential for reductions in GHG and takes a closer look at the quality of data collected in this study, Scope 3 GHG emissions inventory results, carbon reduction strategies, and the suggested decarbonization scenario developed previously to provide recommendations tailored to WSDOT. These recommendations are meant to help WSDOT reduce its upstream Scope 3 GHG emissions. When applicable, the scale of carbon reduction potential associated with actions is considered in the order in which the following recommendations are listed:

- **Establish carbon reduction targets**. Although state-wide carbon reduction targets already exist in Washington State (RCW 70A.45.020), agency-specific targets may be more realistic to achieve. Currently, carbon reduction targets for WSDOT as an agency are not established. The first step in setting carbon reduction targets is to establish baseline values. This research recommends using the five-year upstream Scope 3 GHG emission average between 2017 and 2021 with a value of 310 thousand $MTCO_2$ as a baseline. This report further recommends the following upstream Scope 3 carbon reduction targets: 50% below baseline by 2030, 70% below baseline by 2040, and 90% below baseline by 2050.
- **Data collection**. Upstream Scope 3 GHG emissions accounting relies heavily on the quality and extent of data available. The key data attributes required to better estimate GHG inventories of WSDOT roadway construction and maintenance operations are: material weights, material compositions (e.g., mix designs for asphalt and concrete), fuel usage by trucks and construction equipment, and lifecycle inventory data (e.g., EPDs).
    - *Material weights.* Request material quantity take-offs from construction projects and integrate them into unit bid analysis data. As an alternative, develop a database of typical weights for standard items used in projects (for example, a database indicating the weight of standard manhole types, curbs and gutter types, pavement markings, etc.). As another example, HATS is developed as a program to track maintenance activities and not

necessarily as a material quantity tracking tool. Therefore, the HATS database lacks information regarding material weights used in maintenance and rehabilitation activities (HATS currently only provides an estimated maintained area and a rough estimate of depth). A good starting point is to ask contractors for a report on material quantities at the end of the project for primary materials including asphalt, cement concrete, aggregates (i.e., crushed rocks and earth materials), and steel to be fed into a database. Once enough data is collected throughout the years, software can be developed to track such information.

- *Material composition.* Currently, WSDOT does not have one computer program that tracks material quantities and properties used in a project. Although SAM was developed to implement statistical acceptance of materials and was not intended to be a material tracking tool, its database contains valuable information about asphalt and concrete mix designs and quantities. However, SAM is limited to materials used in pavements and therefore cannot provide a complete picture of the entire project. Expanding SAM to a material tracking database that stores data on the composition of materials other than those used in pavements would be optimal. As an alternative, WSDOT can develop a stand-alone computer program and an associated database of typical material weights and compositions for standard items where project teams would report both material quantities and volumetric properties. Moreover, some constituent materials are not currently being tracked by WSDOT simply because the existing specifications do not ask for them. Good examples are RAP/RAS contents when they are used for less than 20% in an asphalt mix design or SCM contents used in concrete mixes.
- *Fuel consumption tracking.* This seems to be an ongoing process at WSDOT with the use of the Unifier tool to track the operating hours of construction equipment. However, partial exploration of this dataset indicated several shortcomings including a lack of direct measurements for fuel consumption data, lack of fuel consumed by trucks and vehicles used to transport materials to/from job sites, no information regarding

transportation distance for trucks, the use of non-standard equipment names (a unique piece of equipment is not always indicated with the same data string), and lack of engine size information. We recommend developing models to estimate fuel usage given the data already collected in Unifier and modified with the suggested additional data attributes mentioned above.

- *Lifecycle emission factor data.* Product-specific EPDs are currently believed to be the best source of lifecycle emission data. Once material quantities (and in some cases material compositions) are tracked, using EPDs can provide a quick and rather precise account of cradle-to-gate GHG emissions. This report will later provide recommendations on the development and implementation of a Buy Clean act for Washington which essentially helps acquire and collect EPD data.
- *Design-build projects*. Most existing WSDOT databases (most importantly the pay item lists) do not include design-build project data due to their specific delivery method. Design-build projects significantly contribute to both budget and GHG emissions for WSDOT. We recommend integrating data from design-build projects into the existing databases so that better estimates of GHG emissions can be offered without the use of mathematical models that can only predict those emissions.

- **Early engagement**. Implementation of sustainable best practices that reduce GHG emissions is most successful when considered early during the project timeline. Early engagement in sustainability enables project teams in selecting and applying the best practical solutions to design as it offers the most potential for carbon reduction benefits. Particularly in more traditional bidding methods such as design-bid-build and low-bid contracts, contractors are mostly bounded by standard specifications which limit their implementation of carbon reduction strategies. Alternative project delivery methods that help streamline project design and construction can increase the potential of integrating sustainable best practices into project scopes. We also recommend continued partnerships with the industry and trade organizations to better understand the state of the practice in sustainability specific to a product. And finally, training programs targeted at carbon reduction strategies and approaches would help increase awareness of and participation in decarbonization pathways efforts by contractors. For example, a hot topic which demands close partnership with contractors and industry organizations is environmental product declarations (EPDs) and their implementation in Buy Clean programs that are expected to be passed into law soon.

- **Allow and encourage higher RAP contents in asphalt**. When locally available, the use of RAP in HMA shows significant carbon reduction advantages. Due to the concerns about the negative impact of RAP on pavement durability, higher than 20% RAP contents can be used for base layers (including aggregate sublayers) without compromising the pavement's surface durability. Previous research suggests that RAP inventory in Washington State is increasing and there seems to be an oversupply of RAP due to the transition of maintenance and rehabilitation operations to mill-and-fill alternatives (Ashtiani et al., 2019). It must be mentioned that when RAP is hauled for more than 50 miles, the environmental benefits its use may be offset by increased trucking fuel consumption (Ashtiani & Muench, 2020). Through an incentive program, contractors with prior experience with high RAP contents (more than 20% and up to 50%) may show increasing interest in modifying their plant operations for continuous production of high RAP mixes. We recommend the agency consider ways to modify specifications to allow the increased use of RAP and other recycled materials with aid of economic incentives such as grants, rebates, and project-level incentives while maintaining life cycle of pavements. We also recommend considerations be given to allowing higher RAP contents for base and subbase layers which are less prone to top-down cracking, the most typical type of failure in asphalt mixes made with high RAP contents.
- **Allow and encourage higher SCM contents in concrete**. Similar to RAP for asphalt, supplementary cementitious materials show the most significant carbon reduction potential for concrete. Fly ash and ground granulated blast furnace slag are the most commonly used SCMs and they are allowed to be used in concrete mixes by 35 and 50 percent, respectively. Current standard specifications may

be continuously modified to increase maximum allowable contents for some applications that do not endanger the integrity of concrete structures. Such specification modifications can become more effective as performance-based mix design procedures replace the traditional volumetric-based design and/or simple material testing approaches. Once construction considerations such as changes in curing times and workability are taken into account, higher SCMs contents can successfully deliver similar structural functions. However, it must be mentioned from a supply-chain perspective that since fly ash is becoming less available due to the closure of coal plants and there are limited quantities of ground granulated blast furnace slag produced as a byproduct of steel production in Washington State. The use and availability of other SCMs need to be studied which necessitates research funds from WSDOT.

- **Cold mix asphalt and in-place recycling**. HMA production (fuel used to heat up aggregates and asphalt binder) is responsible for 30 to 40 percent of GHG emissions from asphalt pavements. The use of emulsified asphalt eliminates the need for higher temperatures and can offer significant GHG reductions. Usually through cold-in-place recycling, the main drawbacks of cold mix asphalt include longer equipment operation time and thus longer road closure times, the time-consuming curing process of emulsified asphalt, and concerns with the durability of pavements made using this method. WSDOT is currently considering in-place recycling as a design option on a case-by-case basis, primarily targeting low-volume roads. Further research is needed to quantify GHG emission savings and whether that might be offset by additional fuel use by equipment and workzone traffic.
- **Encourage the use of stockpile covers**. Drying aggregates and RAP for HMA production requires a significant amount of energy. Covering stockpiles seems not to be a common practice among asphalt plants since it incurs noticeable capital costs. However, the advantages of lower energy consumption can offset the costs associated with building structures, purchasing plastic covers, or other alternatives that lower the moisture content of raw asphalt ingredients. This is particularly important for locations with high annual rainfall like western Washington.

- **Cleaner fleet**. Transportation vehicles and construction equipment together contribute to about 15% of total Scope 3 GHG emissions found from this research. Similar to how the Washington State Ferries began transitioning to cleaner fuels for ferry vessels, similar initiatives can become effective for other WSDOT bodies that own and operate equipment (e.g., WSDOT's maintenance fleet). Moving forward, WSDOT may consider incentivizing and requiring contractors to consume a minimum bio-fuel content and later shift to hybrid and fully electric vehicles and track these efforts using EPDs.
- **Plant energy and fuel transition**. Energy in both asphalt and cement plants is primarily sourced from fossil fuels like coal and natural gas. EPA's EnergyStar program and certification can become a requirement in the coming years to track and advocate for cleaner energy sources to be used to fire up plants. The pathway should start from a full transition to natural gas and continue to cleaner sources such as renewable natural gas (RNG), hydrogen, biofuels, and full electrification. Although WSDOT may not be the biggest buyer of construction materials, it can spur the transition to cleaner production by taking actions such as 1) the development of incentive programs for the asphalt and cement industries, 2) involvement with trade associations to understand the current state of using fossil fuels and identifying which plants can be good candidates for fuel transition, 3) discussion with plant operators and fuel providers to understand the opportunities and barriers around fuel transition and eventually developing a pilot program, and 4) modifying the bidding process to consider the possible increase in production costs due to the use of cleaner fuels.
- **Use local materials**. Encouraging the use of local material supplies not only can stimulate local economic growth but also reduces fuel consumption by trucks. Incentives can be in place to reward projects that use locally sourced materials based on minimum limits. These limits can be based on the weighted average of transportation distance for materials used in a project according to either weight or price of materials.
- **Mandate minimum recycled/alternative material contents**. Currently, there are no minimum requirements for recycled and alternative material contents in specifications related to asphalt and concrete. Once minimum requirements are

in place, the average recycled or alternative material contents would increase as a consequence. There are three issues with such decisions; first, the liability will be transferred to WSDOT in case of any sort of failure, second, smaller businesses may be adversely affected by such mandates, and third, in cases where recycled or alternative materials are not locally available, longer haul distances might offset the environmental benefits. Good quality control practices and providing exemptions based on the size of businesses or projects (e.g., bid price of a project greater than $10 million) or the volume of materials placed in a project (e.g., projects that use more than 10,000 tons of asphalt or concrete) can help alleviate some of the challenges.

- **Training**. Many of the recommended practices to reduce GHG emissions require increased awareness for involved parties to better understand, accept, and prepare for the upcoming changes to specifications and policies. Through partnerships with academics and industry representatives, training programs can be developed to educate DOT staff, industry organizations, and other stakeholders on basic terminologies, GHG accounting methods, sustainable best practices, and the impact of new policies. This can be considered a crucial first step to help contractors understand the movement towards lower carbon roads.
- **Lifecycle considerations**. This research did not delve into the operation of roadways. However, the GHG emissions associated with the use phase of a roadway can be as significant as its initial construction. Some high-level recommendations regarding the use phase impact of pavements include continued smoothness and density incentives, optimization for pavement durability using PMS data and pavement condition tracking, potential inclusion of a 5-year or longer warranty into the contract for the constructed portion of pavements (with specific terms defined by WSDOT), and consideration regarding pavement damages from studded tires. Research similar to this present study is needed to quantify GHG emissions due to pavement-tire interaction during the use phase of pavements (i.e., emissions from roadway use phase were not considered in this research).
- **Rating systems**. Our research has merely focused on the environmental impacts of material production processes while limiting the impacts to global warming

potential measured in units of CO_2 equivalent. However, several other design, procurement, and construction decisions throughout the project timeline can hardly be evaluated using LCA methods. Due to the complexity of performing LCA and the lack of appropriate metrics and data to measure all aspects of sustainability, the use of rating systems that use common unitless metrics to assess sustainability achievement is recommended. Similar to how the Leadership in Energy and Environmental Design (LEED) has transformed the understanding and achievement of sustainability in the building sector, similar rating systems for roadway infrastructure such as Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), Greenroads, and Envision have been developed (Mattinzioli et al., 2020). Similar to LEED, future roadway projects may be required to obtain certain certification levels from any of the existing rating systems which would eventually help educate, promote, and implement sustainable thinking and design into the state of practice. Furthermore, rating systems provide valuable data collection and management mechanisms that can guide state DOTs to reform their data collection schemes.

- **EPD program development**. Several jurisdictions in the U.S. have started requiring the submission of EPDs with material delivery – also known as Buy Clean policies (e.g., City of Portland, OR, Caltrans thru Buy Clean California, Colorado DOT, Port Authority of New York and New Jersey, etc.) Once sufficient EPD data are collected and analyzed, regionally-specific thresholds and baselines can be established that limit the amount of GHG emissions per product. Similar efforts are undergoing research for Washington State thru the Buy Clean and Buy Fair Washington project partnered with the Washington State Department of Commerce. We recommend piloting a Buy Clean policy for WSDOT in the near future and after conducting more in-depth research on how other states have done this (for example, the FHWA Climate Challenge is an ongoing research project on this topic). Nevertheless, the two major goals of a Buy Clean policy include program development and program implementation:
    - *EPD program development*. We recommend the following steps: 1) require and track EPDs on select projects, 2) research past projects that used the EC3 tool to save EPD data and develop knowledge on the status

quo, 3) identify material reporting categories and establish an appropriate timeline for EPD reporting from producers and contractors, 4) provide financial incentives, technical support, and other accommodations for family businesses, 5) modify existing data tracking systems or develop new ones that comply with EPD data at the bid-item level (similar to the modified pay item list dataset developed in this study), and 6) learn from agencies that have already developed EPD programs, specifically about their EPD tracking system for asphalt and concrete materials.

    - *EPD program implementation*. We recommend the following steps: 1) run pilot projects that use low-carbon materials – this can happen concurrently with program development, 2) analyze EPDs to investigate the most impactful practices that help mitigate GHG emissions (e.g., recycled content, stockpile management, alternative cement materials, renewable energy, etc.), 3) start requiring EPDs for projects as part of the standard specification – this can start with requiring EPDs for big projects (requiring based on material quantities used; for example, projects with more than 10,000 tons of asphalt or 5,000 cubic yards of concrete) and become more inclusive as the agency and the industry become more experienced with EPDs, 4) establish region, material, and/or project-specific GHG emission limits, and 5) gradually lower the GHG emission limits over time by continually analyzing EPD data based on current practices and available technologies.
- **Performance-based specification**. The introduction and use of emerging materials call for the development of additional testing protocols to meaningfully compare their performance to more traditional alternatives. Moreover, the use of higher recycled contents and alternative materials in asphalt and concrete design is believed to influence their long-term performance characteristics. Most current specifications either only rely on volumetric measures or limited performance tests to verify products. We anticipate that future specifications create more room for performance-based validation of products that are less commonly in use today. The concept of the balanced mix design for asphalt pavements is among the highly researched areas that recommend the use of combined volumetric and

performance parameters for alternative selection. WSDOT already implements some form of balanced mix design concept by considering HWTT and IDT test results. However, we recommend WSDOT conduct more research into the potential of introducing new testing protocols or modifications to existing protocols for asphalt and concrete materials while learning from other national and state level efforts on this topic. For example, the addition of other performance criteria for asphalt mixtures using disc shaped compact tension (DCT) and semi-circular bend (SCB) test results at low and intermediate temperatures, respectively, may be considered.

- **Emissions-based bid incentives**. Consider establishing emissions reduction incentives in the form of bid discounts to drive competition on carbon, in addition to cost, during the bid process. This would entail setting an artificial price discount to bids with materials below a specific emissions threshold, or through giving a bid discount (such as 5%) to the lowest emission bid. Only materials that meet the required specifications would be evaluated in the bid and given the chosen bid discount. To effectively implement this practice, we recommend WSDOT to engage with other stakeholders and the industry to evaluate opportunities and challenges from all parties.
- **Support research on agency decarbonization**. Potential research topics include the use of CCS technologies, long-term regional availability of SCMs, the impact of emerging SCMs on cement concrete performance, and pavement use-phase emissions, among others.

Recommendations for Future Study

Finally, we would like to acknowledge the limitations of this study and highlight future potential research topics that would address the limitations and also help WSDOT better account for its GHG emissions inventory and eventually meet its carbon reduction targets:

- Our LCA relies on several assumptions due to the lack of quality reference flow (e.g., material weights, missing data for lump sum items, lack of granular data for design-build projects) and lifecycle emission factor data which suggests that further research in these two areas is warranted.

- Provide funding for research on the Buy Clean program development and its implementation. This is a crucial step in tracking progress towards decarbonization.
- Replace lifecycle emission factors with product-specific EPDs. This would require an extensive collection of EPDs from major manufacturers within the State. This effort can well align with the development of Buy Clean programs.
- Develop systems to streamline annual upstream Scope 3 accounting methods and collect project-specific data. To this end, pilot studies would help identify challenges in collecting project data and further determine additional data needs.
- Apply environmental input-output (EIO)-LCA to upstream Scope 3 carbon accounting methodology and propose hybrid methods to integrate project-specific data into a more comprehensive spend-based accounting method. The power of such method would be in integration into the procurement and bidding process of projects in traditional delivery methods (i.e., design-bid-build).
- Conduct comprehensive surveys and interviews with contractors and manufacturers to find out barriers to implementing carbon reduction strategies listed in this report and elsewhere. This is a crucial step in understanding the market reaction to future policy developments around decarbonization.
- Consider funding research projects for testing or piloting new low carbon materials or mix designs that the agency is less comfortable with.
- Develop decarbonization roadmaps for WSDOT as an agency. Our proposed decarbonization scenarios require several modifications in terms of the assumptions made to perform analysis. Several of the assumptions made in our report rely on speculations and the availability of information within the literature. These assumptions need to be refined after careful consultation and partnership with experts and industry representatives.

CONCLUSIONS

This report outlined the progress made in an effort to estimate the greenhouse gas emissions associated with the production and placement of materials used to build and preserve the Washington roadway network owned and operated by WSDOT. The project team at the Carbon Leadership Forum endeavored on collecting information and obtaining insights from WSDOT staff in the form of formal and informal interviews, group meetings, and email communications to better understand the structure of WSDOT programs and divisions and the entities in charge of maintaining its broad array of databases.

The project team managed to collect the majority of its data needs and understand the breadth and depth of data available from WSDOT. Data needs were prioritized according to the scope of the project and requests were sent out to specific points of contact recommended by the WSDOT research team. Data mostly in the form of spreadsheets were obtained and stored within the CLF's private repository for further analysis. The main WSDOT data sources used in this project include the unit bid analysis data from projects constructed between 2017 and 2021, Statistical Analysis of Materials (SAM), Record of Materials (ROM), Pavement Management System (PMS), and WSDOT's FTP to extract project's design documents and specifications.

We built a so-called modified pay item list dataset that combined all the useful information collected in this project to primarily run lifecycle assessment (LCA). Our analysis mainly included a financial accounting of roadway construction and maintenance expenditures, a pay-item-based LCA of construction materials, mathematical simulations to estimate upstream Scope 3 emissions from roadway construction projects within WSDOT jurisdiction, running uncertainty analysis on input data, and performing scenario analysis to develop decarbonization roadmaps for WSDOT.

Following the goal and scope of this project, the environmental impacts considered in our analysis are limited to global warming potential (i.e., embodied carbon or carbon footprint) measured in units of carbon dioxide equivalent or greenhouse gas emissions. In this project, we limit the scope further to consider emissions from cradle to construction (starting with raw material extraction stages to the installation of items on a roadway). Using a formulated LCA framework built on the modified pay item list dataset, publicly available lifecycle emission factor data, and Monte Carlo simulations, we formulated rough estimates of the overall upstream Scope 3 greenhouse gas emissions.

The five-year average (from 2017 to 2021) upstream Scope 3 emissions for WSDOT construction was estimated at about 310 thousand metric tons. Emissions associated with materials production dominate the source of GHG emissions by an average of 85% and are followed by materials transportation at 11% and construction activities at 4%. Within different material types, asphalt and concrete are the main contributors to upstream Scope 3 emissions with at least 40% of total emissions. Moreover, pavement construction is found to be the most carbon-intensive category in roadway construction.

Furthermore, Scope 1 and 2 greenhouse gas emissions reported to the Department of Ecology were compared with those from upstream Scope 3 emissions estimated here. Based on this comparison, we conclude that Scope 3 emissions for WSDOT as an agency outweigh Scope 1 and 2 emissions. Given that WSDOT owns the largest ferry system in the country, our findings regarding the outsized Scope 3 emissions compared with Scope 1 and 2 emissions can be more pronounced for other states than Washington. This finding highlights the importance of developing programs that help account for upstream Scope 3 emissions from building roadway networks and eventually mitigate those emissions.

Upon analyzing data and reviewing existing literature on carbon reduction strategies, we provided a series of recommendations tailored to WSDOT that would help reduce agency-wide GHG emissions. With enough assumptions, five decarbonization scenarios were proposed and quantitatively analyzed using the dataset developed in this study. The most aggressive of these scenarios is framed to suggest a roadmap to near net-zero in the year 2050. Accordingly, this report suggested the following carbon reduction targets for WSDOT based on the upstream Scope 3 GHG emission baseline of 310 thousand metric tons: 50% below baseline by 2030, 70% below baseline by 2040, and 90% below baseline by 2050. A summary of recommended next steps according to the decarbonization scenarios and existing literature was proposed to help WSDOT accelerate the move towards a decarbonized agency.

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APPENDIX A
LIFECYCLE ASSESSMENT (LCA) FRAMEWORK

APPENDIX A. SUPPLEMENTARY LCA MATERIALS

Material Weight Estimation Models

Table 10 below contains a list of mathematical models used to estimate material weights based on some input variables (mainly unit bid price and total bid price of items). The models in this table contain up to three independent variables (indicated with X) and one dependent variable (Y). The majority of these models are created using linear, multilinear, and power regression analyses between the independent and dependent variables. In some cases, however, simple assumptions are made without the use of any mathematical models.

Table 10. Mathematical models developed to estimate material weights and compositions.

Model Name	**Dependent Variable (Y)**	**Independent Variables**			**Model**	**R^2**
		X or X1	**X2**	**X3**		
Curb and Gutter	Total Weight (tons)	Total cost			y = 0.0013x^1.0561	0.9125
Cement in concrete	Cement %	Compressive strength (psi) in 7 days			y = 2E-05x + 0.0784	0.6014
Cement in concrete	Cement %	Compressive strength (psi) in 7 days	air content		y = 1.414e-05X1 - 2.885e-01X2 + 1.062e-01	0.6002
Cement in concrete	Cement %	Compressive strength (psi) in 7 days	air content	slump (in)	y = 9.358e-06X1 - 3.045e-01X2 -2.536e-03X3 + 1.391e-01	0.6369
FA in concrete	Fine aggregate %	Cement %			y = -0.909x + 0.4377	0.9277
Water content in concrete					6.1% average	NA
Catch Basin	Total Weight (tons)	Total Cost			$y = 0.001158179x^{0.977162841}$	0.9862
Concrete Culvert	Total Weight (tons)	Total Cost			$y = 7.15088E\text{-}05x^{1.263818477}$	0.8663
Polyethylene Pipe/Culvert	Total Weight (tons)	Total Cost			$y = 1.11174E\text{-}05x^{1.156238292}$	0.9574
Concrete Driveway	Total Weight (tons)	Total Cost			$y = 0.006538113x^{0.937029688}$	0.8582

Silt Fence (10% polypropylene, 90% steel)	Total Weight (tons)	Total Cost	$y = 0.000167758x^{0.929028299}$	0.8222
Chain Link Fence (7% cement, 35% CA, 25% FA, 30% steel)	Total Weight (tons)	Total Cost	$y = 2.02766E\text{-}05x^{1.160889772}$	0.9147
Geotextile (100% polypropylene)	Total Weight (tons)	Total Cost	$y = 6.68274E\text{-}05x^{1.008302182}$	0.9686
Guardrail (100% steel)	Total Weight (tons)	Total Cost	$y = 3.11538E\text{-}05x^{1.028560508}$	0.9428
Inlet (18% cement, 35% CA, 37% FA, 5.4% iron, 1% steel)	Total Weight (tons)	Total Cost	$y = 0.001708091x^{0.940592002}$	0.9353
Inlet Protection (100% PP)	Total Weight (tons)	Total Cost	$y = 0.00026969x^{0.903235411}$	0.8858
Junction Box (1% reinforcement)	Total Weight (tons)	Total Cost	$y = 0.000566632x^{1.087600704}$	0.9852
Manhole	Total Weight (tons)	Total Cost	$y = 0.001539569x^{0.954490594}$	0.9909
Pavement Marking Plastic (LF)	Total Weight (tons)	Total Cost	y = 9.33755E-05x + 0.00147829	0.9225
Pavement Marking Plastic (EACH)	Total Weight (tons)	Total Cost	y = 6.06816E-05x - 0.000841837	0.8395
Pavement Marking Paint	Total Weight (tons)	Total Cost	y = 0.000425x	NA
Steel Pile	Total Weight (tons)	Total Cost	$y = 0.000185188x^{0.983353679}$	0.8296
Pipe (Concrete)	Total Weight (tons)	Total Cost	$y = 0.000672916x^{1.04009731}$	0.9908
Pipe (HDPE)	Total Weight (tons)	Total Cost	$y = 6.04304E\text{-}05x^{0.989296117}$	0.7883
Pipe (cast iron)	Total Weight (tons)	Total Cost	$y = 0.000136448x^{1.024176587}$	0.9308
Pipe (polyethylene)	Total Weight (tons)	Total Cost	$y = 2.78365E\text{-}05x^{1.075634004}$	0.9878
Pipe (PVC)	Total Weight (tons)	Total Cost	$y = 5.39667E\text{-}05x^{1.005183995}$	0.935

Guide Post (polypropylene)	Total Weight (tons)	Total Cost	$y=0.0000348837x$	NA
Concrete Ramp	Total Weight (tons)	Total Cost	$y = 0.001435141x^{1.017314166}$	0.8906
Drilled shafts (concrete+steel)	Total Weight (tons)	Total Cost	$y = 0.000417154x^{1.147093602}$	0.9069
Sign (aluminum/steel)	Total Weight (tons)	Total Cost	$y = 2.89046E\text{-}05x^{1.032036348}$	0.8165
Soil	Total Weight (tons)	Total Cost	$y = 0.032608036x^{0.990622825}$	0.9184
Valve (steel/iron)	Total Weight (tons)	Total Cost	$y = 0.000110928x^{0.94139657}$	0.8748
Wall	Total Weight (tons)	Total Cost	$y = 7.21835E\text{-}05x^{1.295025958}$	0.7616
Dome (plastic)	Total Weight (tons)	Total Cost	$y = 0.000659421x^{0.670003773}$	0.981
Barrier (concrete)	Total Weight (tons)	Total Cost	$y = 0.001502837x^{1.001074831}$	0.9695
Barrier (plastic/HDPE)	Total Weight (tons)	Total Cost	$y = 0.00007x$	NA
Impact attenuator (permanent)	Total Weight (tons)	Total Cost	$y = 8.66278E\text{-}06x^{1.201825542}$	NA
Casing (steel)	Total Weight (tons)	Total Cost	$y = 8.68106E\text{-}05x^{0.959887341}$	0.9866
Conduit (PVC)	Total Weight (tons)	Total Cost	$y = 4.72926E\text{-}05x^{1.03043175}$	0.9384
Plants (each)	Unit Weight (lb)	Unit Cost	$y = 1.893485794x^{0.854122921}$	0.8536
Bridge Superstructure (average 5% steel)	Total Weight (tons)	Total Cost	$y = 0.00111162x^{0.998449433}$	0.9952

Pay Item List Dataset Structure

The final dataset of this research (i.e., reference flow data) is a modified and reinforced form of the original unit bid analysis dataset. The latest update of the dataset contains 27,419 rows of data representing 609 contracts. Several data attributes (i.e., data columns) are added to the original pay item list data using the data obtained from WSDOT.

The following lists the main features of this dataset:

- Original unit bid analysis data modification. This includes unit conversions, arrangement in an Excel tabular format, and merging pay item lists from all projects into one master list. Each pay item was identified by a designated unique numeric identifier (ID), contract number, item description, and columns denoting the advertisement, award, and completion dates.
- Inclusion in LCA. A binary variable (1 for inclusion and 0 for exclusion) was assigned to each pay item to indicate whether or not it was included in the LCA. Non-material pay items (e.g., mobilization, administrative, etc.), lump sums (i.e., traffic control), or items composed of several complex components (e.g., traffic signals, electrical cabinets, irrigation systems, etc.) were excluded from the LCA.
- Unit and total prices. The main components of the original pay item list dataset as obtained from WSDOT's unit bid analysis database. In this project, only the 'lowest bid' costs were used.
- Unit of measure and quantity. Each pay item was measured in a specific unit. The most common units of measure were lump sum (LS), ton (TN), pound (LB), cubic yard (CY), square foot (SF), square yard (SY), acre (AC), linear foot (LF), and the number of items (EA). The quantity of each pay item according to the unit of measure was also expressed in the bid item list.
- Material weights and unit weights. All pay item material quantities were converted to weights (many materials are expressed in units of volume or area on pay item lists). See the Unit bid analysis section for more information about material weight estimates.
- Material types. Each pay item is assigned to one or more primary material types (Table 11) and a secondary material purpose. Material types used were aggregate, aluminum, asphalt, concrete, copper, steel, high-density polyethylene (HDPE), lime, iron, polyethylene, polypropylene, polyvinyl chloride (PVC), thermoplastic paint, and non-materials. Material purpose defined its application. Some commonly used material purposes were pavements, pipes, signs, poles, curbs, conduits, signals, manholes, catch basins, walls, culverts, foundations, cables, geotextiles, sidewalks, fences, pavers, etc. For cases where a pay item

was only a construction activity, they were assigned to the material type category operation (or the specific type of operation such as excavation or sawing).

- Primary material contents. For each pay item, the composition of primary material types was assigned by the fraction of weight each represents. For example, hot mix asphalt has four typical ingredients of coarse aggregate, fine aggregate, asphalt binder, and RAP. The mix design would be used to assign the fraction, by weight, assigned to each. The weight of each material constituent could be calculated once total weights are multiplied by material contents.
- Transportation distances. This measure is widely assumed.
- Transportation mode. Transportation vehicles were selected based on hauling distance and material weight. Smaller vehicles were picked for short trips and lightweight materials, while larger vehicles were selected for long distances and heavier weights. Table 5 shows a list of all vehicles used to transport materials from suppliers to construction sites. An MMHDV truck was assumed for all pay items in this project and the sensitivity of this assumption will be assessed in the future.
- Construction equipment. Construction equipment were selected from Table 6. In our model, up to four different pieces of construction equipment could selected for a pay item. Unless an engine size (in horsepower) was selected for each piece of equipment, the default engine size was assumed.
- Operating hours. Construction equipment working hours were found based on total material quantities divided by production rates described previously.
- Construction equipment running time. Since construction equipment may not operate continuously (e.g., downtime, operator breakers, etc.) construction equipment working times were expressed as a percentage of total operating hours. In our accounting, fractions higher than 100% implied that more than one piece of equipment was active at a given time (for example, two breakdown rollers operating concurrently during asphalt paving). Numbers lower than 100% denoted equipment with downtime (for example, cranes may have significant downtimes between operations over the course of a construction workday).

- LCI. Greenhouse gas emission and energy conversion factors were stored in separate worksheets and then linked to the reference flow dataset to calculate embodied carbon and energy for materials, transportation vehicles, and construction equipment.
- Combined pay item list dataset. Table 11 lists all data attributes used in the dataset in more detail.

Table 11. Modified pay item list data structure.

Attribute	Description
ID	A numeric unique identifier assigned to each row of data.
Contract Number (Job Number)	A unique 6-character string assigned to each project by WSDOT.
Design Build	A binary variable (YES/NO) to differentiate design-bid-build projects from design-build projects.
Item Description	General description of the pay item as it appears in the as-built bid tabulation of the projects. Minimal modifications were made to this attribute.
Standard Item Number	If a pay item is in conformance with the WSDOT Standard Manual, its associated section in the standard specification was identified.
Include in LCA (1,2,3,4=Yes, 0=No)	Indicates whether a pay item is included in the LCA analysis of this study. Integers 1, 2, and 3 show if the pay item was included and integer 0 indicated exclusion from the LCA.
Planned Quantity	The quantity of pay items per the unit of measure.
Unit of Measure	The unit in which the pay item is measured with the most commonly used acronyms as follows: ACRE: Unit of measuring area (1 acre = 4840 square yard); BARREL: Unit of measuring volume (1 barrel ~5.6 cubic feet); CD: Continuous Days; CY: Cubic Yard; DAY: Number of days; EA: Each item; EST: Estimated; FA: Force Account: is a payment method for construction work where there is no existing agreement on cost; HR: Number of hours; HUND: One hundred of the unit; IN-FT: Inch - foot; LB: Pounds; LF: Linear foot; LS: Lump Sum: a single payment made at a particular time, as opposed to a number of smaller payments or instalments.; MGAL: Million Gallon; SF: Square foot; SY: Square Yard; TN: Short Ton (US ton; don't get confused with metric ton)
Unit Weight (lb)	The unit weight of the pay item in pounds. This attribute was only applicable to pay items with a materialistic nature. Several sources of information were used to find unit weights.
Weight (ton)	The total weight of the pay item in US tons. This attribute was only applicable to pay items with a unit weight.
Comp Strength (psi)	The 28-day compressive strength of pay items that had cement concrete.
Low Bid (i.e., Unit Cost)	The unit cost of pay items per the unit of measure expressed in USD value in the year of construction.
Total Cost Low Bid	The total cost of pay items in USD value in the year of construction.
Material Type1 *thru 5*	Each pay item is described by up to 5 general material categories. Several material categories depending on the type of material (e.g., concrete) and their functionality (e.g., culvert, pipe, pavement, etc) were considered. The list of materials were further grouped into only 6 *primary material* categories for data analysis.
Material Type All	All related material types grouped into one cell to facilitate data browsing.
Distance (mile)	Distance in miles from the supplier location to the project site.
Vehicle Type	The assumed mode of transportation (based on distance and weight and type of materials) to deliver products to project sites.

Production Rate (unit/day)	Indicates the amount of Unit of Measure that a piece of construction equipment can deliver in a given day.
Operation Hours (assume 8-hour days)	Total operating hours for each construction equipment given the Quantity of pay items.
Construction Equipment Type 1 *thru 4*	The construction equipment types used to deliver a pay item. This spreadsheet can include up to 4 general construction equipment listed under the Construction LCI worksheet.
Construction Equipment 1 *thru 4* % work	This attribute accounts for the downtime of each construction equipment type (1 thru 4). 100% working time means no down time. Numbers higher than 100% imply the use of more than one piece of the same equipment.
Construction Equipment 1 *thru 4* HP	The horsepower (HP) of each construction equipment 1 thru 4. Default values were used if none indicated.
Region	This is the WSDOT-designated regions within the state of Washington: Eastern, Marine, North Central, Northwest, Olympic, Olympic NS, South Central, and Southwest.
AD Date	The date that a project was advertised by WSDOT.
Year	The year that the project was advertised. This data attribute was used to aggregate annual results.
Award Date	The date that a project was awarded to a contractor(s).
Award Year	The year that a project was awarded to a contractor(s).
Execution Date	The date that a project kicked off.
Execution Year	The year that a project kicked off.
Completion Date	The date that a project is considered complete.
Completion Year	The year that a project is considered complete.
Aggregate Base (%)	Rocks used as base and subbase layers in a pavement structure.
Lime (%)	Hydrated lime used mostly in base treatment.
Soil (%)	Any imported soil to the project site which is mostly used as subgrade layers.
Wall Backfill (%)	Rocks used to support retaining walls and mechanically stabilized earth (MSE).
RipRap (%)	Pieces of rock used mostly for landscaping purposes.
Bedding (%)	Rocks used as pipe beddings for both sanitary and sewer.
Rocks (%)	Rocks in general used for aesthetics purposes or river beddings.
Cement (%)	Portland cement used mostly in concrete manufacturing.
CA PCC (%)	Coarse aggregate (larger than 3/8" in nominal maximum aggregate size - typically rounded aggregates for concrete) used in Portland cement concrete.
FA PCC (%)	Fine aggregate (smaller than 3/8" in nominal maximum aggregate size - typically rounded aggregates for concrete) used in Portland cement concrete.
Fly Ash (%)	Fly ash (a byproduct of coal plants) used as a supplementary cementitious material in Portland cement concrete manufacturing.
RCA (%)	Recycled concrete aggregates which are crushed out-of-service Portland cement concrete pieces used to manufacture concrete.
Bitumen (%)	Bitumen (or asphalt binder) used in hot or cold mix asphalt production.
Bitumen + SBS (%)	Bitumen (or asphalt binder) modified with Styrene-Butadiene-Styrene (SBS) used in hot or cold mix asphalt production.
Bitumen + GTR (%)	Bitumen (or asphalt binder) modified with ground tire rubber (GTR) used in hot or cold mix asphalt production.
CA HMA (%)	Coarse aggregate (larger than 3/8" in nominal maximum aggregate size - typically angular aggregates for asphalt) used in asphalt mixtures.
FA HMA (%)	Fine aggregate (smaller than 3/8" in nominal maximum aggregate size - typically angular aggregates for asphalt) used in asphalt mixtures.
RAP/RAS (%)	Reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS) used in asphalt pavement recycling.
HMA (%)	Hot mix asphalt.
WMA (%)	Warm mix asphalt, which is a technology used to decrease mixing temperature of

	hot mix asphalt and is also used as a compaction aid.	
PVC (%)	Polyvinyl chloride (PVC).	
Iron (%)	Iron.	
Hot Steel (%)	Hot-rolled steel.	
Cold Steel (%)	Cold-rolled steel.	
Galvanized Steel (%)	Galvanized steel.	
Recycled Steel (%)	Steel with recycled contents.	
Stainless Steel (%)	Stainless steel.	
Copper (%)	Copper.	
Aluminium (%)	Aluminium.	
Recycled Aluminium (%)	Aluminium with recycled contents.	
Wood (%)	Engineering wood products.	
HDPE (%)	High-Density Polyethylene (HDPE).	
Thermoplastic Paint (%)	Thermoplastic paint used as pavement markings.	
Water Paint (%)	Water-based paint used as pavement markings.	
Polypropylene (%)	Polypropylene.	
Average Plastic (%)	Any average plastic product with no accurate description of its type. The term "average plastic" was adopted from GREET.	
Polyethylene (%)	Polyethylene.	
Aggregate Base (tons), Lime (tons), Soil (tons), Wall Backfill (tons), RipRap (tons), Bedding (tons), Rocks (tons), Cement (tons), CA PCC (tons), FA PCC (tons), Fly Ash (tons), RCA (tons), Bitumen (tons), Bitumen + SBS (tons), Bitumen + GTR (tons), CA HMA (tons), FA HMA (tons), RAP/RAS (tons), HMA (tons), WMA (tons), PVC (tons), Iron (tons), Hot Steel (tons), Cold Steel (tons), Galvanized Steel (tons), Recycled Steel (tons), Stainless Steel (tons), Copper (tons), Aluminum (tons), Recycled Aluminum (tons), Wood (tons), HDPE (tons), Thermoplastic Paint (tons), Water Paint (tons), Polypropylene (tons), Average Plastic (tons), Polyethylene (tons)		These attributes are calculated based on the percent of each material constituent used in each pay item multiplied by the Total Weight.
CO_2eq Aggregate Base (metric ton), CO_2eq Lime (metric ton), CO_2eq Soil (metric ton), CO_2eq Wall Backfill (metric ton), CO_2eq RipRap (metric ton), CO_2eq Bedding (metric ton), CO_2eq Rocks (metric ton), CO_2eq Cement (metric ton), CO_2eq CA PCC (metric ton), CO2eq FA PCC (metric ton), CO_2eq Fly Ash (metric ton), CO_2eq RCA (metric ton), CO_2eq Bitumen (metric ton), CO_2eq Bitumen + SBS (metric ton), CO_2eq Bitumen + GTR (metric ton), CO_2eq CA HMA (metric ton), CO_2eq FA HMA (metric ton), CO_2eq RAP/RAS (metric ton), CO_2eq HMA (metric ton), CO_2eq WMA (metric ton), CO_2eq PVC (metric ton), CO_2eq Iron (metric ton), CO_2eq Hot Steel (metric ton), CO_2eq Cold Steel (metric ton), CO_2eq Galvanized Steel (metric ton), CO_2eq Recycled Steel (metric ton), CO_2eq Stainless Steel (metric ton), CO_2eq Copper (metric ton), CO_2eq Aluminum (metric ton), CO_2eq Recycled Aluminum (metric ton), CO_2eq Wood (metric ton), CO_2eq HDPE (metric ton), CO_2eq Thermoplastic Paint (metric ton), CO_2eq Water Paint (metric ton), CO_2eq Polypropylene (metric ton), CO_2eq Average Plastic (metric ton), CO_2eq Polyethylene (metric ton)		Total CO_2eq emissions related to each of the generic materials. This is calculated by the multiplication of emission factors by the Total Weight of pay items.
Energy Aggregate Base (GJ), Energy Lime (GJ), Energy Soil (GJ), Energy Wall Backfill (GJ), Energy RipRap (GJ), Energy Bedding (GJ), Energy Rocks (GJ), Energy Cement (GJ), Energy CA PCC (GJ), Energy FA PCC (GJ), Energy Fly Ash (GJ), Energy RCA (GJ), Energy Bitumen (GJ), Energy Bitumen + SBS (GJ), Energy Bitumen + GTR (GJ), Energy CA HMA (GJ), Energy FA HMA (GJ), Energy RAP/RAS (GJ), Energy HMA (GJ), Energy WMA (GJ), Energy PVC (GJ), Energy Iron (GJ), Energy Hot Steel (GJ), Energy Cold Steel (GJ), Energy Galvanized Steel (GJ), Energy Recycled Steel (GJ), Energy Stainless Steel (GJ), Energy Copper (GJ), Energy Aluminum (GJ), Energy Recycled Aluminum (GJ), Energy Wood (GJ), Energy HDPE (GJ), Energy Thermoplastic Paint (GJ), Energy		Total energy consumption related to each of the generic materials. This is calculated by multiplication of energy consumption factors by the Total Weight of pay items.

Water Paint (GJ), Energy Polypropylene (GJ), Energy Average Plastic (GJ), Energy Polyethylene (GJ)	
Total CO_2eq Materials Production (metric tons)	Total CO_2eq emissions (in metric tons) related to the transportation of materials included in each pay item.
Total Energy Material Production (GJ)	Total energy consumption (in GJ) related to the transportation of materials included in each pay item.
CO_2eq Transportation (metric tons)	Total CO_2eq emissions (in metric tons) related to the transportation of materials included in each pay item.
Energy Transportation (GJ)	Total energy consumption related to the transportation of materials included in each pay item.
CO_2eq Construction (metric tons)	Total CO_2eq emissions (in metric tons) related to the construction equipment operation to deliver the pay items.
Energy Construction (GJ)	Total energy consumption (in GJ) related to the construction equipment operation to deliver the pay items.
TOTAL CO_2eq (Metric Tons)	Total CO_2eq emissions (in metric tons) of the pay item.
TOTAL ENERGY (GJ)	Total energy consumption (in GJ) of the pay item.