CLF Embodied Carbon Toolkit for
Roadway Infrastructure

PART II:

Accounting for Embodied Carbon in Roadway Infrastructure

CLF Carbon Leadership Forum

Carbon Leadership Forum

Accounting for Embodied Carbon in Roadway Infrastructure

Embodied carbon refers to the greenhouse gas emissions generated during the extraction, production, transportation, placement, repair and disposal processes for all materials used to build and maintain roadways. Embodied carbon accounting is critical to identify key contributors to embodied carbon, evaluate the highest-impact, most cost-effective reduction opportunities, and track progress toward a net-zero carbon future. ***Life cycle assessment (LCA)*** is the agreed-upon method for embodied carbon accounting. This document provides an overview of LCA in the context of roadway infrastructure.

Life cycle assessment (LCA)

LCA is a standardized methodology for quantifying the environmental impacts of a process, product, or system (e.g. building or roadway) over its entire life cycle, from material extraction ("cradle") to disposal ("grave"). LCAs globally follow a family of standards created by the International Organization for Standardization (ISO) through an open stakeholder development process. ISO 14040 and ISO 14044, describe the principles and framework for LCA and lay out basic requirements. This toolkit focuses on LCA related to roadway infrastructure, construction materials, and related processes to manufacture and build roadways.

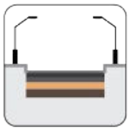
Using LCA, greenhouse gas emissions are added up across the life cycle and reported as *global warming potential (GWP)*. GWP is expressed in carbon dioxide equivalents (CO_2e) and is the agreed upon metric for reporting embodied carbon. LCAs can also include other environmental impacts, such as acidification, eutrophication, ozone depletion, and smog formation.

Levels of LCA: Product vs. Roadway Element vs. Whole Roadway LCA

LCA can be performed on different levels of a system and include different LCA stages depending on the scope and goal of the LCA. For roadways, three main hierarchical levels of LCA can be defined:

Product/material-level LCAs account for the environmental impacts of a roadway product, such as emulsified asphalt, hot mix asphalt, ready mix concrete, precast concrete elements (e.g., bridge girder, PVC pipes), aggregate borrows, etc. Product-level LCA results are typically communicated via ***Environmental Product Declarations (EPDs),*** which also go through a third party verification process. See pg. 3 for more on EPDs. The most common EPDs related to roadway materials are concrete and asphalt mixes.

Roadway element/feature-level LCAs account for a collection of materials used to build a roadway element, such as pavement structures (consisted of hot mix asphalt, sublayers, etc.), bridge structures, traffic control systems, traffic safety features, stormwater management systems, among others. This type of LCA similar to evaluating an assembly (like a wall), rather than a single material, in a building.



Whole roadway LCAs account for all roadway elements necessary to deliver the construction project. We are adopting similar terminology to the building industry (i.e., whole building LCA) and using the term *whole roadway LCA (WRLCA)* for this type of LCA.

For a pavement or roadway-level LCA, results are normally reported for in total and per unit of area (e.g., CO_2e per lane-miles, square foot, or square meter). For a product-level LCA, results are normally reported per mass or volume of the product (e.g., CO_2e per ton of hot mix asphalt or cubic yards of concrete).

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KEY TERMS

Embodied carbon
GHG emissions generated during the extraction, production, transportation, placement, repair and disposal processes for all materials used to build and maintain roadways.

Life cycle assessment (LCA)
LCA is a standardized methodology (ISO 14040:2006 and ISO 14044:2006) developed to quantify the environmental impacts of systems (e.g., buildings, roadways), products (e.g., asphalt, concrete), and processes (e.g., equipment operation) over their entire life cycle, from the extraction of raw materials (i.e., cradle) to the disposal of final products and services (i.e., grave.)

Roadway infrastructure (roadways)
Streets, highways, bridges, tunnels, and their constituents such as pavements, sidewalks, traffic signals, guardrails, lighting systems, stormwater management systems, sanitary water conveying systems, and embankments, among others.

From Cradle-to-Grave: Stages of an LCA

The life cycle of a product or project is broken into modules (A1, A2, etc.) that are grouped into 5 primary stages, in accordance with ISO 21931 and EN 15804:

- **Product stage** (modules A1 - A3)
  - **A1**: Production of raw materials such as asphalt binder, portland cement, aggregates, lime, iron, additives, etc.
  - **A2**: Transport of materials from the point of extraction to the manufacturing facilities using trucks, rails, barges, etc.
  - **A3**: Manufacturing of building products such as hot mix asphalt, ready mix concrete, precast concrete, steel, etc.
- **Construction stage** (modules A4 and A5)
  - **A4**: Transport of products from manufacturing plants/factories to the construction job site using road, rail, or water transportation.
  - **A5**: Construction activities on-site using mechanical or hand tools, such as burning fossil fuels to operate construction equipment such as pavers, material transfer vehicles, rollers, compactors, loaders, etc. The effect of construction on traffic network (i.e., work zone traffic) can also be included under this module.
- **Use stage** (modules B1 to B7)
  - **B1**: Emissions produced during the use phase of a roadway such as heat island effect, cementitious material carbonation, and due to stormwater runoff.
  - **B2-5**: Production, transportation, and construction of materials used to keep roadway functional during its lifetime. Typical roadway treatments include but are not limited to patching, crack sealing, concrete panel replacement, mill-and-fill, fog sealing, chip sealing, full-depth reclamation, cold and hot in-place recycling, etc.
  - **B6**: Energy use mainly in the form of electricity (e.g., roadway lighting, traffic signal operation, etc.) and additional fossil fuel consumption from vehicles due to tire-pavement friction (i.e., rolling resistance.)
- **End-of-life** stage (modules C1 to C4)
  - **C1**: Removing of out of service roadway products using mechanical or hand tools. For example, pavement milling, crack-and-seat, removing guardrails, etc.
  - **C2**: Transport of demolished materials to processing facilities or landfills.
  - **C3**: Processing of waste materials for recovery, such as crushing removed concrete
  - **C4**: Impacts from material disposal (e.g. landfill construction and operation)
- **Beyond system boundary** stage (module D)
  - Loads and benefits from materials reuse (e.g., avoided waste transport), recycling (e.g., avoided virgin material consumption), and energy recovery (e.g., landfill gas capture).

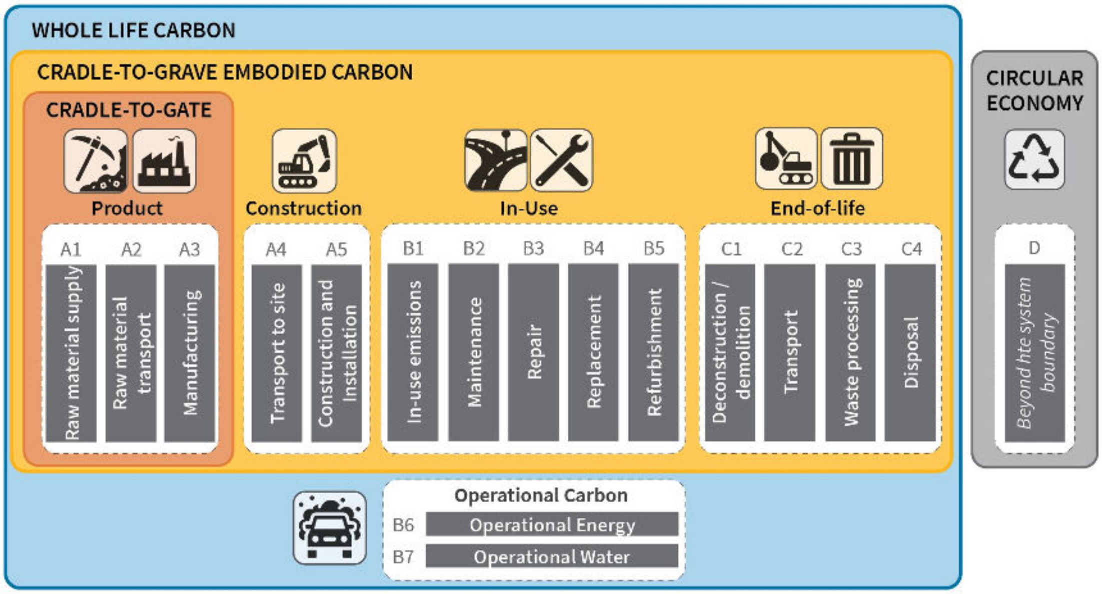

Figure 1. Snapshot of an LCA framework for roadway construction indicating different LCA modules and stages. © *Carbon Leadership Forum*

Product/Material-Level Embodied Carbon Accounting:

Environmental Product Declarations (EPDs)

An environmental product declaration (EPD) is a standardized means of reporting the environmental impacts associated with the manufacture or production of materials based on the results of an LCA. EPDs are third-party verified and governed by standard procedures established by product category rules (PCRs).[1] At a minimum, EPDs must be cradle-to-gate (i.e., include A1 to A3), but their scope varies (see Figure 2).

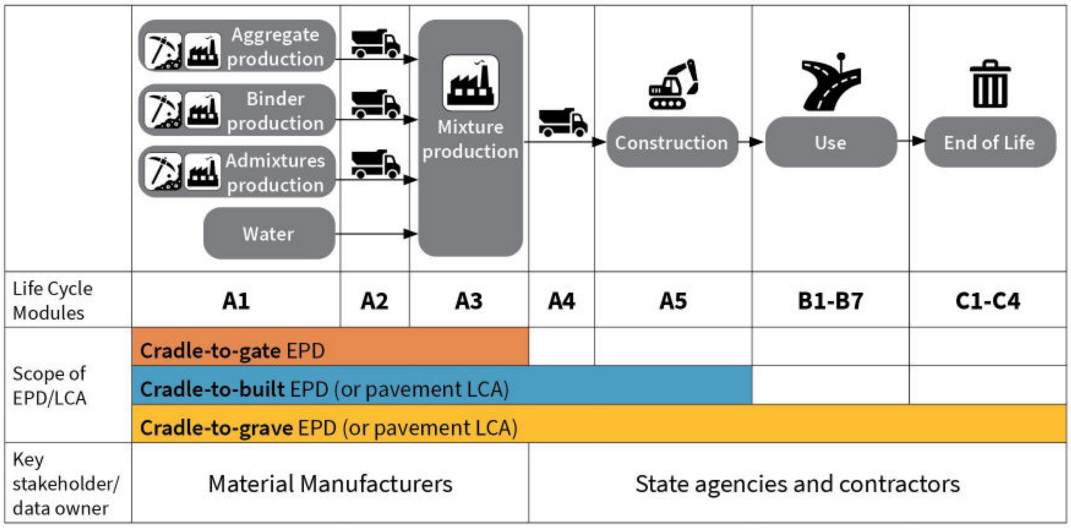

Figure 2. Life cycle stages included in EPDs or pavement LCA with different scope, based on on EN 15804. Image adapted from: Rangelov M, Dylla H, Harvey J, Meijer J, Ram P. FHWA *Tech Brief: Environmental Product Declarations - Communicating Environmental Impact for Transportation Products*, 2021.

Types of EPDs

EPDs vary in their specificity regarding the type(s) of products they cover, the number of facilities they represent, and the background data used to model upstream processes. For example, some EPDs report results based on one manufacturing facility only (referred to as "facility-specific") while others report results based on an average of data from multiple facilities.

Broadly, there are two main categories of EPDs:

- **Industry-wide EPDs,** also called industry-average EPDs, are calculated using data from multiple manufacturers. Ideally, industry-wide EPDs provide representative data of the market that can be used (i) to gauge the relative environmental performance of a specific product by comparing its impacts against the industry-wide EPD, or (ii) as a stand-in for a product before a specific product has been chosen during procurement or if no product-specific data is available. For example, the National Ready Mixed Concrete Association (NRMCA)'s industry-wide EPD for ready-mixed concrete.[2]
- **Product EPDs,** often called "product-specific EPDs," are calculated using data from a single manufacturer's product, and ideally can help procurement professionals choose between competing products based on their embodied carbon footprints or at least compare one to the industry-wide EPD for the same category type. For example, Granite Construction's EPD for a ½" hot mix asphalt with a PG64-22 asphalt binder.

Comparing EPDs

When used to compare products, it must be ensured that EPDs represent functionally equivalent products, follow the same PCRs, and include the same LCA stages. EPDs can help compare competing products (e.g., asphalt mix from producer A vs. asphalt mix from producer B) but are not meant to drive the decision of selecting one material type over another (e.g., concrete mix A vs. asphalt mix B) without considering their whole life cycle impacts (i.e., cradle-to-grave.)

REFERENCES

1 Harvey J, Meijer J, Ram P, Smith K. *Tech Brief: Environmental Product Declarations - Communicating Environmental Impact for Transportation Products.* Published online 2020.

2 The Athena Sustainable Materials Institute. *A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members - Version 3.2, Appendix C: NRMCA Member National and Regional LCA Benchmark (Industry Average) Report - V3.2.* National Ready Mixed Concrete Association (NRMCA); 2021:51-101.

The comparability of EPDs also depends upon the strength of the underlying standards and background data. The FHWA Sustainable Pavements Program is leading excellent research and resources, including advancing the quality of LCA background data.[3] As the use of EPDs and LCA continues to expand, data and methods will continue to improve.

EPD government policies and programs

Although the current practice for DOTs to reduce carbon is heavily focused on tailpipe emissions from vehicles using the infrastructure, the inclusion of embodied carbon from materials provides wider opportunities for reducing carbon and involving different stakeholders.

Inflation Reduction Act (IRA) Section 60506 also established the Federal Highway Administration (FHWA) Low-Carbon Transportation Materials Grants program, which will provide up to $2B in funding for the use of low carbon construction materials for state and local transportation agencies beginning in 2024. In 2022, FHWA also launched the Climate Challenge Initiative, a smaller funding initiative to quantify the impacts of sustainable pavements and demonstrate ways to reduce GHG emissions in highway projects using sustainable construction materials.

A growing number of states are also passing policies referred to as Buy Clean (coined by the California legislature[4,5]) that promote the procurement of construction materials with a lower embodied carbon footprint. EPDs are a core component of Buy Clean policies, as they are the required reporting mechanism for the embodied carbon (GWP) of products. As of January 2024, Buy Clean and similar low-carbon procurement policies have been passed in California, Colorado, Oregon, Minnesota, New York, New Jersey, and Maryland.

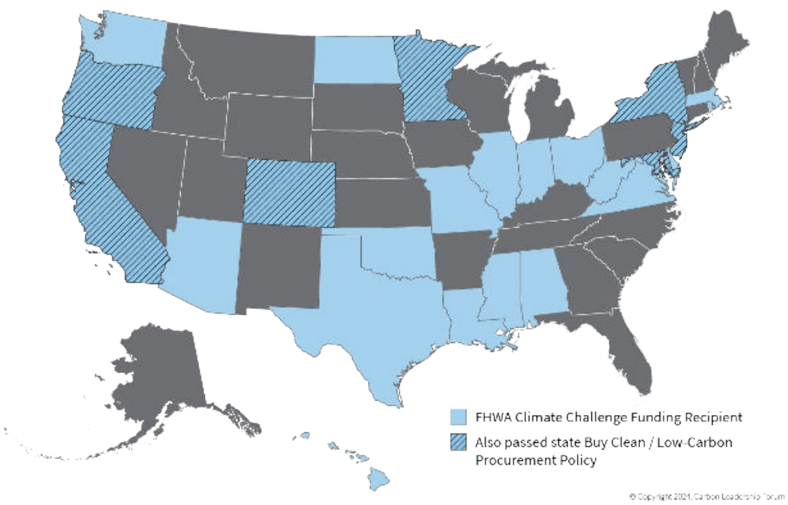

Figure 3. Map of state DOTs that were awarded FHWA Climate Challenge Funding (2022) and the states that have passed Buy Clean or similar policies requiring EPDs and maximum embodied carbon (GWP) limits on eligible projects. Data sources: FHWA, CLF Policy Toolkit Map. *© Carbon Leadership Forum*

Benchmarking materials

Once EPDs from different manufacturers with a representative sample population that captures variability in production are collected, material benchmarks (or baselines) can be determined. Material benchmarks should also capture the production volume of products. Thus, aggregation of product-specific EPDs that do not capture the production rate of products (i.e., how much of each product is actually produced) may not be the best alternative to create material-level benchmarks.

Median, 20th, and 80th percentiles are commonly used as benchmarks for typical, desirable, and achievable embodied carbon values. Many GWP limits in U.S. government programs are based on median or average values. For example, the recently published General Services Administration (GSA) standards set a limit of 85 $kgCO_2e$ per ton of asphalt produced.[6]

Most recently, the Carbon Leadership Forum has published an updated Material Baselines report[7] that represents the expected range of embodied carbon emissions for several construction materials. The National Asphalt Pavement Association (NAPA) is currently conducting an industry survey and collecting EPD data to establish industry average data for asphalt materials.

REFERENCES

3 Lewis M, Waldman B, Carlisle S, Benke B, Simonen K. *Advancing the LCA Ecosystem A Policy-Focused Roadmap for Reducing Embodied Carbon*. Carbon Leadership Forum; 2023.

4 Carbon Leadership Forum (CLF). *CLF Policy Toolkit 2: What Is a Buy Clean Policy?*; 2020.

5 *Buy Clean California Act*; 2017.

6 GSA. *Issuance of Low Embodied Carbon Concrete and Environmentally Preferable Asphalt Standards*. General Services Administration; 2022.

7 Waldman B, Hyatt A, Carlisle S, Palmeri J, Simonen K. *2023 Carbon Leadership Forum Material Baselines Baseline Report V2.* Carbon Leadership Forum; 2023.

Roadway Element/Whole Roadway Embodied Carbon Accounting:

Whole Roadway LCA and Pavement LCA

The most common LCAs related to roadway infrastructure are pavement LCAs. Pavement LCAs are more common than WRLCAs[8] because:

- Pavements are the medium with which vehicles interact the most and thus act as the intersection between tailpipe emissions and the physical infrastructure,
- Pavement LCA is less complex than WRLCA to conduct since it is limited to the three main constituents of pavement (asphalt, concrete, and crushed rocks), and
- Pavements are the largest contributor to the embodied carbon of roadways, responsible for 50% of the roadway construction costs and 28% of embodied carbon on average (Figure 2).

However, roadway LCAs benefit from expansion beyond pavements to draw a full picture of the embodied carbon footprint of the entire infrastructure.

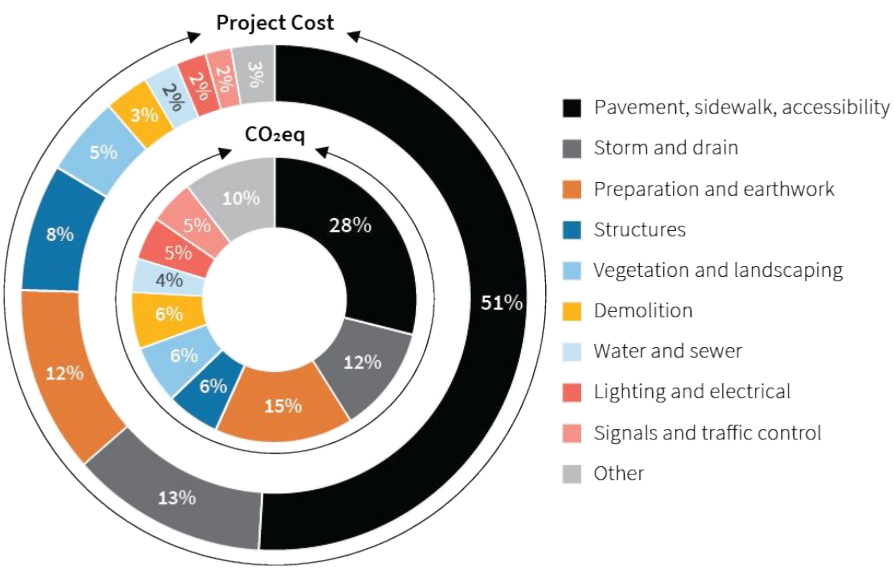

Figure 2. Breakdown of embodied carbon and project costs in roadway construction. Data source: Ashtiani MZ and Muench ST (2022)[9]. *© Carbon Leadership Forum*

Four Steps to Conduct a Whole Roadway or Pavement LCA

This section outlines the four mandatory steps of an LCA as defined by ISO 14040, with guidance specific to a whole roadway LCA or pavement LCA.

Step 1: Goal & scope

The **goal** of an LCA describes the primary purpose and objective of conducting an LCA, which is critical for informing the scope of the LCA. Some examples of goal statements[10] include:

- **Informing design and materials selection** by comparing their embodied carbon footprint of two options. For example, comparing the impact of using high-density polyethylene (HDPE) pipe vs. precast concrete, or concrete vs. asphalt pavements. The options must be *functionally equivalent*, which is described more below.

- **Meeting regulatory or voluntary requirements,** such as a state or local policy or a roadway sustainability rating system credit in Envision or INVEST that includes conducting LCA.

LCA **scope** determines 1) the functional description, 2) the functional and declared units, 3) the analysis period, 4) system boundaries, 5) allocation procedures, 6) environmental impact indicators, 7) limitations of the study, 8) data and data quality requirements, and (9) the critical review process and reporting requirements. The first four are discussed in more detail below.

REFERENCES

8 Harvey JT, Meijer J, Ozer H, Al-Qadi IL, Arash Saboori, Kendall A. [Pavement Life-Cycle Assessment Framework.] Federal Highway Administration (FHWA); 2016:244.

9 Ashtiani MZ, Muench ST. Using construction data and whole life cycle assessment to establish sustainable roadway performance benchmarks. *J Clean Prod*, 2022. doi:10.1016/j.jclepro.2022.135031

10 Bowick M, O'Connor J, Salazar J, Miel J, Cooney R. [National Guidelines for Whole-Building Life Cycle Assessment.]; 2022.

(1) Functional description

Describes the functions and services provided by the product or system, typically including:

- Roadway classification (e.g., local street, arterial, highway) and structure type (e.g., bridge, tunnel, pavement)
- Technical requirements, typically defined by local or state standard specifications
- Functional requirements, typically defined by the project's owner, such as pavement smoothness or other structural performance measures
- Pattern of use during the roadway life cycle, such as expected traffic level and load
- Reference service life. This is the expected life span of the roadway or its subset, typically expressed in number of years.
- Location of use. For roadways, this is the geographic location of the project, and for products, this is the location of the manufacturing facility.

(2) Functional and declared units

The functional description is expressed quantitatively as a *functional [or reference] unit*, which defines both the quantity of a material or system and the key performance aspects that define the function of the system over its full life cycle. An example for a roadway could be: *'new construction of a lane-mile of a highway's pavement structure in 2023 designed to meet the requirements of the Washington State DOT's standard specifications with a traffic loading of 3 million equivalent single axle load (ESAL) in Seattle, WA, with a service life of 40 years.'*

A *declared unit* may be used in lieu of a functional unit when the application and functional requirements of the product or system are uncertain or undefined, but only if (1) the LCA scope excludes B and C or (2) when comparing two materials that have identical functional performance and impacts in use and end of life. Physical quantities are typically used to define declared units (e.g. 1 kg of steel.)

To compare roadway LCA results, the studies **must** be functionally equivalent (i.e., have the same functional unit).

(3) Analysis period

A specific duration of time chosen for assessing the environmental impacts associated with different roadway design options. This period aims to capture the effects of the current decision and on subsequent maintenance, preservation treatments, rehabilitation, or reconstruction.

For new roadway construction, a minimum of 35 and a maximum of 100 years are commonly considered depending on material types and properties.[11] For roadway maintenance and rehabilitation, an analysis period of 15 to 50 years is commonly used.[12] The selection of analysis period has a large impact on LCA results beyond cradle-to-gate and is critical for making comparisons between design alternatives.

(4) System boundary

The physical scope of LCA, life cycle scope, and environmental impacts need to be determined in the LCA system boundary. Environmental impacts are elaborated in Step 3.

- The ***physical scope*** determines which roadway elements are included. Currently, most roadway LCA studies narrow the physical scope to pavement structures only (including all hard surfaces and sublayers).
- The ***life cycle scope*** identifies which LCA stages are included. Product stage (A1-A3) must be included at an absolute minimum, but the best practice is to also include construction impacts (A4 and A5), use (B), and end of life (C) stages in the analysis. This is particularly important for comparisons across material types (e.g., asphalt vs. concrete pavements). In addition, benefits from recycling, carbon sequestration, and biogenic carbon of materials that occur outside of the roadway life cycle (included under Stage D) may need to be considered for more accurate decision-making.

KEY TERMS

Functionally equivalent
Two LCAs with the same functional unit.

Functional unit
"Quantified performance of a product system for use as a reference unit" *ISO 14040*

Declared unit
"Quantity of a product for use as a reference unit in a Type III environmental declaration or footprint communication, based on one or more information modules." *ISO 14027*

REFERENCES

11 Harvey JT, Meijer J, Ozer H, Al-Qadi IL, Arash Saboori, Kendall A. *Pavement Life-Cycle Assessment Framework*. Federal Highway Administration (FHWA); 2016:244.

12 Muench ST. Roadway Construction Sustainability Impacts. *Transp Res Rec*. 2010; 2151(1):36-45. doi:10.3141/2151-05

Step 2: Life cycle inventory (LCI) analysis

Compiling a life cycle inventory of all the inputs and outputs for a roadway consists of two main elements: LCI data and results.

(1) LCI data

LCA data for roadway LCAs primarily includes material quantities and compositions, broken down to the smallest constituent material. For example, the tonnage of hot mix asphalt used in pavement construction, including detailed mix design and production information like percentage of recycled materials, type of asphalt binder and its content, transportation distance of materials pre and post-manufacturing, asphalt plant energy consumption, etc.

Pay item lists, bill of materials, and final quantity take-offs are helpful for tracking major material flows when conducting a roadway LCA. Several other pieces of information may be required to include other LCA stages (e.g., engine size and fuel consumption of construction equipment, waste management and disposal procedures, etc.) LCI data can be either ***primary*** (i.e., collected from specific processes) or ***secondary*** (i.e., data available from existing commercially or publicly available databases).

(2) LCI results

The outcome of LCI analysis that quantify the flows crossing the system boundary. In other words, LCI results establish the link between the physical properties of materials (e.g., weight, volume, area, etc.) and their environmental outputs (e.g., emissions to air and water, pollutions, water use, energy consumption, etc.)

Several proprietary and publicly available LCI databases exist that provide environmental impact data for materials and processes. For example, Ecoinvent, GaBi, US LCI database, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET), and EPA's Motor Vehicle Emission Simulator (MOVES) provide LCI results for a wide variety of unit processes and products.

Ideally, LCI analysis could be done quickly and easily through the use of plug-ins or software already used by roadway designers. By the time of this writing, only limited tools are available for infrastructure and roadways (see page 10 for more information on tools).

Step 3: Life cycle impact assessment (LCIA)

Life cycle impact assessment uses the LCI data (i.e., material and energy flows) and LCI results (i.e., environmental outputs) from step 2 to calculate the environmental impacts of products and processes. Environmental impacts are reported using ***impact categories*** and quantitatively expressed using ***impact category indicators.*** Global warming potential (GWP) is the impact category used to report the estimated climate change impact of a product, process, or project.

Global warming potential (GWP) ← *Impact category*

Carbon dioxide equivalents (CO_2e) ← *Impact category indicator*

Characterization factors are derived from scientific research and are used to convert an assigned LCI result to the common unit of the impact category indicator. For example, over the course of 100 years, methane absorbs about 28 times more radiative energy than carbon dioxide; hence, 1 kg of methane is equivalent to 28 kgs of carbon dioxide. Methane's characterization factor for GWP is therefore 28 kg CO_2e per kg. Characterization factors are used so that an impact category can be reported using a single indicator. For example, GWP is a is a combined weighted measure of GHGs, most importantly the non-fluorinated gasses of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Simply put, quantities of material or energy flows (LCI data) are multiplied by the corresponding environmental impact factor per unit of material and energy (LCI results) and summed up per impact category to calculate total impacts (see Figure 3 for a simplified example). LCA tools can perform these calculations to simplify this process for practitioners.

KEY TERMS

Impact category
Potential environmental issue of concern that LCI results can be attributed to. Global warming potential, acidification potential, eutrophication potential, ozone depletion potential, and resource depletion are the most commonly categorized environmental impacts. Environmental impact categories are selected in step 1.

Impact category indicator
Provides the quantifiable representation of a given impact category to allow meaningful comparisons. For example, carbon dioxide equivalents (CO_2e), sulfur dioxide equivalents (SO_2e), and Joules are the most common impact category indicators for GWP, acidification potential, and resource depletion, respectively.

Global warming potential (GWP)
GWP is the indicator used in LCA to report the estimated climate change impact of a product, process, or project. GWP is measured in the unit of carbon dioxide equivalent (CO_2e, or simply carbon footprint), which

Life Cycle Inventory (LCI) Data
(material and process data)

Mix Design	
375F	HMA mix temperature
5%	Asphalt binder
95%	Aggregates

Life Cycle Inventory (LCI) Results *(emissions data)*

GHGs (kg/kg)	CO_2	CH_4	N_2O
HMA production	1.8E-02	3.7E-06	3.4E-06
Asphalt binder	5.5E-01	2.2E-03	7.8E-06
Aggregates	8.1E-05	4.1E-10	2.5E-09

Life Cycle Impact Assessment (LCIA)

GWP100 (CO_2e)	CO_2	CH_4	N_2O
	1	28	265

MATERIAL INVENTORY
Estimate of quantities materials and processes in the roadway

×

EMISSION FACTORS
Estimate of environmental impacts for each material/process

=

TOTAL IMPACTS
Estimate of total GWP and/or other environmental impacts

Example LCA Calculations

1000	kg HMA production	x	1.9E-02	kg CO_2e / kg HMA	=	19.0	kg CO_2e
50	kg asphalt binder	x	6.4E-01	kg CO_2e / kg asphalt binder	=	32.1	kg CO_2e
950	kg aggregates	x	8.2E-05	kg CO_2e / kg aggregates	=	0.1	kg CO_2e
Total GWP100 from the production of 1000 kg hot mix asphalt					=	*51.2*	*kg CO_2e*

Figure 3. Simplified LCA calculation process for the production of 1,000 kg of hot mix asphalt *(numbers are included for illustrative purposes only)*. Roadway LCA calculators might follow this formula, using a combination of LCI data (emissions per product/material) and LCIA data (potential impacts per emission).

Step 4: Interpretation

The final phase in an LCA study is devoted to understanding the results and interpretation of them. Interpretation typically involves the following elements:

- **Data summaries.** The use of descriptive statistics (e.g., summation, means, medians) and data visualizations (e.g., pie charts, bar charts) to overview and investigate results.
- **Hot spot analysis.** Categorization of LCA results by material type, roadway element, life cycle stage, or other grouping to find the majority of impacts (also referred to as *contribution analysis*). Hot spot analysis also helps identify potential errors.
- **Checking for errors.** Check for obvious or highly expected results, such as by comparing the results to similar existing studies. A valid comparison to other studies should also check for data completeness (i.e., functional unit and system boundary comparability, environmental indicators) and consistency (i.e., assumptions, limitations, methods, and data sources).
- **Uncertainty and sensitivity analysis.** LCI data are uncertain due to data variability, input uncertainty, and model imprecision. Sensitivity analysis can help practitioners understand whether that uncertainty is impacting results. For example, transportation distance can be a source of uncertainty in LCA studies. By assigning a range of possible distances (e.g., 20 to 50 miles), and re-running the LCA based on these assumptions multiple times, the sensitivity of final LCA results on these assumptions can be investigated.
- **Conclusions.** The conclusions of an LCA study should address questions like: Do the results make sense and are they aligned with previous studies? Do results meet the expectations? Are there anomalies, and if yes, why? Also, did the analysis meet the goal of the study?
- **Verification (optional).** This mainly consists of a peer review of your LCA. Verification is not needed for internal purposes and is mainly used for public claims or as required by policy.

KEY TERMS

Life Cycle Inventory (LCI)
A data inventory that creates the foundations for running LCA. Mass and energy flows in and out of any unit process and their associated environmental inputs and outputs comprise an LCI.

Unit process
"[The] smallest element considered in the life cycle inventory analysis for which input and output data are quantified" *ISO 14040*

Life Cycle Impact Assessment (LCIA)
"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" *ISO 14040*

Benchmarking roadways

A ***benchmark*** is a reference value to which different performance metrics (e.g., LCA results) can be compared against. Many state DOTs already require benchmarks for other performance metrics to receive full payment, such as roughness of 52 to 66 inches/mile for new asphalt pavements as measured by the International Roughness Index.[13]

With enough data representation, benchmarks can help establish the current state of the practice for the industry to set carbon reduction targets and help track progress over time towards reaching those targets. Embodied carbon benchmark values are typically normalized according to the unit used in the description of the underlying LCA (e.g., CO_2e per lane-mile or square foot). Similar to buildings, roadway embodied carbon benchmarks are highly dependent on the roadway classification and its intended use and function (e.g., highway, tunnel, bridge, local street, etc.)

Embodied carbon benchmarks for roadways have not been widely developed yet. Once a representative sample of roadway projects that captures the variability of roadway classes and LCA scopes is available, descriptive statistics (e.g., median, first or fourth quartiles) may be used to establish benchmarks.

For the purpose of this toolkit, a limited number of roadway LCA studies were assessed (focusing only on initial construction (A1 to A5)) to showcase the variability of LCA results. Figure 4 summarizes the studies reviewed here by breaking down roadways LCA into pavements, whole roadways, roadways with at least one bridge structure, and roadways with at least one bridge and one tunnel structure. Based on this limited study, there appears to be a significant difference between the median of pavements (379 metric tons CO_2e per lane-mile) and whole roadways (777 metric tons CO_2e per lane-mile), highlighting the need for roadways LCAs to be more comprehensive to capture the full embodied carbon impacts of roadway construction.

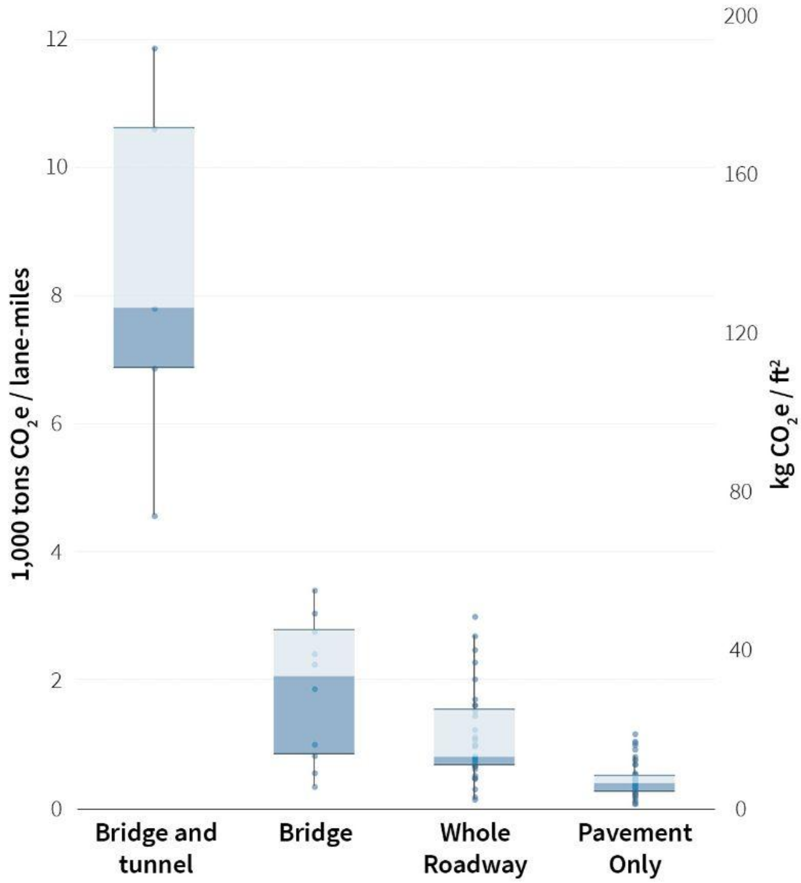

Figure 4. Example upfront embodied carbon benchmarks (A1 - A5) for different roadway classes based on a limited review of the literature (i.e., 18 journal papers and research reports) that have carried out LCA on roadways are reviewed.[13-31] This figure is intended for illustrative purposes only and caution should be taken in using due to its limited research and lack of complete methodological description. Data is available upon request. *© Carbon Leadership Forum*

KEY TERMS

Reference value
"Performance level on a performance scale that represents state of the art or best practice." *ISO 21678*

Benchmarking
"Process of collecting, analysing and relating performance data of comparable buildings or other types of construction works." *ISO 21678*

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Tools for accounting the embodied carbon of roadways

In practice, performing LCA for roadways relies on software or spreadsheet-based tools. In this section, we look at the types and variety of tools available to conduct LCA (in particular, for roadways and pavements) and their key differences.

Roadway LCA tool development is a growing area, with the majority of available tools currently limited to pavement structures. Currently, there are fewer roadway-specific LCA tools available than there are for buildings. However, the landscape of LCA tools for roadways is continuously evolving, and the prospect of new tool options emerging in the near future is promising.

Tool selection

When selecting a roadway LCA tool, it is important to ensure that the chosen LCA tool aligns well with your desired assessment scope. In particular, consider:

- The **life cycle scope** you intend to assess. Are you including the entire life cycle from A to C stage, or focusing on a cradle-to-gate (i.e., A1 to A3) assessment?
- The **geographic relevance** of the data the LCA tool covers. LCA tools primarily rely upon EPDs and LCI databases, which offer LCI and LCIA results for a wide variety of materials and geographies. It is vital to select a tool that employs geographically- relevant data, such as North American data for projects located within North America.
- Is **design integration** possible, i.e., are there tools available that plug-in to engineering software you are using?

Categories of tools

The following sections describes five categories of available roadway LCA tools, with examples of each. This is not an exhaustive list of all available tools in the market.

Calculators and spreadsheet tools

Many of the roadway-specific LCA tools belong to this category, offering a valuable starting point for engineers and roadway designers interested in embodied carbon accounting of projects. Typically, these tools are user-friendly, with simple online or spreadsheet-based interfaces, limited manual data entry, and no design integration. They serve as excellent tools for obtaining embodied carbon estimates and high-level quick decision-making early in design.

Alongside process-based LCA tools that analyze mass and energy flows (i.e., the majority of tools explained above), economic input-output (EIO) LCA models can also be employed to provide rough estimates of embodied carbon based on a project's economic value.

Design-integrated LCA tools

These are LCA tools that are integrated into the software that roadway designers use (for example, integrated with Civil3D or Revit). They extract material quantities and compositions and use material/product-specific LCI to conduct LCA. As discussed earlier, design-integrated tools are not widely available for whole roadway or assembly-specific (e.g., pavements) LCAs.

Transportation-related LCA tools

There are several instances where tailpipe emissions from vehicles need to be considered in roadway LCA. For example, fuel consumption from vehicles within workzone, trucks that haul materials from and to job sites, and part -or all- of the emissions from pavement rolling resistance (i.e., tire-pavement interaction) due to vehicles using the roadway during its life cycle.

Product selection / procurement tools

These are a collection of facility -or product- specific, or industry-wide LCA results, mainly in the form of EPDs, to facilitate comparison between products with similar functionalities. These tools are mainly used for data scraping with less editorial capacities.

KEY TERMS

Process-Based LCA
An LCA method that uses mass and energy flows as inputs and outputs within each stage of any given process.

Economic Input-Output (EIO) LCA
An LCA method that uses sector-level monetary flows of goods and services as inputs to estimate environmental impacts as outputs.

EPD Generators

These tools support manufacturers in quickly producing EPDs (e.g., ThetaEPD, Climate Earth EPD Generator, and NAPA's Emerald Eco Label EPD tool).

Professional LCA tools

These tools are primarily used by LCA experts and consultants. Professional LCA software may be used for any product and are not limited to construction materials and processes. These tools must be accompanied by selection of a LCI database that can be used to create material flows and production processes from scratch. Professional LCA tools are used to create the background datasets of materials and processes used in whole roadway and building LCA tools.

Table 1. Summary of five categories of roadway LCA tools highlighting examples of tools in each category.

Tool Category	User Interface	Tool Name	Developer
Calculators and spreadsheet tools	Web-based calculator	Athena's Pavement LCA tool	Athena Sustainable Materials Institute
		eLCAP	University of California, Davis
		Economic Input-Output (EIO) LCA	Carnegie Mellon University
		Moata Carbon Portal	Mott MacDonald
		Dubo Calc	Rijkswaterstaat
	Spreadsheet	LCA Pave	Federal Highway Administration (FHWA)
		PaLATE	Recycled Materials Resource Center
		Infrastructure Carbon Estimator Tool	ICF International, Inc
		Carbon Tool	Highway England
Design integrated LCA tools	Software plug-in	One Click LCA Infrastructure	One Click LCA
		One Click LCA Civil 3D Integration	One Click LCA
Transportation related LCA tools	Software and database	MOVES	Environmental Protection Agency (EPA)
	Software and spreadsheet	GREET	National Renewable Energy Laboratory (NREL)
	Software	CA4PRS	University of California, Berkeley
Product selection tools	Web-based application	EC3	Building Transparency
EPD Generators	Web-based application	Emerald Eco Label EPD	National Asphalt Pavement Association (NAPA)
		ThetaEPD	WAP Sustainability
		Climate Earth EPD Generator	Climate Earth
Professional LCA tools	Software	SimaPro	PRé Sustainability
		GaBi	Sphera
		OpenLCA	GreenDelta

Read more: carbonleadershipforum.org/clf-roadway-infrastructure-toolkit

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