NAPA
NATIONAL ASPHALT PAVEMENT ASSOCIATION

EPD BENCHMARK FOR NATIONAL ASPHALT PAVEMENT ASSOCIATION

Version 2.0: Including Round 2 of Data Collection

Authors: Lianna Miller, Benjamin Ciavola, Amlan Mukherjee

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TABLE OF CONTENTS

1. ABBREVIATED TERMS

AASHTO American Association of Highway and Transportation Officials

EPA Environmental Protection Agency

EPD Environmental Product Declaration

FHWA Federal Highway Administration

GSA General Services Administration

GWP Global Warming Potential

IRA Inflation Reduction Act

ISO International Organization for Standardization

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LCIA Life Cycle Impact Assessment

NAPA National Asphalt Pavement Association

NETL National Energy Technology Laboratory

NSSGA National Stone, Sand & Gravel Association

PCR Product Category Rules

SBS Styrene-Butadiene-Styrene

TRACI Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

2. SUMMARY

The objective of this study is to evaluate the factors that influence the Global Warming Potential (GWP) of asphalt mixture production and to propose a phase-by-phase method for regionalized benchmarking. This approach is designed to ensure contractors in all regions of the United States are incentivized to transition to low carbon construction materials in accordance with the goals of the Inflation Reduction Act (IRA) (2022).

The proposed method uses a statistical assessment of GWP as reported in Environmental Product Declarations (EPDs) for each life cycle phase. Benchmarking by life cycle phase allows for the selection of lower carbon materials while ensuring equitable access to IRA funds despite factors outside a contractor's control, such as agency-specific material specifications, geology, and regional climate. This is a departure from the current practice of using total GWP reported in EPDs to create blanket national thresholds, which can unfairly burden some regions of the country while advantaging others.

This report develops a method that allows agencies to establish asphalt mixture GWP thresholds that account for regional variations and agency specifications by treating the life cycle phases (A1 – Upstream raw material extraction and manufacturing, A2 – Raw material transportation to production facility, and A3 – Manufacturing) as independent components that, when combined, provide the relevant 20th percentile, 40th percentile, and average GWP values for similar products (i.e. specifications). The combined thresholds can provide a single embodied carbon number representing to the region and material specification.

This revision includes an analysis of the expanded data set collected during Q4 of 2023 and Q1 of 2024.

This report recommends the following:

- **Use Impact Factors for A1 Impacts:** A1 impacts are currently deterministic and entirely dependent on mix design. Agencies can use GWP impact factors for each mix ingredient type (e.g. RAP, virgin aggregate, or binder) to set 'starting point of calculation' A1 GWP values based on local mix specifications. The role of material choice in driving GWP is communicated with this method, and A2 and A3 impacts can then be combined with A1 to form a complete set of localized GWP thresholds.
- **Use Regional Trends for A2 Benchmarks:** The use of region-specific distribution-driven thresholds is recommended for the A2 life cycle phase. Impacts due to the transportation of materials are dictated by availability of local materials, which in turn is a function of local geology. For example, states like Louisiana and Florida have significantly higher A2 impacts than any other regions.
- **Use Regional Trends for A3 Benchmarks:** While A3 impacts are somewhat within the control of material producers, the recommendation is to develop distribution-driven thresholds that account for regional differences, such as AASHTO (American Association of State Highway and Transportation Officials) climate regions. With sufficient data, regions could be more granular than the full AASHTO climatic region or be based on other factors outside the control of the material producer.
- **Use the Sum of A1, A2, and A3 Benchmarks for Compliance with Low Carbon or Buy Clean Asphalt Programs:** By combining the local benchmark value for each of A1 (deterministic), A2 (distribution), and A3 (distribution), an agency can identify a set of fair and reasonably representative GWP thresholds that incentivize improvements in environmental performance by local contractors.
- **Improve Sampling:** The analysis recommends the continued development of more representative data sets when establishing thresholds for procurement, driven by an intentional sampling process that targets states and regions with limited participation.

This report presents the development, justification, and implementation of this framework.

3. GENERAL INFORMATION

This study was commissioned by the National Asphalt Pavement Association (NAPA). This study uses data derived from NAPA's Emerald Eco-Label EPD program, and a sample of facility and mixture specific EPD data collected independently for this study to develop a benchmark for asphalt mixture EPDs. There were 161 participating organizations representing 526 production facilities. A full list of study participants may be requested from NAPA. The study is aligned to meet the reporting requirements of ISO 21930 and ISO 21678, as well as the FHWA Expectations for Industry Averages for IRA 60506. However, as this is a benchmark study and not a Product Category Rule or an Environmental Product Declaration, complete conformance with ISO 21930 is not guaranteed.

Third Party Review Statement

This study was subjected to third-party review by Sevda Rosenbaun of John Beath Environmental, LLC. The project report and underlying data were made available to the reviewer with the requirements on confidentiality stated in ISO 14025. It was reviewed to the "FHWA Expectations for Industry Averages for IRA 60506." The review was also conducted with reference to ISO 21678, though conformance to the standard was not reviewed. Additionally, this study was third-party reviewed by a panel of experts convened by FHWA, comprised of Joep Meijer of The Right Environment; Tomas Van Dam of Wiss, Janney and Elstner Associates, Inc.; John Harvey of the UC Davis Department of Civil and Environmental Engineering; and Kristoph Koffler of Sphera.

4. GOAL AND SCOPE OF THE STUDY

This study is an evaluation of Asphalt Mixtures (UNSPSC 30111509) and guided by NAPA's Product Category Rules for Asphalt Mixtures v2.0, published in April 2022 and valid through March 2027[1]. Asphalt mixtures are typically comprised of virgin or recycled construction aggregates (>90% by mass), virgin or recycled asphalt binders (typically 4% - 8% by mass), dry additives (<2% by mass), and wet additives (<1% by mass). Asphalt mixtures are typically incorporated as part of the structure of a roadway, parking lot, driveway, airfield, bike lane, pedestrian path, railroad track-bed, or recreational surface. Additional information about the environmental impacts of asphalt mixtures can be found as part of NAPA's recycling report[2] and Greenhouse Gas Inventory[3].

This study was undertaken to establish a global warming potential (GWP) benchmarking methodology for asphalt mixtures that accounts for the sensitivity of GWP to factors outside a contractor's influence (such as climate, geology, and mixture specification requirements) and provide initial estimates of industry average GWPs for use in implementing Sections 60503 and 60506 of the IRA. The intended audience for this study is local, state, and federal agencies that have set or are considering setting performance thresholds for asphalt mixture procurement, as well as asphalt industry professionals seeking to understand the methodological approach and benchmark their own products against relevant industry averages. FHWA and other federal agencies can use the report and calculations to be referenced by recipients of the Low Carbon Transportation Materials Program to identify substantially low carbon materials.

Sections 60503 and 60506 of the IRA provide funding to the General Services Administration (GSA) to reimburse and Federal Highway Administration (FHWA) to pay for the differential cost or incentives for agencies to purchase construction materials with substantially lower embodied than estimated industry averages as reported in EPDs. The material categories identified in the IRA and EPA Interim Determination include asphalt, concrete, flat glass, and steel. The EPA issued an interim determination in December 2022 establishing a cascading set of thresholds to define what it means to be "substantially lower" than industry averages. Under this rubric, the first threshold is materials that are the best performing 20% for GWP values. If not available locally, the next threshold is the best performing 40%. The EPA's determination goes on to state, "If materials/products in the Top 40 percent are not available in a project's location, then a material/product qualifies for funding… if its GWP is better than the estimated industry average."

This study assesses the extent to which factors that producers cannot control influence the GWP of asphalt mixtures. A phase-by-phase regionalized benchmarking approach is proposed to support the implementation of the programs set forth in the IRA in a way that does not disadvantage contractors based on factors that are outside their control. This study follows the ISO 21678 standard,

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[1] "PCR for Asphalt Mixtures." https://www.asphaltpavement.org/uploads/documents/EPD_Program/NAPA_PCR_AsphaltMixtures_v2.pdf
[2] National Asphalt Pavement Association, "Sustainability Resources: Recycling." https://www.asphaltpavement.org/expertise/sustainability/sustainability-resources/recycling
[3] Joseph Shacat, Richard Willis, Ph.D., and Benjamin Ciavola, Ph.D., "GHG Emissions Inventory for Asphalt Mix Production in the United States." https://www.asphaltpavement.org/uploads/documents/Sustainability/SIP-106_GHG_Emissions_Inventory_for_Asphalt_Mix_Production_in_the_US_%E2%80%93_NAPA_June_2022.pdf.

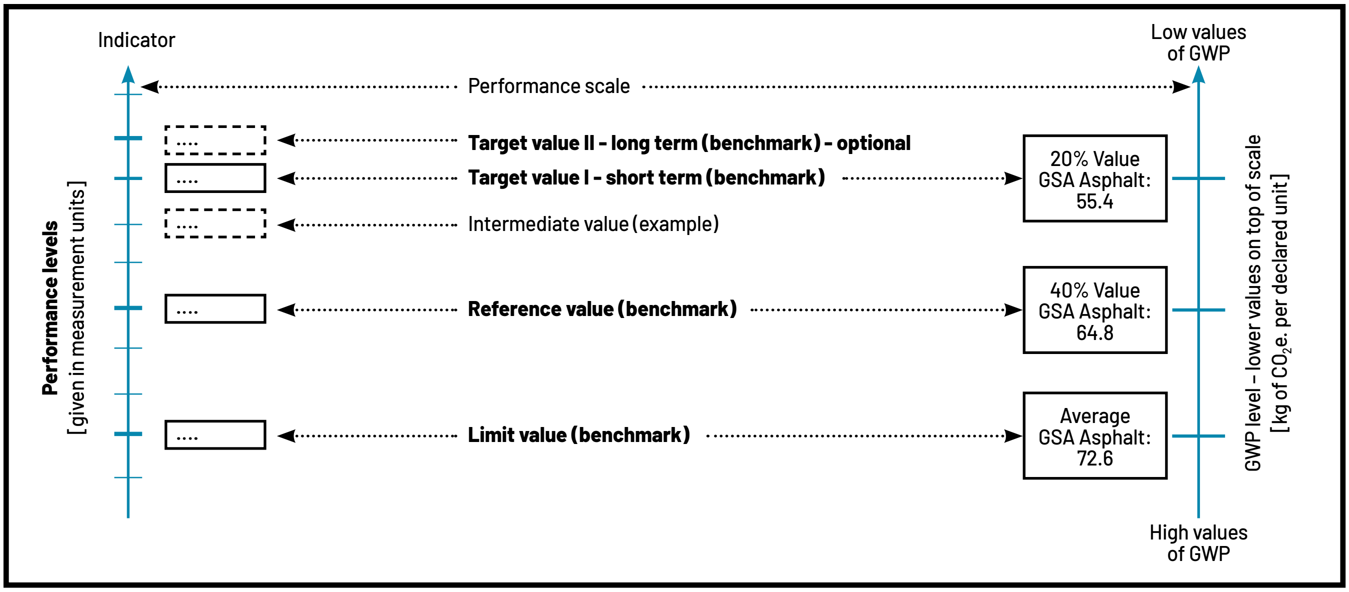

Figure 1. **Illustration of Limit, Reference, and Target Values as defined in ISO 21678 mapped onto EPA's Interim Determination Performance Levels and Reference Values set by GSA.**

Sustainability in buildings and civil engineering works: Indicators and benchmarks — Principles, requirements and guidelines. Additionally, the protocols outlined in the PCR document *Product Category Rules (PCR) for Asphalt Mixtures* for the calculation of GWP are adopted, specifically with respect to impact assessment methodology, allocation procedures, and the use of upstream inventories. The scope of this study is limited to only the GWP midpoint indicator, even though the methods outlined here can be extended to any of the other indicators as well.

ISO 21678 defines the development of a benchmark as the *process of collecting, analyzing, and relating performance data of comparable buildings or other types of construction works*. Consequently, a benchmark is defined as a reference point against which comparisons can be made. Reference values are defined as a points on a scale that represent state of the art or best practice, with the typical points of reference as: (i) a limit value indicating upper or lower acceptable performance level on a performance scale, (ii) a target value indicating a point on a scale that represents an objective that goes beyond the reference value, and (iii) point estimator reference values such as the mean, median and mode values of the reference value data sample. Limit values and target values are typically set by policy, while point estimator reference value benchmarks are set to represent industry trends.

In the context of the Inflation Reduction Act (2022), GWP thresholds are based on the GWP metric as reported in EPDs to assess embodied carbon levels of an asphalt mixture relative to other asphalt mixtures in its own category. In the thresholds set by agencies such as the EPA, the limit values map to the industry average (minimum qualification) while the target value maps to the 20th percentile (preferred qualification) as discussed in the next section. The industry average and quintiles established by GSA, are point estimator reference values as illustrated in Figure 1. The benchmarking process, laid out in this document is used to develop the underlying GWP reference scale and accompanying GWP thresholds to justify the reference values and their use in procurement processes. Reference values are estimated for each of the life cycle stages, A1, A2 and A3. The schema in Figure 1 is used later in the report to establish the estimated reference values.
The declared unit for asphalt mixtures is one metric

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

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

Figure 2. ISO 12930 system boundary declaration from the Asphalt Mixtures PCR.

tonne (one short ton) of mix. Both units are provided since ISO 21930 requires the use of SI units, but asphalt mixtures are typically procured based on short tons in the United States. The scope of this study is limited to cradle-to-gate and includes the life cycle phases and the processes within the system boundaries shown in Figure 2 and the processes within the system boundaries in Figure 3. This study follows all procedures for calculation of impacts detailed in the PCR for Asphalt Mixtures[1]. The PCR takes a prescriptive approach, fully describing the required upstream data sets, allocation procedures, cutoff criteria, and treatment of missing data, among other requirements.

Additionally, this study uses the procedures detailed in the underlying LCA[4] for quantification of energy and material inputs and outputs, considering how plant-level data are allocated to the declared products, description of the application of cut-off criteria and assumptions, and list of excluded processes. A list of Master Format Codes and relevant technical specifications can be found in the PCR.

The values for GWP are characterized using the TRACI 2.1 methodology. As with all midpoint indicators, the LCIA results given are relative expressions and do not predict impacts of category endpoints, exceedance of thresholds, safety margins, or risks[5].

[4] Mukherjee, Amlan. "Update to the Life Cycle Assessment for Asphalt Mixtures in Support of the Emerald Eco-Label Environmental Product Declaration Program." https://www.asphaltpavement.org/uploads/documents/Programs/Emerald_Eco-Label_EPD_Program/PCR_Public_Comment_Period/LCA_Asphalt_Mixtures_07_29_2021.pdf
[5] Bare, J.C. (2012). Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 — User's Guide. Report No. EPA/600/R-12/554 2012. U.S. Environmental Protection Agency, Cincinnati, Ohio. https://nepis.epa.gov/Adobe/PDF/P100HN53.pdf

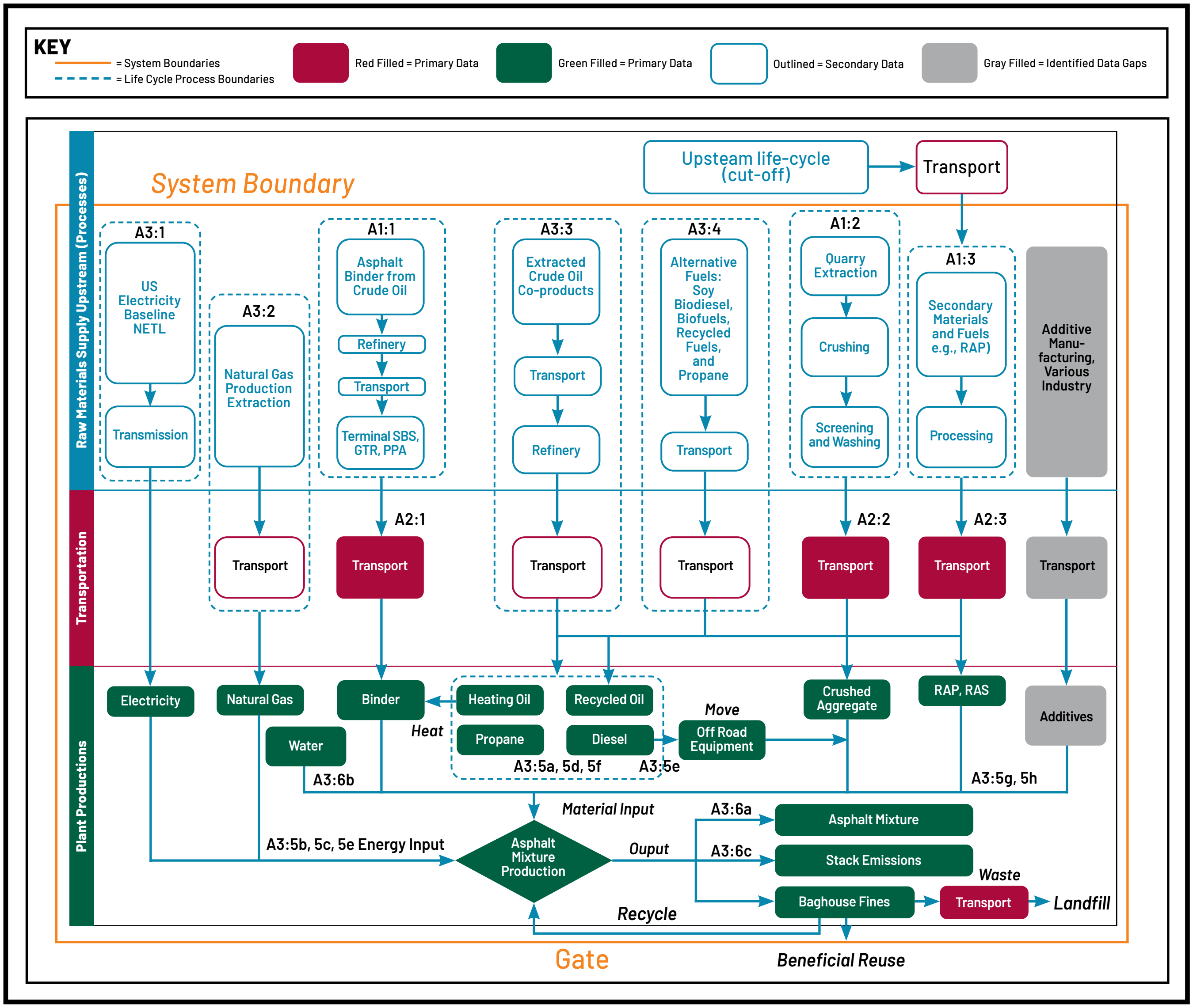

Figure 3. System boundary for asphalt mixture production.[5]

5. BACKGROUND

The GSA's document *Interim IRA Low Embodied Carbon Material Requirements*, released May 16, 2023,[6] establishes thresholds for asphalt based on the methodology outlined in the EPA documents Interim Determination on Low Carbon Materials under IRA and COVER MEMO – EPA's *Interim Determination for GSA & DOT/FHWA on low greenhouse gas construction materials under IRA Sections 60503 and 60506* released December 22, 2022.[7,8] The GSA thresholds are shown in Figure 4. Note that GSA has not accounted for functional differences between alternative asphalt mixture designs.

An accompanying FAQ identifies the data sources used for these thresholds: "GSA's GWP limits were developed based on industry average EPDs and actual products publicly available EPD data, filtered by material type, PCR(s) specified in GSA's requirements, North American geographical scope and current validity."[9]

The EPA Interim Determination provides the following calculation guidance:

materials/products qualify if their product-specific GWP is in the best performing 20 percent (Top 20 percent or lowest 20 percent in embodied greenhouse-gas emissions), when compared to similar materials/products (for example, materials/ products within the same product category that meet the same functional requirements). If materials/ products in the Top 20 percent are not available in a project's location, then a material/product qualifies per this determination if its GWP is in the Top 40 percent (lowest 40 percent in embodied greenhouse gas emissions). If materials/products in the Top 40 percent are not available in a project's location, then a material/product qualifies per this determination if its ***GWP is better than the estimated industry average****. [emphasis added]*

GSA IRA Limits for Low Embodied Carbon Asphalt - May 16, 2023 (EPD-Reported GWPs, in kilograms of carbon dioxide equivalent per metric ton - kgCO_2e/ t)		
Top 20% Limit	**Top 40% Limit**	**Better Than Average Limit**
55.4	**64.8**	**72.6**

Figure 4. **GSA's GWP limits as published**[6]

[6] "U.S. General Services Administration Interim IRA Low Embodied Carbon Material Requirements." https://www.gsa.gov/system/files/Interim%20IRA%20LEC%20Material%20Requirements%20-%20used%20in%20Pilot%20May%202023%2005162023.pdf

[7] "Interim Determination on Low Carbon Materials under IRA 60503 and 60506." https://www.epa.gov/system/files/documents/2023-01/2022.12.22%20Interim%20Determination%20on%20Low%20Carbon%20Materials%20under%20IRA%2060503%20and%2060506_508.pdf

[8] "COVER MEMO - EPA's Interim Determination for GSA & DOT/FHWA on low greenhouse gas construction materials under IRA Sections 60503 and 60506." US Environmental Protection Agency, December 22, 2022. https://www.epa.gov/system/files/documents/2023-01/2022.12.22%20COVER%20MEMO%20Interim%20Determination%20under%20IRA%20Sections%2060503%20and%2060506_508.pdf

[9] "FAQs: GSA Interim IRA Low Embodied Carbon Material Requirements Pilot." https://www.gsa.gov/system/files/FAQs-on-GSAs-IRA-LEC-Material-Requirements.pdf

The document then addresses data sets that may be used in threshold calculation:

Estimating the best performing 20 percent and 40 percent and industry averages.

Agencies shall estimate the GWP at the 20th and 40th percentiles and the industry average, as needed, for each material/product category using data from a verified source (e.g., an open source EPD database, industrywide EPDs or a 3rd party verified LCA developed using the relevant PCR). In addition, agencies shall disclose the GWPs, the methodology for determining the percentiles and averages, the source(s) used for each material/product, and the parameters (including performance specification) that can be used to set the GWP.

The Interim Determinations – while a significant step in furthering sustainable public procurement – presents the following opportunities for further investigation:

- First, the EPA determination does not describe a particular calculation method for determining the 20%, 40%, and estimated industry average. For example, it is unclear whether the average is intended as an arithmetic mean, or as the median.
- In the absence of available industry averages, GSA has used publicly available databases as a source for EPDs. While these databases serve as a useful industry resource, they are not third-party verified for correctness or representativeness.

Using the above as points of departure, this study intends to analytically support the process that EPA and GSA have set forth, as follows:

- Develop an analysis framework for characterizing the sensitivity of the GWP metric to different drivers of uncertainty using industry specific data. Asphalt mixture production is a distributed, local production process that is highly sensitive to uncertainties arising from exogenous regional factors through each of the A1, A2, and A3 life cycle phases. Hence, using a nationwide, region-invariant benchmark to drive procurement can unfairly disadvantage some producers and should be avoided if possible.
- Assess the sensitivity of GWP to exogenous factors will support thresholds that do not unfairly limit contractors from accessing the IRA funding intended to help them reduce their emissions.
- Establish a set of statistical approaches that, while simple, provide a formal approach that can be applied consistently to generate thresholds. This includes, but is not limited to, clarifying the ramifications of using either arithmetic mean or median as alternative definitions of average.
- Establish separate functional categorization-driven benchmarking techniques for each of these phases as a candidate alternative to the existing single-valued cradle-to-gate approach covering A1-A3, which will ensure that thresholds reflect differences in functional mixture design.

This study builds on the work done by EPA and GSA by establishing a larger dataset and examining multiple sources of uncertainty for each of A1, A2, and A3 phases of the asphalt mixture life cycle.

6. METHODOLOGICAL FRAMEWORK

The methodological framework is organized by sub-objectives that support the overall objective of developing industry benchmarks that account for the sensitivity of the GWP metric to various exogenous factors. The three primary sub-objectives are as follows:

Objective 1: Develop a Data Collection and Sampling Methodology

- Generate a representative dataset for analysis.
- Develop a data collection protocol that is easy to implement.
- Conduct a data quality assessment of the collected sample.

Objective 2: Uncertainty Characterization

- Identify the exogenous factors, or categories by which the GWP can be classified, for example, climate, geography, availability of aggregate, and material specification, among others.
- Characterize the extent to which GWP of asphalt mixtures is influenced by each of the categories and test for statistical significance.
- Establish a list of statistical tests used for making comparisons.

Objective 3: Proposed Benchmark Calculation Method: Guidance for Agencies

- Devise a method that agencies can use to assist decision-making.
- Establish a defensible set of coefficients/formulas based in LCA outcomes to calculate benchmarks.

Each of these components is addressed in detail in the rest of this section.

Objective 1: Data Collection and Sampling Methodology

From May to June of 2023 followed by a secondary collection from November 2023 to April of 2024, NAPA conducted an industry benchmarking survey to collect data from producers regarding their plant operations and material transport distances. An updated version of the Emerald Eco-Label tool was used to collect data spanning a 12-month period within the last 5 years. The objective of the data collection was to establish industry averages for transportation (A2) and mixture production (A3) life cycle phases. A reproduction of the modified input page (Figure 5) and full list of additional data types collected (Appendix 1) are included in this document. Participation was free to producers and performed on a voluntary basis. Pavement performance data were not collected, as pavement performance-related impacts are reported and influenced by factors outside the scope of the current asphalt mixture PCR. Furthermore, performance-related impacts are not currently included in the scope of the proposed or forthcoming regulations outlined in the EPA and GSA Interim Determination.

The data were evaluated for representativeness by the following criteria:

Time Period	Good	All data were from a 12-month period within the past 5 years.
Climate Region	Good	The number of participants in a climate region varied from 68 to 201.
State / Market Coverage	Adequate	47 states and the District of Columbia were present in the benchmarking dataset. Since asphalt plants operate within a limited geographic region, state participation was used as a proxy for market coverage. Alaska, West Virginia, and Rhode Island did not have participating locations. The total production of the participating locations is estimated to be about 25% of the national production. 27 states had a sufficient degree of company participation (N>=3) to report state-level numbers. A total of 161 organizations participated.
Technology	Good	Batch plants (81), parallel flow plants (70), and counter flow plants (375) participated.

Geographic representation is evaluated for representativeness by both climate and political / market boundaries. Combining phases one and two of this benchmarking study, 526 plants provided data. The additional 221 plants that participated in the secondary data collection round represented 7 states not included in the first round and increased the number of states with three or more participating locations by 10.

Objective 2: Uncertainty Characterization

Bhat & Mukherjee (2019)[10] discuss the different kinds of uncertainty that influence the GWP measure. The first is uncertainty arising from factors that can be characterized as random variables such as those that are outside the system boundaries of an LCA – in this case as set forth in the asphalt mixtures PCR. An example of such a factor is climate. It is not accounted for in an LCA even though it directly influences energy use in ways that are beyond the control of producers. In the context of GWP, such external factors influence the foreground LCA parameters that distinguish one facility and its product specific EPDs from another. In this document aleatory uncertainty is referred to as parametric uncertainty.

The second source of uncertainty arising from gaps in knowledge about a system and/or data gaps resulting from incompleteness in, limited quality of background LCI, or due to inconsistencies in LCA modeling approaches. As these factors are directly within system boundaries, and can be managed, every attempt should be made to isolate and evaluate them as alternative cases. For example, given two sets of EPDs where one set was calculated using background database A and

[10] Bhat, C. G., & Mukherjee, A. (2019) Sensitivity of Life-Cycle Assessment Outcomes to Parameter Uncertainty: Implications for Material Procurement Decision-Making, Transportation Research Record, Journal of the Transportation Research Board of the National Academies, 2673(3) 106:114.

Aggregates

This section aims to assess the impacts of aggregate transport. Over the course of the 12-month data reporting period, which two quarries or pits supplied the most aggregates to this plant?

For each of the top two aggregate sources report the total quantity supplied to this plant (tons) and the one-way transport distance and mode(s). The transport distance should be the entire distance from the quarry or pit where the aggregates were extracted to your plant. If your plant is co-located with the aggregate source, enter a distance of 0 miles.

For portable plants that sourced aggregates from the same quarry or pit while at multiple locations during the 12-month data collection period, enter the total tonnage sourced from the same quarry and the weighted average distance. Contact Joseph Shacat with questions.

Most Used Quarry/Pit

Approximate quantity purchased from this source*

shtn

If you do not have exact numbers please estimate to the nearest 5000 tons.

Truck Distance (mi) — miles — Enter the truck distance in miles

Train Distance (mi) — miles — Enter the train distance in miles

Barge Distance (mi) — miles — Enter the barge distance in miles

Ocean Distance (mi) — miles — Enter the ocean distance in miles

Second-Most Used Quarry/Pit

Approximate quantity purchased from this source*

shtn

If you do not have exact numbers please estimate to the nearest 5000 tons. Enter 0 if this plant only sourced aggregates from a single quarry/pit.

Truck Distance (mi) — miles — Enter the truck distance in miles

Train Distance (mi) — miles — Enter the train distance in miles

Barge Distance (mi) — miles — Enter the barge distance in miles

Ocean Distance (mi) — miles — Enter the ocean distance in miles

Asphalt Binder

Please provide the transportation distance and mode(s) for this plant's most-used asphalt binder supplier. Enter the one-way transport distance from the asphalt binder terminal to this asphalt plant.

Binder Truck Distance (mi) — miles — Enter the truck distance in miles

Binder Train Distance (mi) — miles — Enter the train distance in miles

Binder Barge Distance (mi) — miles — Enter the barge distance in miles

Binder Ocean Distance (mi) — miles — Enter the ocean distance in miles

Figure 5. A subset of inputs from the benchmarking survey tool.

the other with background database B, each should undergo a separate analysis of the parameters, while controlling for the use of different databases. Such a conditional analysis of GWP would ensure that the benchmarking is a function of statistical uncertainty due to external factors, and not due to a choice of background data. Typically, a PCR can be written to manage and reduce the source of such uncertainties by specifying background datasets, selection of proxies for data gaps, and modeling approaches.

The first step to assessing uncertainty is to classify the data into independent categories. Classification allows assessment of uncertainties arising from each category independently one at a time holding all the other categories constant, thus eliminating confounding interactions between multiple variables. For example, climate impacts energy requirements during asphalt mixture production (A3), while geology, impacts material availability and therefore travel distance (A2). Hence, the sensitivity of GWP to travel distances should be assessed across each climate zone separately, requiring a classification of the EPD data by climate. Classifying the data provides the opportunity to individually characterize the impact of each factor and enable the estimation of context specific thresholds with a higher level of confidence. Specifically, in this report the choice of classifiers focuses on factors that are outside the control of an asphalt producer.

Uncertainty Associated with Data and Model

The PCR for Asphalt Mixtures prescribes all background LCI datasets using the USLCI except where there is a data gap. In addition, the underlying LCA modeling method is implemented in the Emerald Eco-Label tool and is the same for all asphalt mixture EPDs. The data prescriptions can be found in Annex 1 of the Asphalt Mixtures PCR.[11] The only differences in background LCI are due to intentional choices that reflect regional differences.

Electricity data are drawn from the 2019 NETL dataset, which accounts for production, power sharing, and transmission to the user and provides at-user impact information at the balancing authority level. Based on the structure of this database, more than one balancing authority may be reported as servicing a particular plant location. In such a case, the balancing authority with the highest GWP value is used.

This prescriptive approach to background data sets eliminates the potential for uncertainty due to differences in background data set choices. All calculated GWP indicators in this study use the same background data sets, leaving foreground or parametric data as the main source of uncertainty. Any uncertainty in the LCI used to estimate the A1 impacts will uniformly impact the estimation of GWP for all asphalt mixtures and not advantage or disadvantage any mix evaluated under this system.

Consequently, in the current version of the PCR, the impacts from the A1 category can be treated as a deterministic quantity that can be calculated as a function of the mixture design (more on this in a later section). However, this situation may change in future as asphalt mixture EPDs incorporate supply chain specific EPDs for upstream materials like asphalt binder and aggregate. Even then, the impact associated with A1 will remain a deterministic quantity for a given design and supplier(s). However, with many EPDs per mix ingredient type, the characterization for A1 impacts may require additional treatment to continue to ensure fair benchmarking.

Assessing Substantially Low Carbon

The EPA's Interim Determination and the GSA's quintile-based threshold[6] are referenced in this study. As originally conceived, this method was intended to account for uncertainty in GWP reporting. The method proposed here develops a metric for identifying "substantially lower" levels of embodied carbon through application of the EPA quantile method to each life cycle phase. This phase-by-phase application of the method

[11] "Prescribed Upstream (Secondary) Data Sources." https://www.asphaltpavement.org/uploads/documents/EPD_Program/NAPA_PCR_AsphaltMixtures_v2_Annex1_v2.pdf

allows the development of regionalized benchmarks such that materials are judged as "substantially lower" levels of embodied carbon as compared to those designed and produced under similar geographic and technological circumstances.

Following the system established by GSA, the average, median, 40th percentile, and 20th percentile GWP were calculated for each region or category. In all cases for A2 and A3, states or regions with fewer than 5 participating sites or 3 participating organizations were excluded from reporting and identified as high priority for additional data gathering. The 20% thresholds were calculated via the quintile measurement, such that if 100 values are reported, the lowest 20 data points would be included, and the value of the 21st number is the threshold. The 40% thresholds are then the 41st number in this example. The 50% thresholds reported follow this method and are also the mathematical median. Finally, arithmetic means and medians were both calculated and are reported as averages.

While it is unclear if the GSA threshold for the "Better Than Average Limit" is based on arithmetic mean or median, this study assumes that the GSA used the arithmetic mean. This report includes both mean and median values whenever presenting 20%, 40%, and "Better Than Average" benchmarks for ease of comparison.

Objective 3: Assessment Method

This section outlines the benchmarking method. The separation of the benchmark by the three phases A1, A2 and A3, allows the individual characterization of each phase. The impacts from A1 can be formulaically calculated and/or estimated from reference mixture designs as well as from A1 ranges of EPDs published in the Emerald Eco-Label tool as of July 2023. To characterize the uncertainty, the GWP values for A2 and A3 were calculated for the participating locations in the benchmarking data. Comparisons were performed within the benchmarking data, and against the published EPDs. The following population and sub-population comparisons were evaluated for statistical significance:

Published EPDs [A1 – Upstream Materials]

- A1 EPD data classified by state, mix design classifiers (discussed later)
- A1 reference values computed from mix design ranges
- A1 for Colorado and California from EPD data (chosen to highlight the role of hydrated lime in driving GWP because Colorado includes hydrated lime in many mix specifications)

Benchmarking data [A2 – Materials Transport]

- Each climate region A2 vs national average A2
- State level A2 vs national average A2 (performed on states where initial screening showed large variance from national average)
- National average A2 vs average of published EPDs A2

Benchmarking data [A3 – Production Data]

- Each climate region A3 vs national average A3
- Each climate region A3 vs other climate regions A3
- State level A3 vs climate region A3 (where sufficient state data existed)
- National average A3 vs average of published EPDs A3

National Benchmark development

- National level A1 benchmarks regionalized by state for mix design classification + state level A2 benchmark using benchmarking data + state level A3 benchmark using benchmarking data
- Specific cases for Colorado and California as examples

[12] Chapter 7. Recommendations - Evaluation of Long-Term Pavement Performance (LTPP) Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide (MEPDG) Calibration and Other Pavement Analysis , May 2015 - FHWA-HRT-15-019. (2015, May). Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/15019/008.cfm
[13] "Prescribed Upstream (Secondary) Data Sources."
https://www.asphaltpavement.org/uploads/documents/EPD_Program/NAPA_PCR_AsphaltMixtures_v2_Annex1_v2.pdf

All comparisons of data used the two-tailed t-test to determine if differences between populations were of statistical significance. P values below 0.05 were deemed significant. This test is considered adequate for comparisons of means of non-normal distributions if the sample size is sufficiently large (n>35). All populations and sub-populations in this study met this requirement except for plants in several individual states. The implications of low sample size for those populations are covered in the relevant Discussion sections. A full listing of all comparisons and values is in Appendix 3: Statistical Test Outcomes.

Assessment Methodology for A1

When developing a benchmark for the A1 life cycle stage, it is very important to ensure the following:

- Benchmarks should be developed for distinct functional applications that asphalt mixtures serve. For example, mixture designs typically used for *heavy traffic highway surface courses* should not be treated the same way as mixtures used for *base and intermediate courses*, which are not subject to the same weather or traffic as surface courses.
- The percentile reference values should be based on a representative range of mix designs that represent a given functional classification category rather than statistical averages for specific design parameters. For example, avoid using an "average mix design" based on average values of asphalt binder from a range of unclassified asphalt mixes. Instead, identify a family of realistic mixture designs for each functional classification.
- As the asphalt PCR already specifies the background data a deterministic approach is recommended for calculating the impacts associated with the A1 stage for a given mixture design. In future as supply chain specificity increases with EPDs being available for asphalt binder, this deterministic approach can still be used with upstream EPDs used as necessary instead of the PCR specified background inventories.

Equation 1 provides the formulaic approach to estimating the impacts of A1 for a given mixture design, where the coefficients x_i indicate the design proportions (in fractions) for each of the constituent materials and the factors y_i indicate the associated GWP based on background LCI specified in the PCR for each constituent material. Hence, the summation of the x_i coefficients to 1 (as expressed in Equation 2) is a requirement for mass balance. The methodology supporting the calculation of GWP from upstream materials in A1 is outlined in detail in the LCA supporting the PCR.[4]

$$GWP_{A1\text{-}bench} = (x_1y_1 + x_2y_2 + \cdots + x_ny_n)$$

Equation 1. **Breaking out A1 from cradle-to-gate GWP calculation.**

$$s.t. \sum_{i=1}^{n} x_i = 1\ tonne$$

Equation 2. **Mass-based constraint on Equation 1.**

Where:

- $GWP_{A1\text{-}bench}$ = Total reported A1 life cycle impacts
- x_i = Total amount of ingredient i in tonnes per tonne of mix (% total mix by mass)
- y_i = GWP intensity of one tonne of ingredient i

Appendix 2: GWP Intensity Factors for A1, provides a complete set of y_i factors, including GWP factors derived from EPDs for various additives. In future, this table will be updated to reflect product and facility specific EPDs become available, particularly for upstream materials like aggregate and asphalt binder. However, as this can become an unwieldy table to operate, users of this study are encouraged to use the Emerald Eco-Label Simulator tool available through NAPA that will always have the most up to date supply chain specific EPDs.

An alternative to use this formula is to directly use the Emerald Eco-Label Simulator tool that has the most up to date list of upstream EPDs and LCI based GWP intensity factors already programmed and available for use. The calculated A1 GWPs using equations 1 and 2 and the Emerald Eco-Label Simulator tool should be identical for a given mixture design.

Defining A1 Mix Classifications

EPDs published using the Emerald Eco-Label were surveyed and analyzed for different mix types based on Nominal Maximum Aggregate Sizes (NMAS), types of binder and use of additives as summarized in Table 1. The percentages of different mixture classifications are not production weighted, but reflect the number of EPDs in Emerald Eco-Label. States are encouraged to develop a similar table based on different types of asphalt mixtures typically procured for their projects.

As is expected, a higher percentage of mixes with NMAS <= 12.5 mm (likely surface course applications) used modified asphalt binders compared to NMAS > 12.5 mm (likely intermediate or base course applications). Similar trends can be seen for the use of additives such as lime, warm mix, and anti-strip.

Table 1. Mix Design Trends in Nationally Published EPDs

Mix Binder Type Proportion with NMAS <= 12.5 mm	% of Mixes
Unmodified	62.6
SBS modified - 3.5% styrene-butadiene-styrene	31.2
PPA Modified - up to 1% polyphosphoric acid	5.8
GTR modified - up to 10% ground tire rubber	0.4
Mix Binder Type Proportion with NMAS > 12.5 mm	**% of Mixes**
Unmodified	80.1
SBS modified - 3.5% styrene-butadiene-styrene	14.7
PPA Modified - up to 1% polyphosphoric acid	5.2
Lime Additive Proportion	**% of Mixes**
NMAS <= 12.5 mm	6.5
NMAS > 12.5 mm	8.3
Warm Mix Additive Proportion (% of mixes)	**% of Mixes**
NMAS <= 12.5 mm	28.4
NMAS > 12.5 mm	32.4
Anti-Strip Additive Proportion (% of mixes)	**% of Mixes**
NMAS <= 12.5 mm	25.8
NMAS > 12.5 mm	13.6

It is also important to recognize that mix designs should not be averaged. A mix design with 20% Reclaimed Asphalt Pavement (RAP) and a mix design with 40% RAP have different applications and cannot be represented by an "average" mix with 30% RAP. Similarly, "average" GWP for the two mixes do not result in a meaningful number. Hence, it is crucial to avoid the language of "averages" and to instead think of mixes classified by functional class with associated representative GWP ranges. For example, if a functional class allowed for "no more than 40% RAP", then a GWP range can be defined for the functional class based on the extreme cases of a virgin mix (0% RAP), and a 40% RAP mix.

With this understanding, EPDs published using the Emerald Eco-Label were classified into a two-by-two table along the following two dimensions:

- Mixes characterized by NMAS less than or equal to 12.5 mm, versus mixes characterized by NMAS greater than 12.5 mm.
- Mixes that used unmodified asphalt binders, versus mixes that used modified asphalt binders using modifiers such as Styrene Butadiene Styrene (SBS).

This classification scheme was selected to draw a distinction between the typically higher GWP intensities of modified asphalt binders compared to unmodified asphalt binders; and the likely application of smaller NMAS mixes to surface courses versus non-surface courses for larger NMAS mixes. The total number of mixes as per this classification is illustrated in Table 2. In addition, we consider the impact of local requirements that may have a high impact on GWP, such as the use of hydrated lime in Colorado.

Table 2. Counts for mixture classification categories.

	NMAS <= 12.5 mm	NMAS > 12.5 mm
Unmodified Binder	938	490
Modified Binder	561	122

Asphalt mixes are engineered to serve numerous functional requirements that vary by application ranging from heavy truck traffic highways to residential streets and parking lots. In addition,

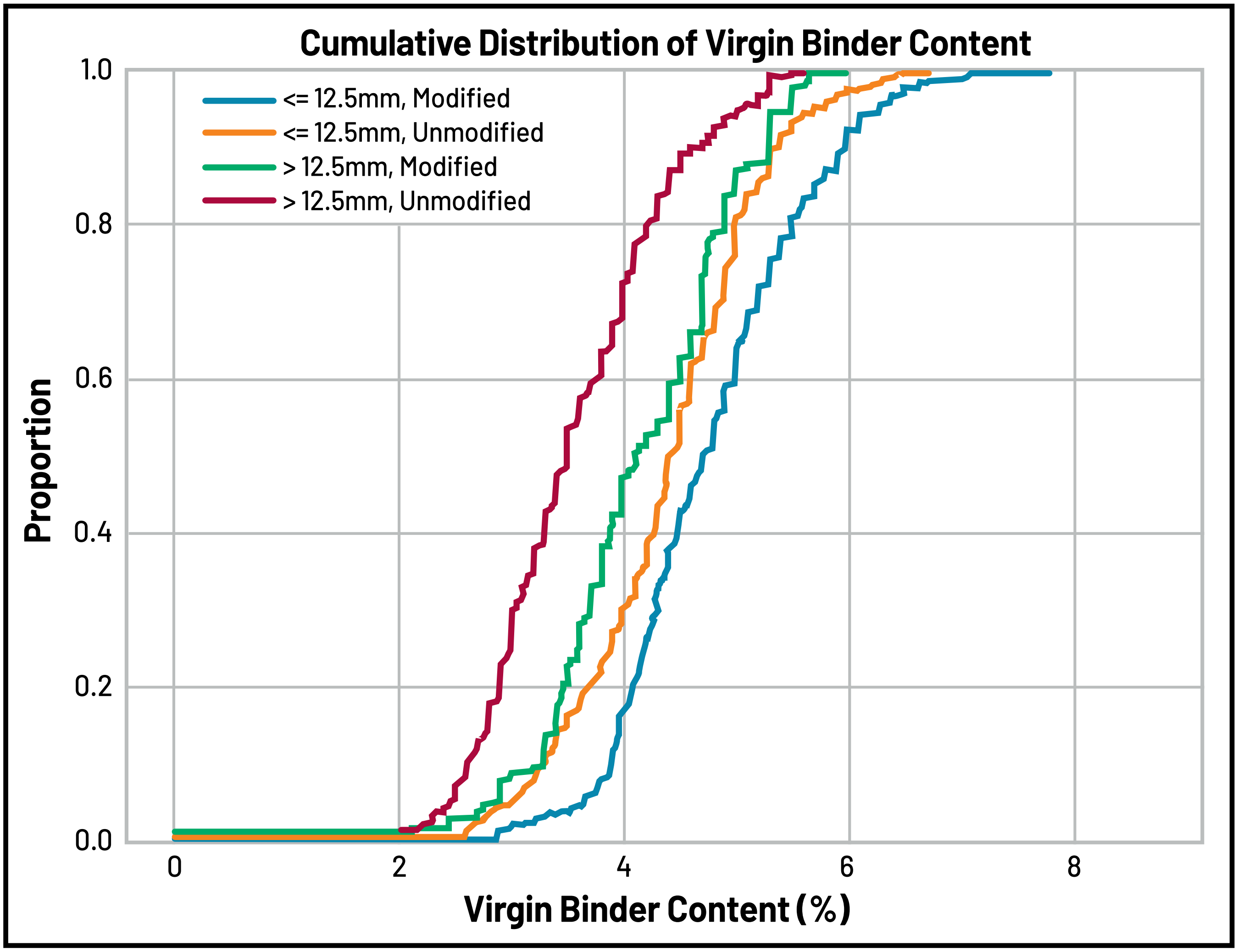

Figure 6. Virgin Asphalt Binder Content for the Classification Categories

for the same functional class, there can be variations in mix design and asphalt binder grade due to climatic differences. For a national level study, a classification as shown in Table 2, while the most defensible, may not be the most representative of the actual functional classes that the EPDs were developed for. Hence, this classification suffices only to meet the purpose of methodological illustration in this report and while it is the closest to a national average, it should not be used for any meaningful decision support. ***State DOTs should develop their own classification of mixes by identifying representative functional class that relate to their construction specifications.***

Identifying Representative Mix Designs

The next step is to identify representative asphalt mix designs for each classification category.

For a DOT conducting a similar study a sample of representative mixtures can be selected for each classification based on the typical approved mixture designs. In this study, due to the national scope of the data the mix designs for each of the categories in the Emerald Eco-Label tool were surveyed. Figure 6 illustrates the range of virgin asphalt binder (modified and unmodified) used for the two NMAS size categories.

Using the plot in Figure 6, representative virgin asphalt binder contents were identified at each of the reference value positions (20th percentile, 40th percentile, median and average), and associated mixture designs for typical RAP contents were established as listed in Table 3 (all Asphalt Binder contents in Table 3 refer to virgin asphalt binder). Henceforth these reference mixtures will be

Table 3. Mix designs identified to compute reference values for GWP – Benchmarking (BM) Mixes

Category	*Mix Design Coefficients (x_i) – percentage by mas (%)			
Unmodified > 12.5 mm	**Asphalt Binder* (%)**	**RAP* (%)**	**Net Binder (%)**	**Aggregate* (%)**
20th percentile	2.90	30.00	4.40	67.10
40th percentile	3.30	25.00	4.55	71.70
Median	3.50	20.00	4.50	76.50
Average	3.58	20.00	4.58	76.42
Unmodified <= 12.5 mm	**Asphalt Binder* (%)**	**RAP* (%)**	**Net Binder (%)**	**Aggregate* (%)**
20th percentile	3.72	30.00	5.22	66.28
40th percentile	4.30	20.00	5.30	75.70
Median	4.44	20.00	5.44	75.56
Average	4.40	20.00	5.40	75.60
Modified > 12.5 mm	**Asphalt Binder* (%)**	**RAP* (%)**	**Net Binder (%)**	**Aggregate* (%)**
20th percentile	3.50	20.00	4.50	76.50
40th percentile	3.88	15.00	4.63	81.12
Median	4.12	15.00	4.87	80.88
Average	4.16	15.00	4.91	80.84
Modified <= 12.5 mm	**Asphalt Binder* (%)**	**RAP* (%)**	**Net Binder (%)**	**Aggregate* (%)**
20th percentile	4.10	20.00	5.10	75.90
40th percentile	4.50	20.00	5.50	75.50
Median	4.75	15.00	5.50	80.25
Average	4.81	15.00	5.56	80.19

referred to as "A1 Benchmark Mixes" or "BM-Mixes", to differentiate the A1 GWPs calculated from them compared to the A1 GWPs estimated from the published EPD data in Emerald Eco-Label (last draw on May 2024).

The net binder content in Table 3 is computed based on the asphalt binder reclaimed from RAP at 5% by mass. All the other mass components (indicated with *) are the constituents of the asphalt mixture and sum to 100% ensuring mass balance. The proportions of the constituent materials (indicated with *) are the x_i coefficients in Equation 1, and as per Equation 2, they sum to 1 (or 100%). Substituting the mix design coefficients in Table 3 in Equation 1 and using the y_i GWP intensities for the constituent materials from Table 7, the GWP reference values for the A1 stage can be computed and are listed in the second column from the left in Table 4.

The computed values for the reference mixtures were compared to the A1 GWP values distribution observed from the EPDs in the Emerald Eco-Label tool for the same categories, and the percentage difference (with respect to the calculated values) is reported in the fourth column from the left.

State Level A1 Assessment: Case of Colorado and California

Appendix 4: Example State A1 GWP Tables provides a full listing of the A1 reference values (RV) classified by states and NMAS size for the following categories:

Table 4. Calculated GWP from BM Mixes versus EPD A1 GWP – all GWP in kg of CO_2 e. per tonne

Category	GWP Calculated from BM Mixes vs GWP from EPD A1 Ranges		
Unmodified > 12.5 mm	**GWP Calculated**	**GWP from EPD**	**% Difference**
20th percentile	19.85	19.92	-0.4%
40th percentile	22.43	22.49	-0.3%
Median	23.74	23.71	0.1%
Average	24.25	25.65	-5.5%
Unmodified <= 12.5 mm	**GWP Calculated**	**GWP from EPD**	**% Difference**
20th percentile	25.01	25.19	-0.7%
40th percentile	28.78	28.80	-0.1%
Median	29.66	30.12	-1.5%
Average	29.41	30.94	-4.9%
Modified > 12.5 mm	**GWP Calculated**	GWP from EPD	**% Difference**
20th percentile	28.20	27.49	2.6%
40th percentile	31.13	30.54	1.9%
Median	32.95	31.33	5.2%
Average	33.25	34.02	-2.3%
Modified <= 12.5 mm	**GWP Calculated**	**GWP from EPD**	**% Difference**
20th percentile	32.74	32.38	1.1%
40th percentile	35.76	35.33	1.2%
Median	37.71	37.08	1.7%
Average	38.17	40.64	-6.1%

GWP RV was estimated based on the published EPD data as per the distribution in Figure 6, and classified by state as follows:

- Table 18: A1 GWP RV for NMAS > 12.5 mm using EPD data as available
- Table 19: A1 GWP RV for NMAS <= 12.5 mm using EPD data as available
- Table 20: US Averages for A1 GWPs (i) Based on EPD data and (ii) Based on BM Mixes

A US national GWP RV calculated using the EPD data and BM Mix based GWPs in Table 4, weighted by the counts in Table 2, to represent the modified and unmodified asphalt binder classes. The "% difference" column is calculated as (GWP Calculated – GWP from EPD)/GWP Calculated.

The modified and unmodified classifications had to be merged for comparison at the state level to EPD based A1 data as the EPDs do not indicate whether the asphalt binder is modified by polymer or not, though the NMAS size is available for assessment. First, two state level EPD datasets with enough publicly available EPDs (N>15), California and Colorado (both states with Buy Clean legislation in place) were assessed. Figure 7, illustrates the EPD based A1 RV for California and Colorado along with a US national RV set based on the BM Mixes (weighted average of modified and unmodified binders using summary of column 3 in Table 4).

As is expected the mixes with NMAS <= 12.5 mm are consistently higher than the mixes with NMAS > 12.5 mm. While California reference values track very closely to the US national reference values,

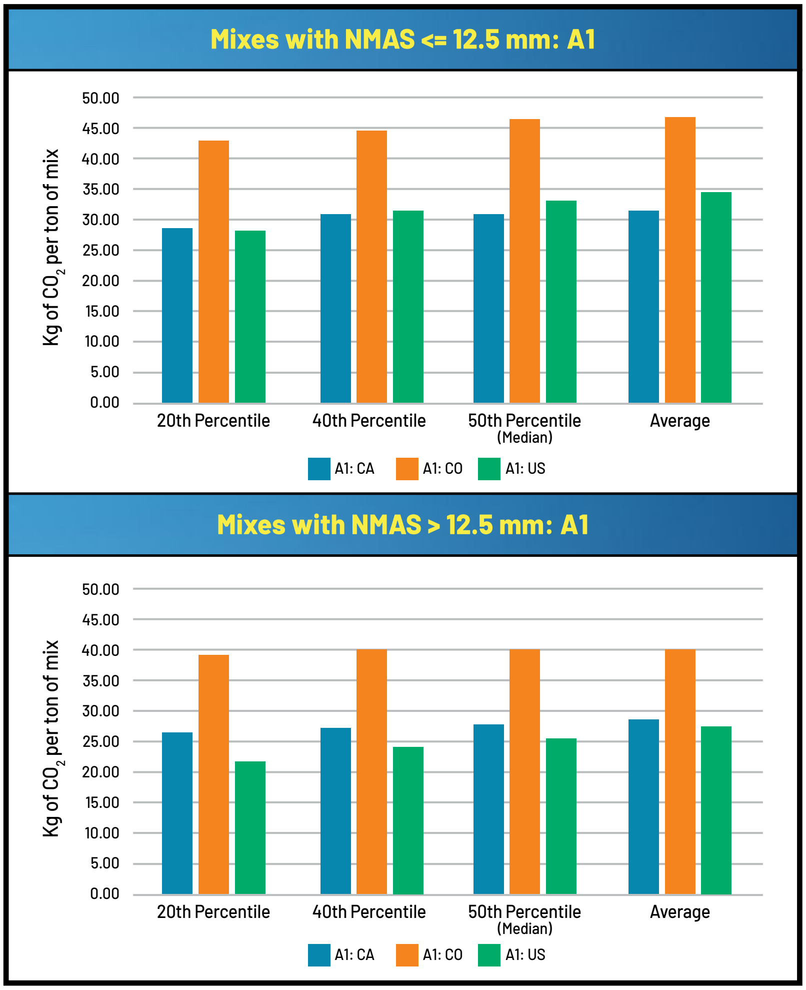

Figure 7. **Comparison of Percentile and Average GWP Reference Values for California and Colorado, for (i) NMAS <= 12.5 mm and (ii) NMAS > 12.5 mm.**

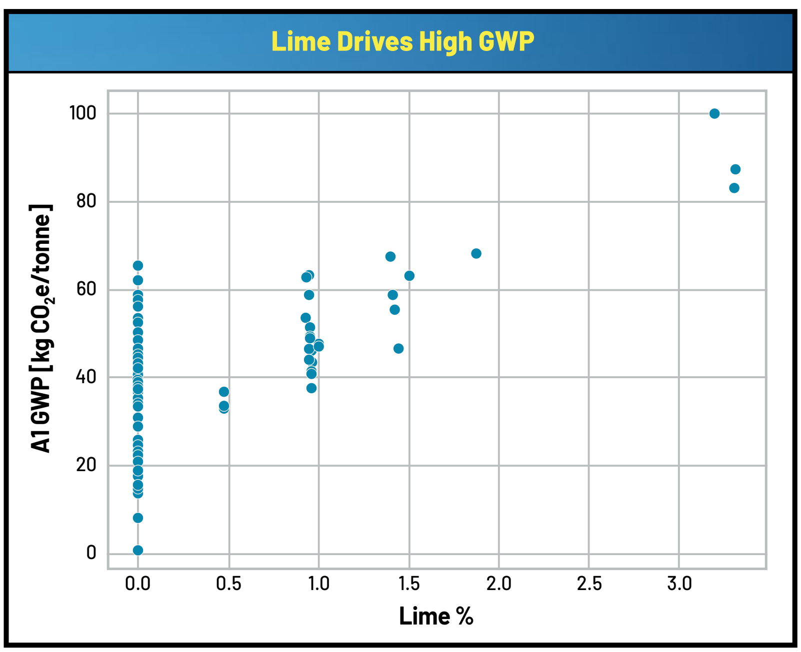

Figure 8. **Correlation between high GWP (in kg of CO_2e. per tonne) and use of hydrated lime in asphalt mixtures.**

it turns out that Colorado is consistently significantly higher than the national reference values as well as the California reference values.

The higher value for Colorado illustrates how state level specifications can drive GWP impacts by requiring the use of materials and mixture designs that bias the GWP estimates. Colorado specifies the use of hydrated lime that directly displaces some of the virgin aggregate on a 1:1 mass basis. While the lime fraction is low (~1% of total mixture mass), lime has a GWP intensity 715 times that of virgin aggregate (Table 7). An evaluation of high-A1-GWP mixes in the Emerald Eco-Label tool shows that all mixes over 75 kg CO_2e/tonne A1 include large amounts of lime (Figure 8). This is directly influencing the overall higher reference values for Colorado.

Statewide reference values for several states classified by NMAS have been provided in Appendix 4. A further investigation was conducted to assess the variance of the average GWP RV for each state based on A1 based EPD data. The average GWP RV is calculated as an arithmetic mean, and by central limit theorem, means are normally distributed. Hence, a *Z-value* for each state S, i.e., the difference of the average GWP for the state S and the mean of state average GWPs divided by the standard deviation of state GWP Averages, was computed. The *Z-value* establishes the number of standard deviations a state's average is removed (higher is +ve, and lower is -ve) from the typical national average GWP. Figure 9 and Figure 10 illustrate the *Z-values* for the sates.

As expected from the previous discussion, Colorado is 1.5 standard deviations higher for mixes with NMAS <= 12.5 mm and on the higher side for NMAS > 12.5 mm. Other states that stand out for the NMAS <= 12.5 mm

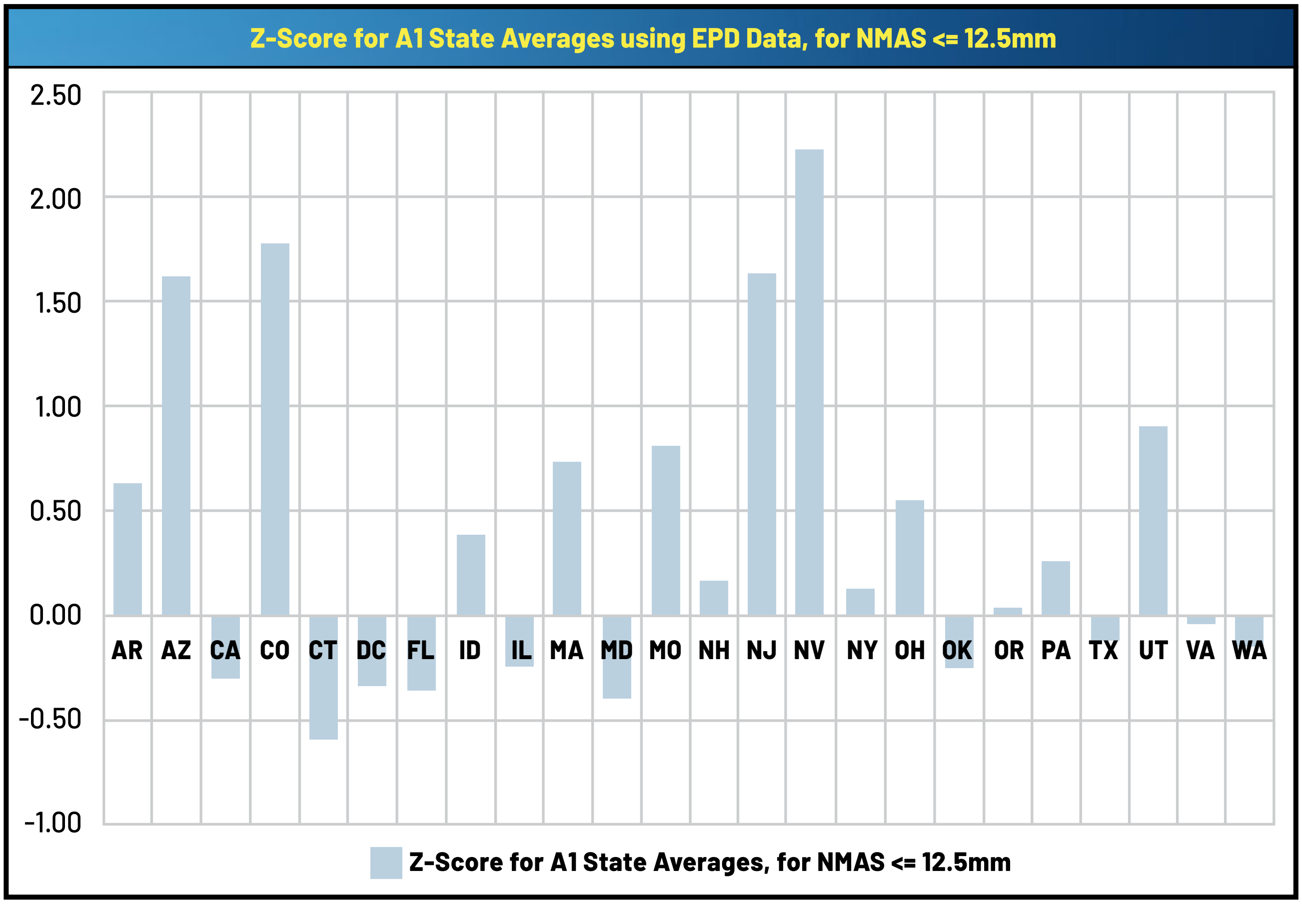

Figure 9. Assessing Sate Wide Variation of A1 GWP for NMAS <= 12.5 mm from EPD Data

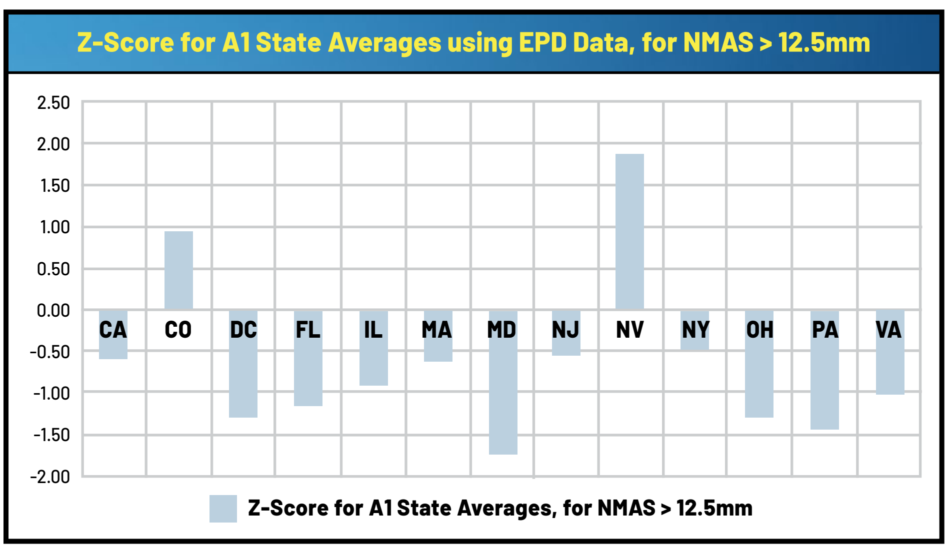

Figure 10. Assessing Sate Wide Variation of A1 GWP for NMAS > 12.5 mm

case are Arizona, New Jersey and Nevada. As the NMAS <= 12.5 mm classification often is used for surface course applications, this trend is likely an outcome of mix design specifications in each of these states. This argument is particularly likely for New Jersey where in the NMAS > 12.5 mm category, the GWP goes below the mean. Nevada and Colorado remain consistently high in both cases, and it is expected that the use of lime in both states is a root cause of this. The case of Maryland is interesting. While it tends to trend lower than average, it is 1.5 standard deviations lower than the average for mixes with NMAS > 12.5 mm.

Identifying the underlying state design specifications for New Jersey, Nevada and Maryland is beyond the scope of this study. However, this analysis points to the need to establish benchmarks for A1 at the state level rather than nationally, ideally using a classification of the mixtures that reflect the construction specifications and mix design requirements for each state.

Table 5. GWP for Sample Mixtures with Recycling Agents (RA) and Lime.

All Mix proportions in % and GWP in in kg of CO_2 e. per tonne							
Mix with NMAS > 12.5 mm	**Asphalt Binder**	**RAP**	**Effective Binder**	**Agg.**	**RA**	**Lime**	**GWP**
20% RAP Unmod. + Lime	4.8	20	5.80	74.31	0	0.892	44.30
40% RAP Unmod. w/ RA + Lime	3.6	40	5.60	55.51	0.036	0.892	37.47
0% RAP 3% SBS + Lime	6	0	6.00	93.11	0	0.892	59.72
20% RAP 3% SBS + Lime	4.8	20	5.80	74.31	0	0.892	50.41
40% RAP 3% SBS w/ RA + Lime	3.6	40	5.60	55.51	0.036	0.892	42.05
Mix with NMAS < = 12.5 mm	**Asphalt Binder**	**RAP**	**Effective Binder**	**Agg.**	**RA**	**Lime**	**GWP**
20% RAP Unmod. + Lime	7	20	8.00	72.11	0	0.892	58.15
40% RAP Unmod. w/ RA + Lime	5.6	40	7.60	53.51	0.036	0.892	50.06
0% RAP 3% SBS + Lime	4.2	0	4.20	94.91	0	0.892	46.10
20% RAP 3% SBS + Lime	7	20	8.00	72.11	0	0.892	67.05
40% RAP 3% SBS w/ RA + Lime	5.6	40	7.60	53.51	0.036	0.892	57.18

Role of Additives in A1 Estimation

Besides hydrated lime, there are a set of other additives that also tend to nudge the GWP of the A1 stage upwards. Appendix 2: GWP Intensity Factors for A1, provides the GWP intensities for warm mix additives, hydrated lime and recycling agents. As these constituents tend to increase the A1 GWP, a state must be cognizant of mix categories with functional requirements that call for the use of additives. Table 5 provides a sample set of mixes with additives and their associated GWPs (mass balance: neat binder + RAP + aggregate + RA + lime = 100%). The inclusion of small quantities of recycling agents and lime significantly pushes the GWP well above the reference values.

The reference values provided in column 3 of Table 4 include in them mixes with recycling agents (RA) and lime.

Discussion

The percentage difference between the GWPs calculated and arrived at from the EPD distribution as listed in Table 3 provide meaningful insights into the benchmarking process.

First, the difference between modified and unmodified asphalt binders reflects that even when polymer modified binders are used at the same volumetric values as unmodified binders, they incur higher GWP impacts. Asphalt binder that has been modified at the terminal to include 3.5% Styrene-Butadiene-Styrene (SBS) has GWP impacts 20.1% higher than neat binder, according the USLCI data prescribed by the PCR for Asphalt Mixtures and acquired from the Asphalt Institute's 2019 LCA.[12] The impact of SBS use can be approximated by 1.675 kg of CO_2e/short ton (1.675 kg of CO_2e/short ton) per % SBS for the baseline mixture design described in the LCA in Support of the Emerald Eco-Label tool.[13] This factor may require revision for additional mixture designs.

Next, the use of RAP influences overall mixture GWP by replacing both virgin aggregate and binder. While aggregate represents most of the mass replaced, GWP reductions are primarily due to binder replacement. Given the use of an asphalt binder and some percentage of RAP, the amount of GWP reduction a mixture will see

[12] Wildnauer, Mulholland, and Liddie, *Life Cycle Assessment of Asphalt Binder*. https://trid.trb.org/view/1645171

[13] Mukherjee, "Update to the Life Cycle Assessment for Asphalt Mixtures in Support of the Emerald Eco-Label Environmental Product Declaration Program." https://www.asphaltpavement.org/uploads/documents/Programs/Emerald_Eco-Label_EPD_Program/PCR_Public_Comment_Period/LCA_Asphalt_Mixtures_07_29_2021.pdf

can be approximated as 6.52 kg CO_2e per tonne (5.92 kg CO_2e per short ton) per % asphalt binder replacement (% ABR). This dynamic is borne out by this current study, as all mixes with RAP show a significant reduction in A1 GWP compared to their virgin counterparts.

For all categories, excepting for modified binders with NMAS > 12.5 mm, the difference between the 20th, 40th percentiles and median are relatively small (typically less than 2%) while the average varies by a higher margin (between 4% - 6%). It is not unexpected for positional reference values such as percentiles to align, and this is indicative that in this case, the selection of the mix designs represents the reference values. However, the consistently higher average value is because unlike the percentiles it is not a positional point in the distribution, and the average value for binder content does not fully capture the weighted contributions of mixes on either ends of the distributions in Figure 8. In addition, as illustrated in Table 5, and in the case of Colorado, mixtures with additives and lime tend to push up the average value and are not represented in the reference mixtures. Hence, preferably, the average reference value must be based off the calculated GWPs of a set of mixtures that represent the full range.

For the category of modified binder mixes with NMAS > 12.5 mm, the difference between the calculated GWP, and the GWP from the EPD distribution is relatively higher for the percentiles, particularly for the median. Given the granularity and context available for the EPD data analyzed, this trend is difficult to interpret, though it does raise questions regarding the representativeness of the mixtures identified at the percentile points. Inspection of the cumulative binder distribution curve in Figure 8, shows that the shape of the S-curve is less uniform compared to the other three categories. This irregularity in distribution is possibly an outcome of this category representing disparate functional classes. For mixes with NMAS <= 12.5mm, the applications are likely to be both base and intermediate courses, with the use modified binder hinting at specialized applications. This category also has the fewest number of mixes as listed in Table 1.

A critical limitation of this analysis is that at the national level it is difficult to identify meaningful functional classifications when analyzing EPDs from across multiple states responding to different specifications. Hence, the classifications used in this analysis should only be considered useful for illustrating the methodology and the benchmarks here should therefore be used with caution.

Assessment Methodology for A2

A2 categories were established by analyzing benchmarking data on a state-by-state basis followed by identification of clusters of dissimilar performance. The working hypothesis for this study is that regions with low availability of high-grade construction aggregates would have a significantly higher A2 GWP due to the need to import aggregates from distant producers. This hypothesis was tested statistically.

A2 GWP impacts were calculated based on the combined transport impacts of aggregate, binder, and RAP. Aggregate and binder transport distances were directly reported in the benchmarking tool. Average RAP transport distance was estimated at 6.74 miles based on industry-wide surveys conducted by NAPA. The GWP estimation for A2 used the same LCI as prescribed in the asphalt mixtures PCR and using the 1.35 factor to account for return hauls. The estimated A2 GWP RV, by state based on the collected benchmarking data is listed in Appendix 5: Example State A2, A3 GWP Tables, in Table 21.

Significant regional variability exists for A2, as some states have far greater transport impacts than the national average (Figure 12). Since the GSA threshold is set for the sum of A1 to A3 impacts, these cases of unavoidably high transport impacts are a strong argument for separate benchmarking values for the A2 phase.

Florida and Louisiana had A2 median values of 36.32 kg CO_2e/tonne and 39.42 kg CO_2e/tonne, respectively. The median of all other states was 3.65 kg CO_2e/tonne. In some cases, the transport phase impacts alone were enough to exceed even the most forgiving GSA threshold (72.6 kg CO_2e/tonne).

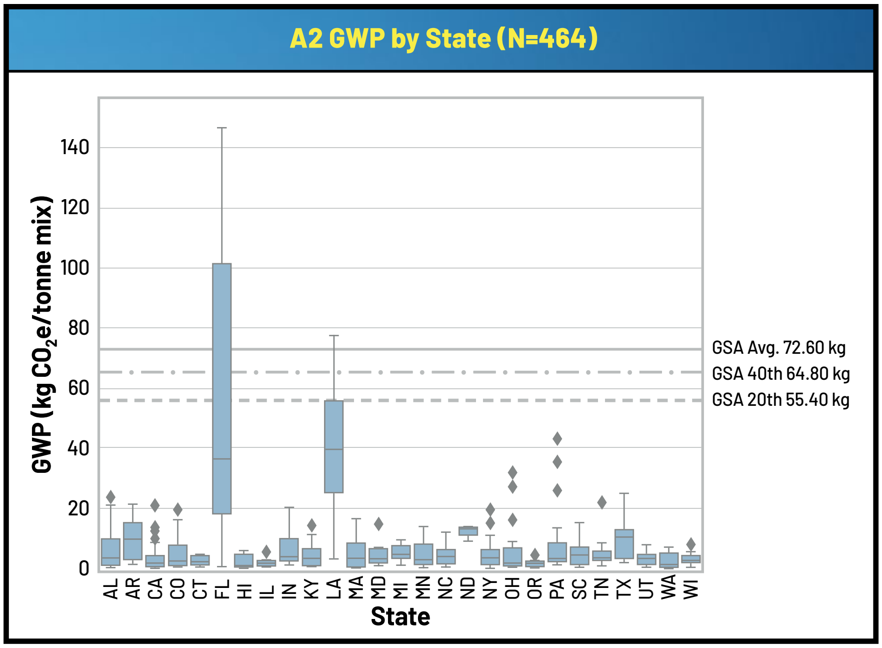

Figure 11. Aggregate-poor states such as Florida and Louisiana have very high A2 impacts.

Some states with anecdotally high transport distances did not have enough data for this study to draw conclusions. Similarly, smaller states may have a sole supplier for an upstream material (such as aggregate), rendering the A2 numbers uncompetitive. It is recommended that these states (notably Alaska) be targeted in future updates.

Industry consensus is that this extreme degree of transport is driven primarily by a lack of locally available road-quality aggregate and additionally in some cases by economic factors such as 1:1 local production: consumption in nearby regions requiring acquisition from farther afield.

Assessment Methodology for A3

A3 categories should be established based on well-justified, statistically significant regionalization methods. For example, given the role of stockpile moisture content in driving consumption of burner fuel, a climate-based regionalization is a good candidate. To demonstrate the A3 categorization process, AASHTO climate regions were used for a first order examination of climate effects. Additionally, it is important to review other categorization or regionalization methods as the available data allows.

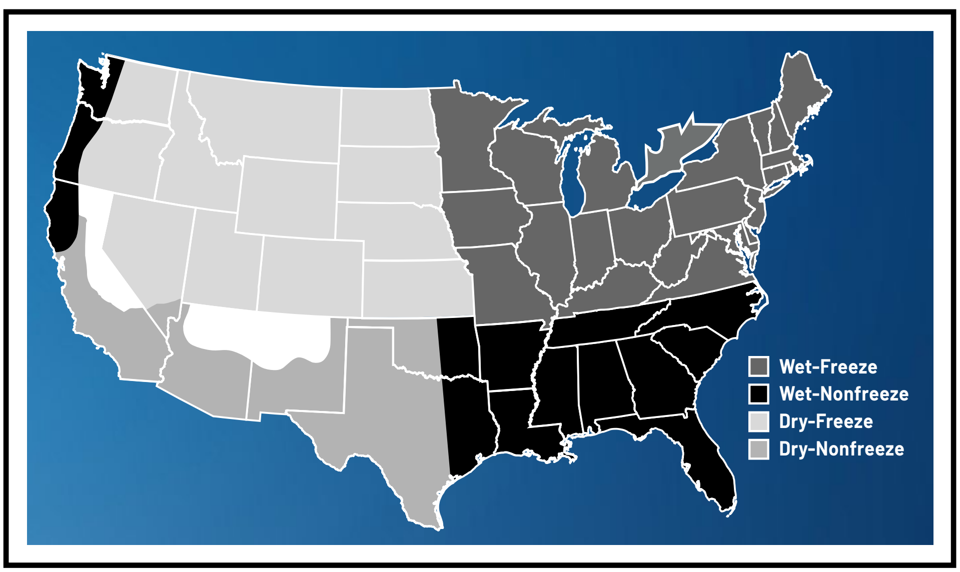

Figure 12. LTPP/AASHTO Climate Regions [15]

AASHTO splits the continental United States into four regions, depending on rainfall and temperature. Wet regions receive an annual rainfall above 508mm (20"), and non-freeze regions have a freezing index above 83.3°C-days[14]. The resulting regions of Wet No Freeze (hot-wet), Dry No Freeze (hot-dry), Wet Freeze (cold-wet), and Dry Freeze (cold-dry) are shown in Figure 6.

[14] Jackson, N., & Puccinelli, J. (2006). Long-Term Pavement Performance (LTPP) Data Analysis Support: National Pooled Fund Study TPF-5(013) Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost (p. 69). Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/06121/06121.pdf

[15] Chapter 7. Recommendations - Evaluation of Long-Term Pavement Performance (LTPP) Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide (MEPDG) Calibration and Other Pavement Analysis , May 2015 - FHWA-HRT-15-019. (2015, May). Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/15019/008.cfm

Though more granular regions for climate are available, the number of participating sites limited the detail that could be examined with statistical relevance. In limited cases where the sub-population data for an individual state was great enough, the A3 data could also be examined by state.

A3 categories were established regionally using both state boundaries and the four AASHTO climate regions (Wet No Freeze/hot-wet, Dry No Freeze/hot-dry, Wet Freeze/cold-wet, and Dry Freeze/cold-dry). State boundaries provide a more granular view into regional energy consumption patterns and electricity grid performance, while AASHTO climate regions allow a high-level evaluation of the role of climate on plant performance.

A3 impacts are driven by the consumption of energy by the production facility. Energy sources include grid electricity and fuels combusted in the asphalt burner, oil heaters, and onsite equipment.

AASHTO climate regions had statistically significant effects on GWP per short ton of asphalt (Figure 13). The Wet No freeze region had the highest average value (27.44 kg CO_2e/tonne) and Dry No freeze the least (24.05 kg CO_2e/tonne) (Table 23).

Examining the A3 distributions by state appears to reveal elevated impacts in Hawaii as shown in Figure 14. Possible elevations in the states of Alabama and Utah were also investigated.

Note that Figure 14 displays a subset of the sample, n=464 of a total sample size of 526. To protect potentially sensitive data, A3 values from states with fewer than five unique producers participating are not displayed. The estimated A3 GWP RV by state and by climate region based on the collected benchmarking data is shown in Appendix 4, Table 22.

The second round of data collection targeted areas that were underrepresented in the first analysis and uncovered potential trends that may justify alternative regionalization approaches.
The standout revelation from this effort is elevated A3 impacts in

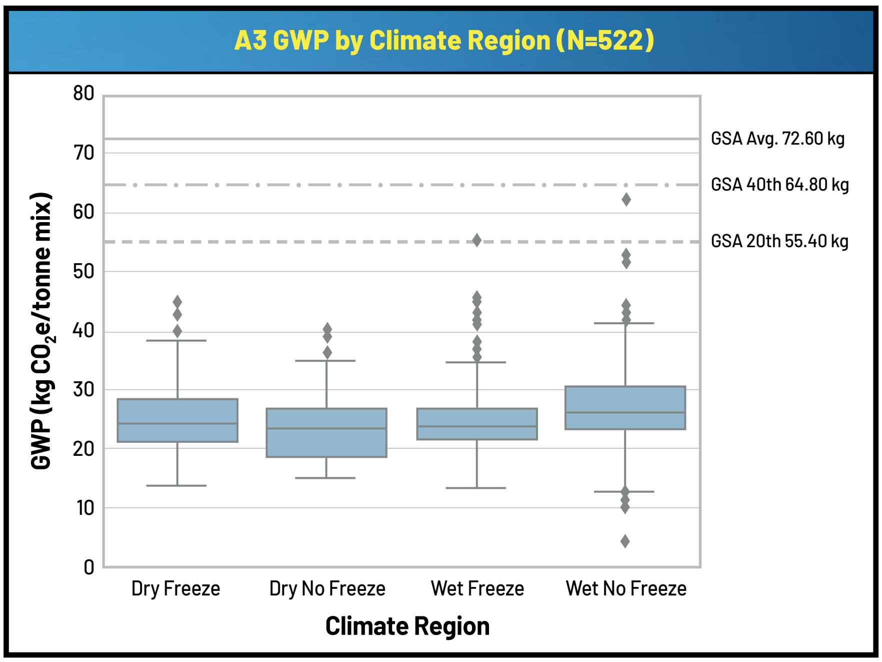

Figure 13. Dry Freeze and Wet No-Freeze regions exhibited higher average GWP values.

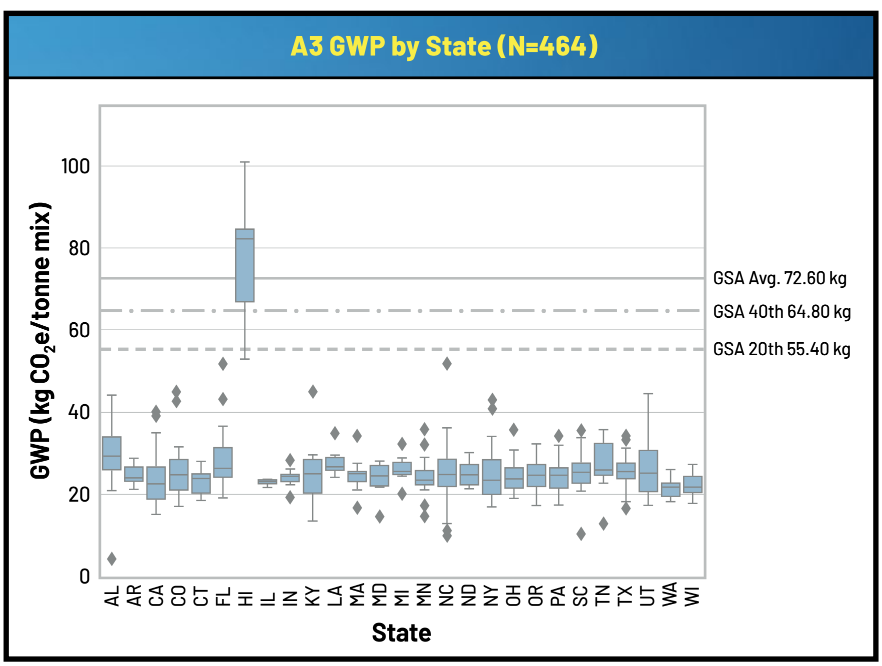

Figure 14. A3 GWP by state.

Hawaii. Hawaii's average A3 value was 77.6 kg CO_2e/tonne, more than doubling the Wet No Freeze value of 28.7 kg CO_2e/tonne. While the sample size for Hawaii is limited (n=6), the difference is great enough to leave no question of statistical significance.
As Hawaii is the United States' only island state and only tropical state, it perhaps deserves a region of its own, as well as an in-depth analysis of the driving factors behind its asphalt plants' performance, as non-climate factors such as fuel type availability may be more meaningful. It is recommended that future data collection include Puerto Rico both for its own sake and to compare against Hawaii.

The first iteration of data collection showed a potential difference in A3 values for the states of Alabama and Utah from their respective climate regions. As found before, the average of Utah A3 values does not significantly differ from the Dry Freeze average or national average. Confidence in this statement has increased as sample size has increased, from n=7 to n=16 participating sites in Utah, and the Dry Freeze characterization is now based on n=70 sites, up from n=30.

Previous analysis of Alabama A3 data revealed a statistically significant increase above the average GWP for Wet No freeze. Expanding data sets in Alabama (n=29 to n=37) and the Wet No Freeze region (n=134 to n=187) nullified this effect from both an increase in the average Wet No Freeze and a decrease in Alabama A3 values. However, Alabama still maintains a statistically higher average than the national average, making a strong argument for the adoption of regional values.

Process for Future Updates

As data collection, processing, and reporting for both EPD and benchmarking data are performed using the Emerald Eco-Label tool, future updates to this benchmark can be made at reasonable intervals. At a minimum, this will be concurrent with PCR updates to reflect any significant changes in the PCR, which happens at least every five years. Ideally, updates should occur more frequently when market conditions allow or interim updates to the PCR drive the need for new revised data. Preferably, these updates will occur as often as possible while balancing the burden of data collection and reporting, with the goal of continually increasing participation. Updates may provide value to the industry by including more specific climate region data, updates to primary energy use, or reflect efforts by industry to reduce impacts.

It was recently announced that NAPA was selected to receive a grant from the EPA. A portion of this grant will be developing additional benchmarks, filling in data gaps which would allow for a more robust GWP value, and standardizing mix classifications so more granular functional classifications can be developed with benchmarks.

7. DEVELOPING INDUSTRY AVERAGE BENCHMARKS

In the last section the benchmarking methodological framework was discussed. An analysis was conducted to establish RV for GWP for each of the life cycle stages A1, A2 and A3. The final step is to develop the national level industry benchmarks by simply adding up the GWP RV for the 20th, 40th percentiles, the median and the average for each of the stages. The relevant question is which GWP RVs to add up, particularly for the A1 life cycle stage where significant variation was identified across states making the national level sum less than representative.

Hence, the goal in this section is to establish a scheme for summing the individual life cycle stages in a way that the nuances identified in each of the stages is still reflected. As a result, the best path forward is to avoid a single national benchmark and to instead provide a ***national level benchmark regionalized by state.***

There are two primary pathways to establishing the benchmark values as follows:

- State level GWP RV by summing:
  a. A1 (from published EPDs) (Table 18 and Table 19)
  b. Benchmarking (BM) Data for (A2 + A3) (Table 21 and Table 22).
- State level GWP RV by summing:
  a. A1 (from US average BM Mixes) (Table 20)
  b. BM Data for (A2 + A3) (Table 21 and Table 22).

In addition, the above pathways are to be reported for mixes with NMAS <= 12.5 mm and NMAS > 12.5 mm.

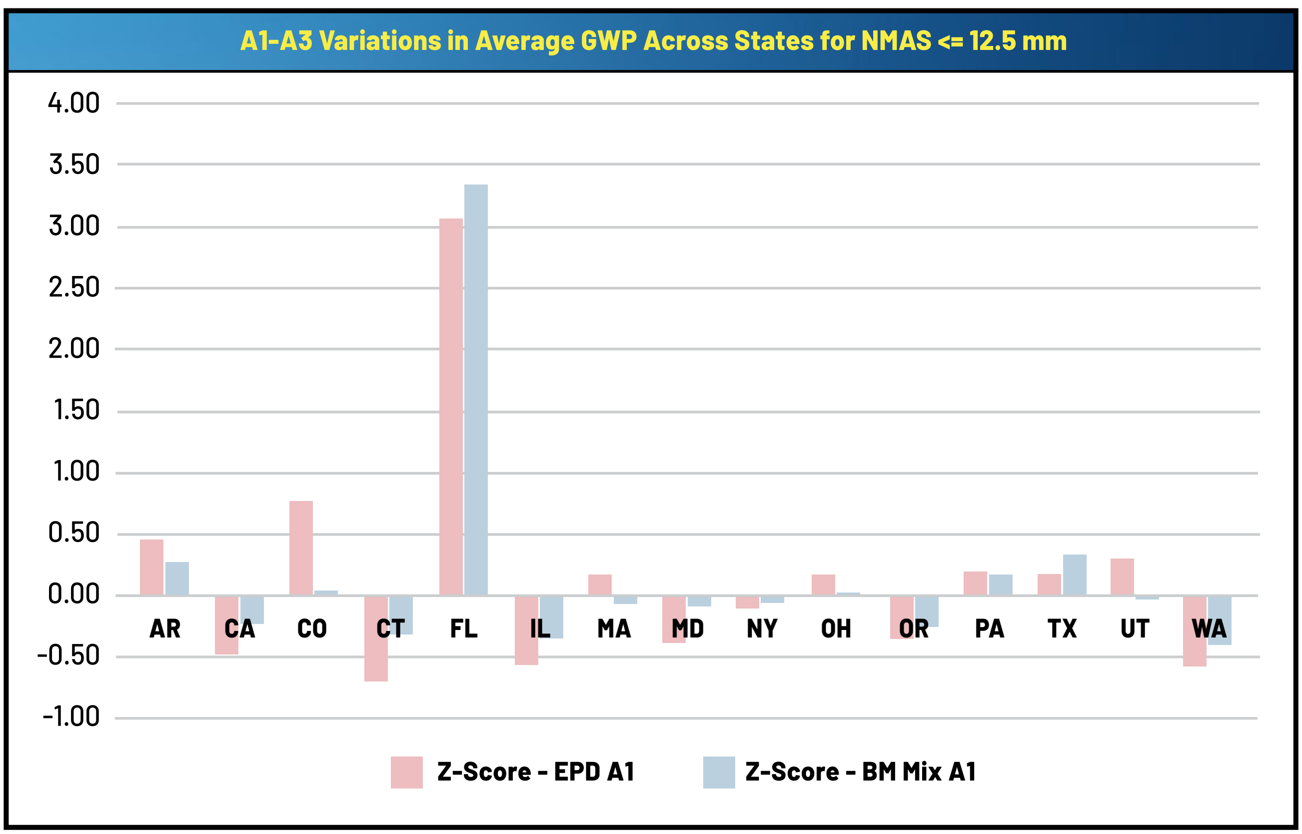

Figure 15. GWP Variations for A1-A3 benchmark for NMAS <= 12.5 mm for alternative A1 numbers

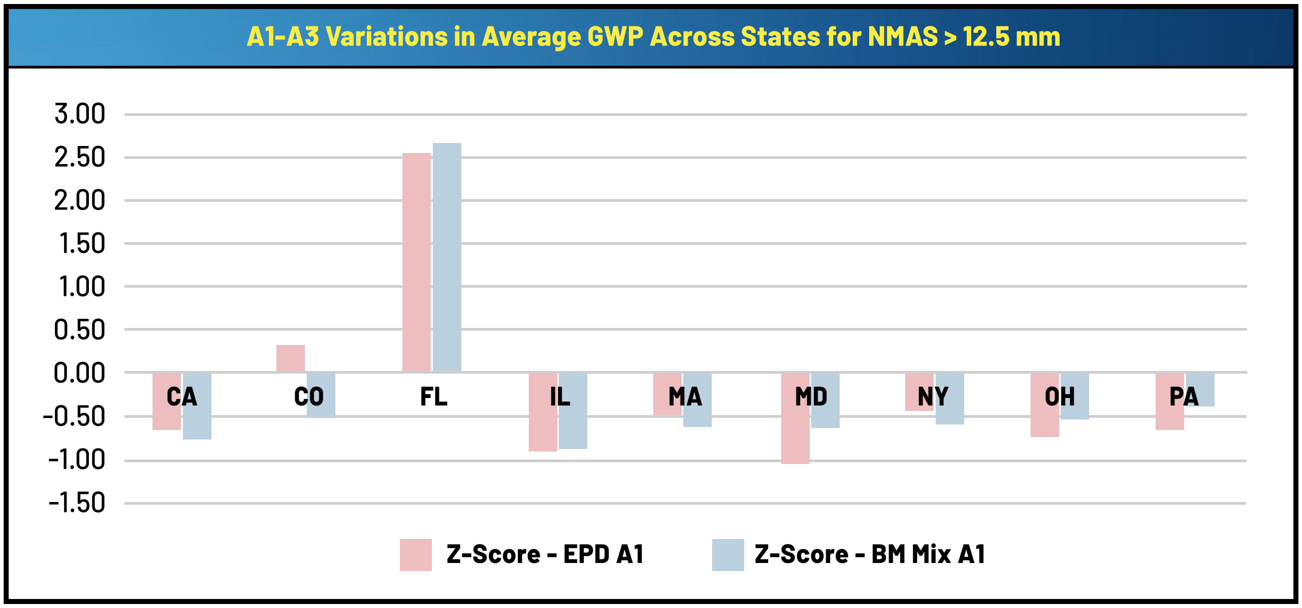

Figure 16. GWP Variations for A1-A3 benchmark for NMAS > 12.5 mm for alternative A1 numbers

The selection of data for A2 and A3 is based on the BM dataset and common to both pathways. However, there is a selection to be made on whether the A1 component should be from the BM Mixes discussed here or the EPD based state level data. Both the pathways were calculated for NMAS <= 12.5 mm and NMAS > 12.5 mm, and the state level GWP RV have been reported in Table 26 and Table 27, and Table 24 and Table 25, respectively. It is worth noting that there was not an exact match between the states with a reasonable number of EPDs (for A1) and states that had contribution to A2 and A3 benchmarking data. As a result, the number of states for which the benchmarks are reported are the ones that had both a reasonable number of EPDs and also had contributions to the benchmarking study for A2 and A3.

A *Z-value* for the GWP average reference value was calculated. The *Z-value* calculation used the same approach as in the State Level A1 Assessment analysis, with the goal of assessing variation from the mean of the state averages. For each of the A1 alternatives the *Z-values* for NMAS <= 12.5 mm and NMAS > 12.5 mm are illustrated in Figure 15 and Figure 16, respectively.

The key take-aways are as follows:

- In both cases, the GWP for Florida remains consistently high for both the data sets, reflecting the spike in Florida's A2 numbers. As the A2 component drives Florida's GWP, the impact of the A1 selection is not as significant.
- In the case of Colorado, where we have acknowledged the contribution of the A1 stage, there is a significant difference in the variation from average when using the more representative EPD based GWP RV than the BM Mix based GWP RV, clearly indicating that the use of the BM Mixes is not representative of the mix designs used in Colorado.
- Further assessment is required to line up the state level benchmarks to reflect the requirements and specifications.

It is also adequately clear that when developing a benchmark, it is crucial to ensure that the underlying data for A1, A2 and A3 should be adequately representative and regionalized. Methodologically some key takeaways from this analysis are:

- When benchmarking the A1 stage, mix designs should be classified into meaningful functional classes ideally associated with construction specifications. The classifications in this report are for the sake of methodology illustration. DOTs are expected to establish functional classes that adequately reflect their construction specifications.
- Any statistical parameter such as an average should be estimated from the calculated GWPs of a representative sample of mixes. It is OK to average GWPs, if each GWP is based on an actual set of mix designs.

$$GWP_{average} = \frac{1}{K}\sum_{k=1}^{K} GWP_k$$

Equation 3. Acceptable Calculation of GWP Reference

Where, GWP_k is the calculated GWP of the kth actual mix of the K mixes representing a functional classification. Percentiles are also to be estimated from the set of calculated GWP values, i.e., $\{GWP_k\}$.

- As a corollary, when mix design data and application contexts are not adequately available (as in this case), it is preferable to estimate reference values from EPD A1 GWP distributions, as expressed in column 2 of Table 3.
- **Avoid** calculating GWP reference values based on statistical estimates of mix designs. Hence, the following is **not preferred**.

$$GWP_{average} = (x_{binder}y_{binder} + x_{aggregate}y_{aggregate} + x_{RAP}y_{RAP})$$

Equation 4. Unacceptable Approach to Estimating GWP Reference Values

Where x_{binder}, $x_{aggregate}$ and x_{RAP} are averaged values from a set of mix designs, and are coefficients as represented in Equations 1 and 2.

All things considered, in the context of this report, in Table 3, the reference values recommended for any meaningful use are expressed in column 2 of Table 3.

Summary Guidelines

In summary, the guidance for a DOT developing A1 benchmarks can be summarized by following these steps:

- Establish mix categories to reflect functional classifications in construction specifications.
- For each mix category identify representative mix designs ensuring that a wide range of mixes are identified and represented.
- For each mix design identify the proportions of constituents (x_i in Equation 1) and ensure that they meet the mass balance as in Equation 2.
- Using Equation 1 and the GWP intensity factors for each constituent as listed in Table 7, calculate the GWP for each of the mixes in the representing each of the categories.
- Use Equation 3 to estimate statistical and percentile reference values for GWP. Avoid using Equation 4.

Similarly, for A2 and A3 reflect regional trends and constraints through appropriate benchmarking data collection. Indeed, EPD data can be an adequate source for A2 and A3 data. It is strongly recommended that, as in this study, the analysis be conducted for each of the three life cycle stages to identify any trends that could create undue advantages or disadvantages for market participants.

8. SUMMARY AND RECOMMENDATIONS

Using the current set of published EPDs to create national thresholds without regard for regional differences or material specifications results in GWP limits that unfairly burden some regions of the country. This approach should be avoided until EPD creation has happened at a large enough scale to fully represent the industry.

Agencies looking to procure low embodied carbon asphalt mixtures under Sections 60503 and 60506 of the IRA should establish thresholds for each life cycle phase (A1, A2, and A3) that are appropriate for the agency's geographic location and material specifications. These thresholds can be added up for each agency mix type to give a single set of embodied carbon thresholds at the 20th percentile, 40th percentile, and average levels that is appropriate to the region, state, and mixture design specifications. Benchmarking by life cycle phase allows for selection of lower carbon materials while not preventing a region or state from accessing IRA funds because of the influence of factors such as agency specifications, geology, and climate, that are beyond the control of the contractor.

Limitations of this study

This study is a first attempt at establishing regionalized benchmarks for the asphalt mixture industry. The emphasis and primary takeaway from this report is the proposed underlying methodology that serves as a first step and is expected to evolve over time as the use of EPDs mature in the industry and more insights are gained on their role in public procurement. Hence, the limitations discussed in this section are also possible next steps in improving the benchmarking process. In discussing the limitations, the underlying principle is articulated to provide context for future steps. The primary limitations can be discussed as follows:

As a principle, representativeness of the data samples analyzed is critical to developing useful benchmarks. At this time, all regions/states have not been represented equally or adequately, though representation was improved through the second round of data collection in Q1 of 2024. Alaska, North Dakota, and Rhode Island, and the territories had no participating locations, while 10 other states had fewer than three sites. Additionally, some states may still fall short of representativeness due to voluntary reporting practices. While statistical tests can be conducted to assess the likely skew in the data, at present due to a lack of uniform adoption of EPDs it is difficult to establish the skew. That said, the analysis does reveal important findings such as the impact of geology on the A2 impacts reported due to a lack of material availability. In the phase two of data collection, a deeper data pool can help validate (or rectify) current findings, assess skew in reporting and/or shed new light on other relevant trends.

In this methodology, A1 has been treated as a definite quantity because of the prescriptive nature of the current PCR and the predominant use of average LCI for upstream materials like asphalt binder. As EPDs for upstream suppliers become more available, this approach may need an amendment. As a principle, it will still be true that the upstream impacts (A1) are a definite and calculable quantity given the design and selection of materials. Indeed, for a given mixture design, a contractor can intentionally select between two asphalt binder producers based on their EPDs to deliver a mixture with target GWP. Similar selections can be made with respect to selection of additives. In effect, the A1 GWP component is likely to become more competitive than it is now. The future benchmarking process will have to account for availability of supply chain specific EPDs for different upstream materials to develop intervals for A1 benchmarks. The fundamental principles of (i) allowing contractors the ability to compete based on selection of supply chain partners, and (ii) recognizing that A1 impacts are an outcome of choice that should not be treated as a random variable will still apply.

Finally, the benchmarking process is driven by EPA's Interim Determination that only accounts for A1-A3 GWP values and does not explicitly account for performance outcomes. Clearly, the materials procured by a DOT will have to meet design requirements, negating the possibility of a race to the bottom and selection of mixtures that are competitive on GWP only. However, the current framework with its emphasis on selecting lower GWPs discourages contractors from using additives and other material science innovations that deliver significant performance improvement with potentially higher GWPs. Future work will have to account for a benchmarking framework that accounts for GWP in addition to mixture performance properties.

Conclusions and Recommendations for Future Work

Based on the analysis this report recommends the following:

- Impacts of upstream materials are dependent on mixture design specifications that are often outside the control of asphalt mix producers. Hence, the use of a baseline mixture with constituent-specific adjustment factors is recommended for estimating A1 impacts. The impacts of material choices are clearly communicated using this method while also reflecting sensitivities of a mixture's GWP to locally specified mixture design.
- Impacts due to the transportation of materials are dictated by availability of materials locally which in turn is a function of local geology. For example, states like Louisiana and Florida have significantly higher A2 impacts than any other regions due to a lack of locally available aggregates with sufficient quality for use in asphalt mixtures. Hence, the use of region-specific thresholds is recommended for the A2 life cycle phase.
- Impacts due to production vary to a smaller but statistically significant degree across different AASHTO climate regions. While A3 impacts are within the control of material producers, the recommendation is to develop thresholds that account for climatic variations.
- The analysis recommends the use of a representative data set when establishing thresholds for procurement, including an intentional sampling process that targets states and regions with limited participation so far.

The contribution of the benchmarking framework discussed in this study is that (i) it affords a web-based user-friendly data collection platform across different mixtures, (ii) can be scaled to include multiple regions, and (iii) can be updated over time to reflect changes in technology and other factors.

9. APPENDIX 1: ADDITIONAL DATA COLLECTION

Table 6. Additional data and metadata collection established during benchmarking activity.

Plant type
Whether the plant is portable
Rated Capacity
Drum diameter
Operating months per year
Operating days per week
Operating hours per day
Total operating hours
Whether operating hours is an estimate
Percent mixes modified with polymers
Short tons of mix modified with polymer
Average mix RAP %
Total RAP used
Quarry A: Total aggregate supplied
Quarry B: Total aggregate supplied
Quarry A: Total transport by mode
Quarry B: Total transport by mode
Electricity meter type
Electricity meter sharing by operation
Whether electricity meter data is from billing
Gas meter type
Gas meter sharing by operation
Whether gas meter data is from billing
Notes

10. APPENDIX 2: GWP INTENSITY FACTORS FOR A1

Data gaps for A1 materials are being filled at an exceptional rate as upstream suppliers work to quantify their own impacts. Below is an incomplete list of suppliers who have created product specific EPDs for inclusion in the calculation of the environmental impacts of asphalt mixtures and links to their EPDs.

Cargill: https://www.cargill.com/bioindustrial/anova-asphalt
Ingevity: https://www.ingevity.com/sustainability/sustainability-resource-library/
Surface Tech: https://surface-tech.com/documents-all/

Table 7. GWP Intensity Factors for Upstream Materials used to Calculate A1 GWP

A1 Material	GWP Intensity kg CO_2e/tonne (*/shtn)
Neat Binder	631.51 (573.06)
3.5% SBS Modified Binder	758.71 (688.49)
0.5% PPA Modified Binder	649.24 (588.98)
8% GTR Modified Binder	616.17 (558.98)
SBS Modifier	Forthcoming
Lime	1388.4 (1259.9)
RAP	0.781 (0.710)
Aggregate (USLCI, prescribed)	1.94 (1.761)
Aggregate (forthcoming, explosive mining)	5.32 (4.83)
Aggregate (forthcoming, non-explosive mining)	3.76 (3.42)
Cargill Anova 1501 WMA Cargill Anova 1815 Rejuv.	1594 (1446) 1288 (1168)
Ingevity Evotherm M1	2650 (2404)
Surface Tech AceXP Surface Tech AQU	6134 (5563) 7820 (7094)
[Additional Future Ingredient types]	....

11. APPENDIX 3: STATISTICAL SUMMARIES & TESTS

Appendix 3 report the typical summary statistics of mean, standard deviation, and confidence interval (on the mean) for each grouping discussed in this report. It also contains the outcomes of the statistical tests performed (not including initial screening level analysis). All comparisons were performed using a two-tailed t-test. P-values are reported in the tables below, where $p < 0.05$ was considered significant. All values reflect the second round of data from Q4 of 2023 and of 2024.

Table 8. Summary statistics of benchmarking A3 data, climate regions (all values in kg CO_2e / metric tonne)

Category	Wet No Freeze	Wet Freeze	Dry No Freeze	Dry Freeze	Nationwide
Count (N)	187	201	68	70	526
Mean	28.72	25.00	24.04	25.14	26.22
Standard Deviation	11.28	5.99	5.35	6.57	8.47
Confidence Interval	1.63	0.83	1.29	1.57	0.73

Table 9. Summary statistics of benchmarking A2 data (all values in kg CO_2e / metric tonne)

Category	All	Minus FL + LA	Just FL	Just LA
Count (N)	522	481	35	6
Mean	9.6	6.2	54.5	40.1
Standard Deviation	14.9	8.2	32.9	19.4
Confidence Interval	1.3	0.7	11.3	20.3

Table 10. Summary statistics of benchmarking A3 data, Alabama, Utah, & Hawaii only, (all values in kg CO_2e / metric tonne)

Category	Alabama A3	Utah A3	Hawaii A3
Count (N)	37	16	6
Mean	30.0	26.6	77.6
Standard Deviation	7.3	7.7	17.3
Confidence Interval	2.4	4.1	18.2

Table 11. T-test p values for benchmarking A3 data, climate regions vs each other and nationwide

Category for comparison	Wet No Freeze	Wet Freeze	Dry No Freeze	Dry Freeze	Nationwide
Count (N)	187	201	68	70	526
Wet No Freeze	n/a	0.0001	0.0002	0.0019	0.0060
Wet Freeze	....	n/a	0.2183	0.8744	0.0302
Dry No Freeze	....	....	n/a	0.2827	0.0043
Dry Freeze	....	....	....	n/a	0.2173

Table 12. T-test p values for benchmarking A3 data climate regions and nationwide vs. published EPDs A3 data

Category for comparison	Wet No Freeze	Wet Freeze	Dry No Freeze	Dry Freeze	Nationwide
Count (N)	187	201	68	70	526
All Published EPDs A3 (n=1070)	8.02E-06	0.75	0.23	0.72	0.0009

Table 13. T-test p values for benchmarking A3 data, Alabama, Utah, and Hawaii vs. local climate regions and nationwide

Category for comparison	Wet No Freeze	Dry Freeze	Nationwide
Count (N)	187	70	526
Alabama A3 (N=37)	0.3821	....	4.15E-03
Utah A3 (N=16)	....	0.5010	0.8621
Hawaii A3 (N=6)	0.0009	....	7.55E-04

Table 14. T-test p values for benchmarking A2 data, climate regions vs nationwide

Category for comparison	Wet No Freeze	Wet Freeze	Dry No Freeze	Dry Freeze
Count (N)	187	201	68	70
All Benchmark A2 (N=526)	0.0012	5.79E-06	0.0001	0.0004

Table 15. T-test p values for benchmarking A2 nationwide vs. published EPDs A2 data

Category for comparison	Nationwide A2
Count (N)	526
All Published EPDs A2 (n=1070)	0.02

Table 16. T-test p values for benchmarking A2 data, Florida, Louisiana, and all but FL & LA vs. nationwide

Category for comparison	All except Florida & Louisiana	Florida	Louisiana
Count (N)	481	35	6
All Benchmark A2 (n=526)	3.81E-04	1.03E-06	0.0368

Table 17. T-test p values for published EPD A1 data, Colorado vs nationwide

Category for comparison	Colorado EPDs A1
Count (N)	88
All Published EPDs A1 (n=1070)	2.60E-32

12. APPENDIX 4: EXAMPLE STATE A1 GWP TABLES

A1 reference values (RV) from states based on the published EPD data in Emerald Eco-Label tool classified by NMAS size and the benchmarking reference mixes ("BM Mixes"). All GWP in the following tables are expressed in Kg of CO_2e. per tonne of asphalt mixture.

Table 18. A1 GWP RV for NMAS > 12.5 mm using EPD data as available

A1 GWP RV by NMAS > 12.5mm and States Where EPD Data Available					
State	**N**	**20%**	**40%**	**50%**	**Avg**
CA	52	26.40	27.18	27.60	28.59
CO	22	39.06	40.31	40.42	40.16
DC	27	20.02	20.80	21.12	23.40
FL	25	18.10	22.93	24.54	24.45
IL	21	23.29	24.33	25.60	26.32
MA	21	23.60	28.14	30.19	28.42
MD	23	17.57	19.46	19.86	20.11
NJ	33	19.58	27.42	29.66	29.01
NV	24	45.13	48.34	48.34	47.05
NY	45	21.05	28.05	30.29	29.33
OH	34	19.93	21.76	22.73	23.39
PA	132	19.24	20.66	22.41	22.30
VA	16	22.44	23.64	23.65	25.37

Table 19. A1 GWP RV for NMAS <= 12.5 mm using EPD data as available

A1 GWP RV by NMAS <= 12.5mm and State Where EPD Data Available					
State	**N**	**20%**	**40%**	**50%**	**Avg**
AR	41	31.44	33.77	34.70	38.16
AZ	30	37.93	40.20	40.85	45.45
CA	79	28.49	30.74	30.75	31.29
CO	64	42.69	44.83	46.14	46.62
CT	16	25.83	27.47	29.29	29.13
DC	33	27.85	29.23	29.31	30.97
FL	414	22.84	26.96	29.42	30.85
ID	20	31.78	35.49	36.92	36.35
IL	39	28.61	30.46	31.83	31.72
MA	56	34.72	36.08	36.69	38.88
MD	33	22.36	24.27	27.59	30.54
MO	57	28.12	29.80	30.69	39.46
NH	17	31.03	33.51	33.78	34.72
NJ	20	29.86	35.13	36.67	45.58
NV	20	46.98	50.03	51.18	49.96
NY	59	28.16	35.09	35.63	34.45
OH	49	33.11	35.11	37.00	37.53
OK	35	25.35	29.22	30.75	31.62
OR	15	29.84	34.09	34.58	33.76
PA	132	29.37	32.00	32.63	35.41
TX	65	28.79	30.68	31.82	32.66
UT	43	31.92	34.42	37.08	40.19
VA	29	28.05	29.12	29.37	33.19
WA	44	29.11	30.87	31.99	32.40

Table 20. US Averages for A1 GWPs (i) Based on EPD data and (ii) Based on BM Mixes

US Weighted Average GWP RV for Modified and Unmodified Asphalt Binders from EPD

	NMAS > 12.5mm	NMAS <= 12.5mm
20th percentile	21.41	27.88
40th percentile	24.07	31.24
Median	25.21	32.72
Average	27.30	34.57

US Weighted Average GWP RV for Modified and Unmodified Asphalt Binders from Benchmarking (BM) Mix Selection

	NMAS > 12.5mm	NMAS <= 12.5mm
20th percentile	21.49	27.90
40th percentile	24.14	31.24
Median	25.55	32.72
Average	26.02	34.57

13. APPENDIX 5: EXAMPLE STATE A2, A3 GWP TABLES

A1 reference values (RV) from states based on the collected benchmarking data ("BM Data") from across the country for A2 and A3. All GWP in the following tables are expressed in Kg of CO_2e. per tonne of asphalt mixture.

Table 21. A2 GWP Reference Values by State using Benchmarking Data

A2 GWP RV by State					
State	**N**	**20%**	**40%**	**50%**	**Avg**
AL	37	1.38	2.69	3.75	6.54
AR	6	2.10	6.88	9.97	10.24
CA	42	0.95	1.41	2.08	3.80
CO	20	1.32	2.16	2.79	5.71
CT	7	1.55	1.90	2.36	2.94
FL	35	8.11	26.69	36.32	54.56
HI	6	0.87	1.03	1.42	37.04
IL	6	1.20	1.48	2.10	2.50
IN	11	2.39	3.91	4.16	7.33
KY	8	1.26	1.74	2.01	4.85
LA	6	22.54	33.15	39.43	40.05
MA	14	0.93	2.88	3.74	5.07
MD	6	1.49	4.44	5.30	5.92
MI	7	2.97	4.94	4.97	5.57
MN	21	0.99	2.66	3.06	4.76
NC	27	1.47	3.75	4.30	4.78
ND	6	10.74	13.40	13.44	12.48
NY	36	1.43	2.62	3.87	4.95
OH	20	1.12	1.51	2.01	6.19
OR	11	0.82	1.50	2.04	2.01
PA	25	2.60	3.39	3.71	8.52
SC	17	1.19	3.55	4.89	5.12
TN	16	2.68	3.63	3.84	5.17
TX	33	3.50	9.08	10.76	10.22
UT	16	1.45	3.06	3.64	3.85
WA	9	0.61	1.13	1.50	2.67
WI	16	1.98	3.04	3.08	3.45

Table 22. A3 GWP Reference Values by State using Benchmarking Data

A3 GWP RV by State					
State	**N**	**20%**	**40%**	**50%**	**Avg**
AL	37	24.84	28.38	29.28	30.01
AR	6	22.95	23.76	24.09	24.74
CA	42	17.80	21.39	22.53	23.33
CO	20	19.81	22.01	24.79	25.59
CT	7	19.94	22.10	23.83	22.95
FL	35	23.64	25.82	26.32	28.32
HI	6	62.49	80.30	82.41	77.62
IL	6	22.41	23.18	23.26	22.95
IN	11	22.65	23.79	24.30	24.05
KY	8	18.00	23.32	24.94	25.38
LA	6	25.86	25.95	26.63	27.92
MA	14	22.50	23.93	24.99	24.61
MD	6	21.70	23.08	24.57	23.45
MI	7	24.57	25.37	25.56	26.11
MN	21	22.20	22.92	23.56	24.42
NC	27	20.91	23.31	24.80	24.96
ND	6	22.01	23.50	24.78	25.09
NY	36	19.56	21.44	23.50	24.96
OH	20	21.33	22.84	23.71	24.85
OR	11	21.70	23.75	24.52	24.71
PA	25	20.43	23.10	24.79	24.93
SC	17	21.93	23.47	25.40	25.15
TN	16	24.47	24.82	26.00	27.49
TX	33	23.47	24.90	25.55	25.72
UT	16	20.26	23.33	25.18	26.57
WA	9	19.42	21.11	21.87	21.80
WI	16	19.90	20.93	21.77	22.29

Table 23. GWP Reference Values by Climate Region.

A2 by Climate Region	N	20%	40%	50%	Avg
Dry Freeze (DF)	70	1.20	2.21	2.97	5.63
Dry No Freeze (DN)	68	1.04	2.20	2.85	5.29
Wet Freeze (WF)	201	1.43	2.63	3.36	5.37
Wet No Freeze (WN)	183	2.15	4.89	7.01	18.16

Note: *Use of AASHTO Climate Region is not a recommended strategy for A2 GWP Reference Value regionalization and no claim of statistical significance or meaningful difference due to climate is made here.*

A3 by Climate Region	N	20%	40%	50%	Avg
Dry Freeze (DF)	70	20.16	22.26	24.26	25.15
Dry No Freeze (DN)	68	19.64	22.57	23.67	24.05
Wet Freeze (WF)	201	20.93	23.08	23.79	25.01
Wet No Freeze (WN)	183	23.16	25.29	26.15	27.44

14. APPENDIX 6: EXAMPLE NATIONAL GWP BENCHMARKS

GWP reference values (RV) from states based on two scenarios:

- GWP = A1 (from published EPDs) +BM Data for (A2 + A3)
- GWP = A1 (from BM Mixes) +BM Data for (A2 + A3)

For NMAS classification of <= 12.5 mm and > 12.5 mm. All GWP in the following tables are expressed in Kg of CO_2e. per tonne of asphalt mixture.

Table 24. State Level GWP Benchmarks for NMAS > 12.5 mm, using EPDs for A1

For NMAS > 12.5 mm GWP = A1 (from EPD) +BM Data for (A2 + A3)				
State	**20%**	**40%**	**50%**	**Avg**
CA	45.16	49.98	52.21	55.72
CO	60.19	64.48	68.00	71.46
FL	49.85	75.44	87.19	107.32
IL	46.91	49.00	50.96	51.78
MA	47.03	54.96	58.92	58.10
MD	40.77	46.98	49.72	49.49
NY	42.04	52.11	57.66	59.24
OH	42.38	46.11	48.45	54.43
PA	42.28	47.15	50.91	55.76

Table 25. State Level GWP Benchmarks for NMAS > 12.5 mm, using BM Mixes for A1

For NMAS > 12.5 mm GWP = A1 from BM Mixes + BM Data for (A2 + A3)				
State	**20%**	**40%**	**50%**	**Avg**
CA	40.25	46.94	50.16	53.15
CO	42.62	48.31	53.13	57.33
FL	53.25	76.65	88.19	108.90
IL	45.11	48.81	50.92	51.48
MA	44.92	50.95	54.29	55.70
MD	44.69	51.66	55.42	55.39
NY	42.49	48.20	52.93	55.93
OH	43.94	48.49	51.26	57.06
PA	44.53	50.63	54.06	59.47

Table 26. State Level GWP Benchmarks for NMAS <= 12.5 mm, using EPDs for A1

For NMAS <= 12.5 mm GWP = A1 from BM Mixes + BM Data for (A2 + A3)

State	20%	40%	50%	Avg
AR	56.48	64.41	68.77	73.14
CA	47.24	53.55	55.36	58.42
CO	63.82	69.00	73.72	77.92
CT	47.32	51.47	55.49	55.02
FL	54.60	79.47	92.07	113.72
IL	52.23	55.12	57.20	57.18
MA	58.15	62.90	65.43	68.56
MD	45.55	51.79	57.46	59.91
NY	49.16	59.15	63.00	64.36
OH	55.56	59.46	62.71	68.57
OR	52.36	59.34	61.14	60.48
PA	52.40	58.49	61.14	68.86
TX	55.77	64.66	68.12	68.60
UT	53.64	60.81	65.90	70.62
WA	49.15	53.11	55.37	56.88

Table 27. State Level GWP Benchmarks for NMAS <= 12.5 mm, using BM Mixes for A1

For NMAS <= 12.5 mm GWP = A1 from BM Mixes + BM Data for (A2 + A3)				
State	**20%**	**40%**	**50%**	**Avg**
AR	52.94	61.89	66.79	69.55
CA	46.66	54.05	57.33	61.70
CO	49.03	55.41	60.31	65.88
CT	49.39	55.24	58.92	60.46
FL	59.66	83.75	95.37	117.44
IL	51.52	55.91	58.09	60.03
MA	51.33	58.06	61.46	64.25
MD	51.10	58.76	62.59	63.94
NY	48.90	55.30	60.10	64.48
OH	50.35	55.60	58.44	65.61
OR	50.42	56.49	59.28	61.29
PA	50.94	57.73	61.23	68.02
TX	54.88	65.22	69.03	70.51
UT	49.62	57.63	61.54	64.99
WA	47.94	53.48	56.10	59.04