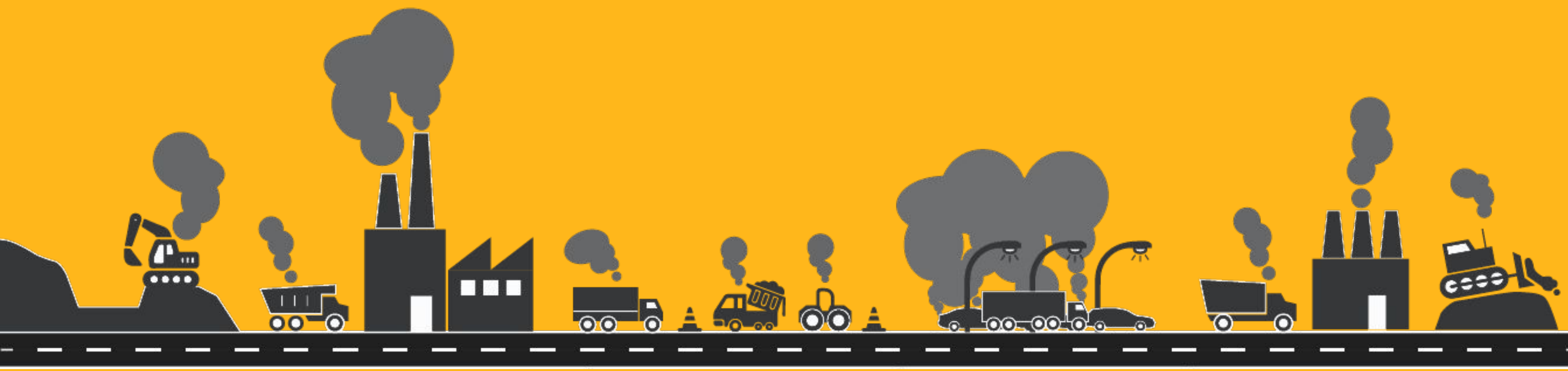
PART I:

Introduction to Embodied Carbon and Roadway Infrastructure



CLF Carbon Leadership Forum

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Embodied Carbon Toolkit For Roadway Infrastructure

Embodied Carbon and Roadway Infrastructure

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Climate change has contributed to the majority of recently experienced impacts on natural and human systems.[1] As of 2017, human-related activities (mainly in the form of releasing greenhouse gases - GHGs) are estimated to have caused a rise of 1°C in global temperature,[2] which has and will have tremendous impacts on the ecosystem and its species.

Legislation like the Infrastructure Investment and Jobs Act, Bipartisan Infrastructure Law, and Inflation Reduction Act and growing interest from engineers and stakeholders has increased opportunities for addressing the significant emissions associated with the design and construction of transportation infrastructure including roadways. *Embodied carbon* – the GHGs released during the extraction, production, transportation, placement, repair and disposal of construction materials – has gained even more traction with adoption of Buy Clean policies federally and in states like California, Colorado, Oregon, and Minnesota.[3]

Embodied carbon due to the construction and maintenance of roadways is a large contributor to overall GHGs attributed to transportation agencies owning and managing these public assets. This toolkit aims to help departments of transportation (DOTs) and other transportation agencies better understand the sources of GHG emissions from building the roadway infrastructure.

Roadway infrastructure has a significant embodied carbon footprint

Infrastructure is a broad term used to describe the physical and organizational systems that form the backbone of a functioning society. It provides the foundation for economic activities, connectivity, and human well-being. Transportation, energy, water and sanitation, communication, and other urban infrastructure (e.g., buildings) are among the most essential components of our modern civilization. Transportation infrastructure, in particular, encompasses a variety of forms including roadways, airports, railways, waterways, etc., that constitute the arteries through which goods and individuals are moved from point A to point B.

This toolkit focuses on ***roadway infrastructure,*** *or roadways* for short, where the most research has been done related to GHG emissions accounting for infrastructure. Roadway infrastructure projects include both new construction and maintenance of existing components. Building and operating this vast infrastructure requires energy and resources, most of which emit GHG emissions.

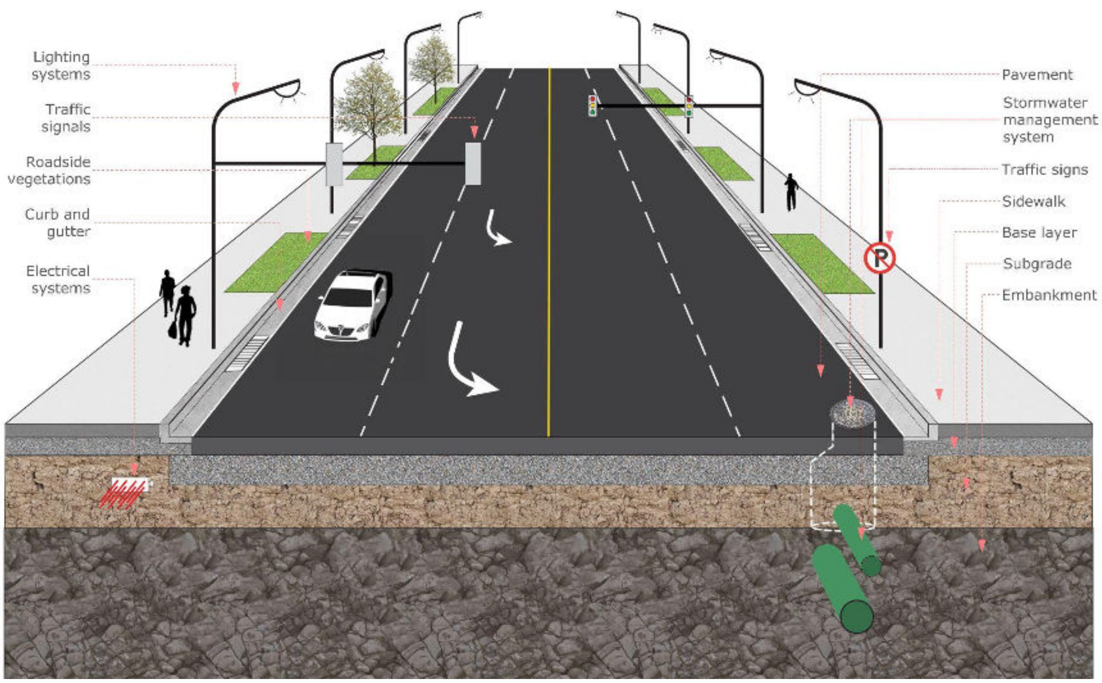

Figure 1. Roadway infrastructure components include not just pavement, but also sidewalks, traffic signals, lighting systems, stormwater management systems, curbs and gutters, sanitary water conveying systems, embankments, among others. *Graphic Credit: Sindhu Raju. © Carbon Leadership Forum*

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.

Roadway infrastructure (roadways)
Roadways include 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.

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1 IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2021.

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

Roadway infrastructure is a large contributor to global emissions

Roadway infrastructure emissions are shared between the two broad categories:

- **Transportation (17% of global emissions)** covers the energy used to fuel vehicles, trains, aircraft, boats, etc. in order to transport people and goods. Motor vehicles driving on roads are a major contributor to GHG emissions globally.
- **Industrial emissions (31% of global emissions)** captures the significant emissions from *building* these massive infrastructures. Concrete, asphalt, and steel are the most commonly used materials to build roadway infrastructure. Concrete and steel alone are responsible for about 14% of global GHG emissions.[4] The share of roadway construction materials is comparatively a small fraction of the GHG emissions inventory of a state but there are some nuances that make it worthy of further consideration.

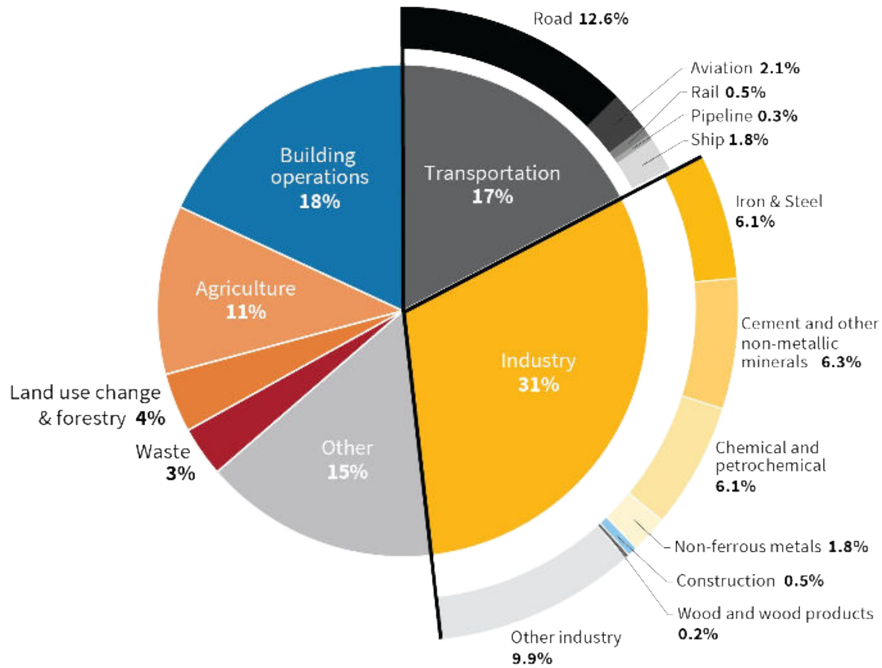

Figure 2. Global greenhouse gas emissions breakdown by sector in 2019. Source: World Greenhouse Gas Emissions: 2019, World Resources Institute (WRI), 2022. © *Carbon Leadership Forum*

DOTs are uniquely poised to address industrial emissions from roadways

First, unlike the case for the energy consumption from vehicles, state DOTs and other transportation agencies are the primary purchasers of building materials and thus most if not all embodied carbon emissions can be allocated to those entities. Second, unlike many initiatives and progress towards producing cleaner energy and electricity, embodied carbon emissions from materials and processes to build roadways are “critical to abate” for two reasons:

- High-temperature heat is required in processing and manufacturing key construction materials like cement (above 2,700° F) and steel (above 3,000° F). Providing such high temperatures using renewable energy sources is yet to become fully available.
- Manufacturing processes emit emissions (CO_2, in particular) due to chemical reactions between raw materials. For example, calcination of limestone during clinker production (the main component of cement) releases significant amounts of CO_2 such that around 60% of GHG emissions from cement are due to this chemical reaction.

In summary, **shifting to renewable energy and electrification cannot become the sole solution for reducing embodied carbon emissions.** There needs to be close collaboration between key players throughout the supply chain of construction materials (i.e., designers, producers, engineers, etc.) to reduce emissions additionally by 1) substituting with low-carbon materials, 2) implementing advanced technologies to improve efficiency in manufacturing processes, and 3) reducing, reusing, and recycling those materials in a circular economy environment.

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Transportation infrastructure and environmental justice

Transportation infrastructure is closely tied to environmental justice and equity, impacting social justice through planning decisions.[5] As a simple example, choices like building highways over metro lines affect different socioeconomic groups unequally. Carbon emissions from factories and roads have local health and environmental effects, beyond their global impact (e.g., near-source air pollution). Assessing emissions through life cycle assessment (LCA) helps understand local impacts like smog and particulate matter, as well as more global impacts like GHG emissions. Understanding these impacts on communities near factories and roads is crucial.

Embodied carbon from material supply chains also affects climate justice. Manufacturing facilities and power plants, often in poorer neighborhoods, expose disadvantaged communities (most often Black and brown communities) to higher pollutants and emissions.[6] Lower-income communities are also more vulnerable to climate change's severe impacts due to less resilient infrastructure. Addressing roadway embodied carbon indirectly reduces vulnerability and directly promotes community health by mitigating industrial emissions.[7]

Small businesses, particularly those owned by historically disadvantaged communities, may also face challenges when competing for infrastructure projects. Initiatives like disadvantaged business enterprise (DBE) programs adopted by some state DOTs aim to promote diversity and inclusivity in government contracting, addressing past discrimination. Policies favoring low-carbon materials should consider how they can remove barriers to access for small businesses related to additional accounting and reporting requirements.

The intersection of transportation infrastructure and environmental justice reveals significant disparities in community impacts, urging the need for strategies that address environmental concerns while upholding social equity.

Reducing roadway embodied carbon is critical and urgent

Globally, climate change concerns have pushed the world toward greenhouse gas emission reduction targets (e.g., the 2015 Paris Agreement.[8]) National legislation has begun to provide substantial funding for embodied carbon reduction efforts, and state agencies are beginning to address their GHG emissions through reduction targets and procurement policies. Most targets envision a [near] net-zero carbon by the year 2050. At the state level, for example, Washington State RCW 70A.50 establishes a 45% and 95% GHG reduction target below 2005 levels by 2030 and 2050, respectively. Achieving these targets requires comprehensive efforts and strategies to reduce carbon emissions starting *now*.

Acting to reduce embodied carbon on roadways must be a climate priority to address the upfront nature of embodied carbon and to allow technology development to accelerate and ‘catch up’:

- Once the infrastructure is built and the embodied carbon emissions released into the atmosphere, the process is irreversible. Embodied carbon, in this essence, is similar to capital investments. By building our infrastructure now, we are taking a huge upfront loan from the total budgeted GHG emissions we are allowed to emit into the atmosphere. This is contrary to operational carbon, where emissions will be gradually released into the atmosphere which gives us more time to invest in lower emitting processes by relying on future technological advancements. Consequently, by 2050, the share of embodied carbon is expected to increase in proportion of total roadway impacts.
- Technological developments to support industrial decarbonization and embodied carbon reductions are behind, likely due to the focus on tailpipe emissions alone (i.e. operational carbon for roadways).

The bottom line is that a comprehensive carbon reduction strategy should consider **all** sources that emit GHGs. If we wait until clean energy and electricity generation are achieved, we may already be too late to adopt embodied carbon reduction solutions for a net-zero carbon future.

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Greenhouse Gas Emissions Accounting

GHGs are substances that absorb and emit the sun's radiation within the thermal infrared range. Human activities such as burning fossil fuels, deforestation, and agriculture have increased the concentration of GHGs in the atmosphere which causes more heat to be trapped impacting Earth's climate (i.e., global warming). Among GHGs, carbon dioxide (CO_2) contributes the most to global warming and climate change due to its highest concentration in the atmosphere. Accordingly, the environmental impacts of GHGs are expressed in relation to an equivalent mass of CO_2. This is why *carbon footprint* is used as shorthand.

Private companies, individual government agencies, and entire cities or countries all use a similar framework for GHG emissions accounting that categorize emissions into scope 1, 2, and 3 emissions, described below from the perspective of any agency like a state DOTs:

- **Scope 1 emissions:** Direct GHG emissions from sources that are owned or controlled by the agency, such as burning natural gas to fuel an agency's building furnace or combusting diesel in vehicles or equipment used by the agency. An agency has some control over these emissions sources because of the type of fuel and efficiency of the equipment it uses.
- **Scope 2 emissions:** Indirect GHG emissions from electricity purchased by the agency for activities like lighting in buildings or roadways. An agency has some control over what type of electricity it purchases.
- **Scope 3 emissions:** All other indirect emissions not included in Scope 1 and 2. Scope 3 emissions are a consequence of an agency's activities that are not directly under its control. For a DOT, Scope 3 emissions may include employee commute, transmission and distribution losses due to electricity purchase, contracted solid waste and wastewater treatment, emissions due to the production, transportation, and placement of materials used to build infrastructure (also referred to as ***upstream Scope 3 emissions***), and the tailpipe emissions due to the operation of the roadway, including the fuel consumption of vehicles (broadly referred to as *downstream Scope 3 emissions*).

Upstream Scope 3 emissions are a critical and often overlooked source of GHG emissions from an agency's perspective. Embodied carbon from material manufacturing constitutes a large fraction of upstream Scope 3 emissions which is less often tracked mainly due to the complexities in or lack of standardized accounting methods tailored to roadway infrastructure.

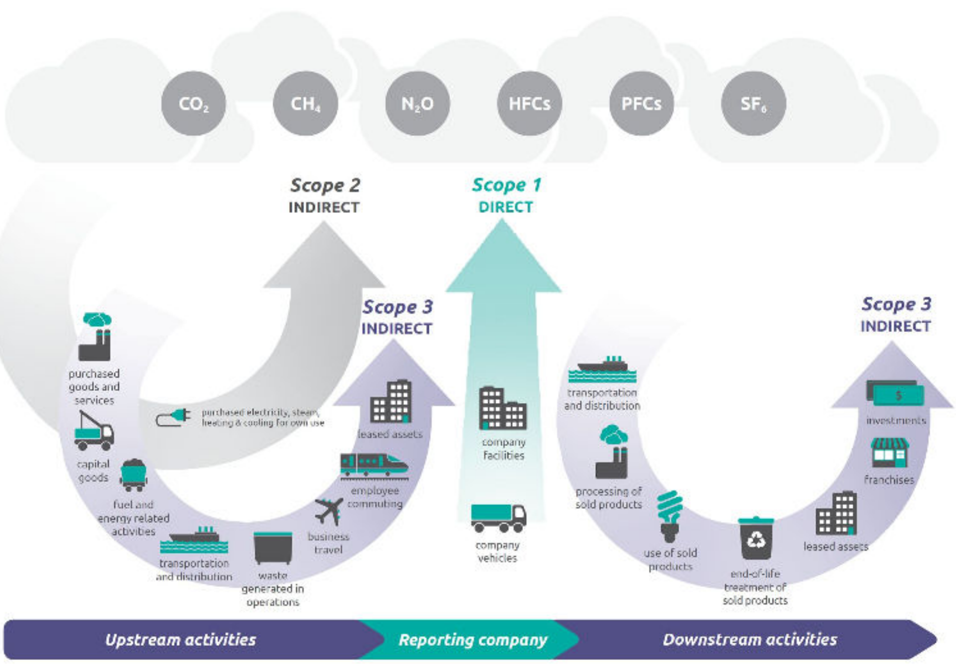

Figure 3. GHG emissions scopes across the value chain of an agency. Image Source: [Corporate Value Chain (Scope 3) Accounting and Reporting Standard](), World Resources Institute (WRI), 2011.

KEY TERMS

Greenhouse gas emissions (GHGs)
Substances that absorb and emit the sun's radiation within the thermal infrared range. The primary GHGs in the Earth's atmosphere are water vapor and clouds, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).

Upstream Scope 3 emissions
Emissions due to the production, transportation, and placement of materials used to build infrastructure.

Embodied Carbon Accounting

In addition to general emissions accounting frameworks, a roadway's carbon footprint can also broken into the broader categories of embodied carbon and operational carbon.

Embodied carbon

Embodied carbon emissions are those generated during the extraction, production, transportation, placement, repair and disposal processes for all materials used to build and maintain roadways. Quantification of embodied carbon of materials released during the initial construction of roadways (also known as *upfront embodied carbon*) can be used for upstream Scope 3 emissions accounting. For roadway construction, the majority (around 85%[9]) of embodied carbon comes from the material manufacturing processes.

Operational carbon

Operational carbon emissions are those that are generated from the operation of the roadway. Major sources of operational carbon for roadways include radiation heat absorption (due to the albedo effect) from hard surfaces, emissions due to pavement and tire interaction, electricity used in roadway lighting, traffic signal operations, and other intelligent transportation systems, work zone traffic emissions due to roadway construction and maintenance, and others.

Although the GHG emissions due to the fossil fuel consumption of vehicles driving on the road (i.e., *tailpipe emissions*) are a major contributor to Scope 3 emissions from the transportation sector, the full allocation of those to the physical roadway infrastructure is debatable. However, it is widely agreed that the additional fuel consumption by cars due to the decay in pavement roughness and smoothness from its original condition and work zone-related tailpipe emissions are attributable to roadway infrastructure.[10,11]

The ***total carbon*** or ***whole life carbon*** of a roadway is the sum of embodied and operational carbon. Carbon reduction strategies, thus, should aim at both embodied and operational carbon.

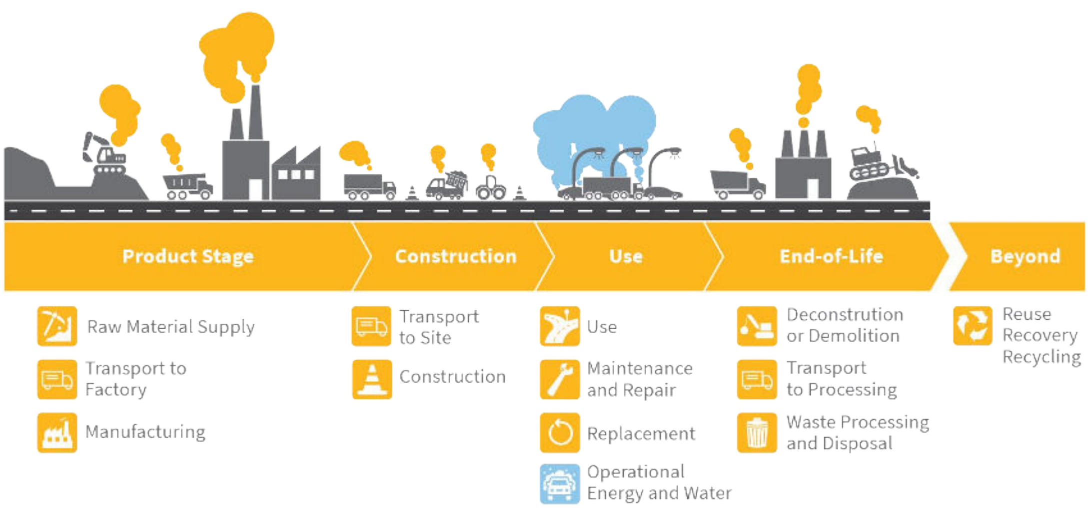

Figure 4. Embodied and operational carbon across the life cycle of roadways. Embodied carbon is generated during the extraction, production, transportation, placement, repair and disposal processes for the materials used to build and maintain roadways. Operational carbon is generated during the operation of the roadway. Although the GHG emissions due to the fossil fuel consumption of vehicles driving on the road (i.e., *tailpipe emissions*) are a major contributor to Scope 3 emissions from the transportation sector, the allocation of those to the physical roadway infrastructure (versus fossil fuel companies) is highly debated.*Graphic Credit: Meghan Lewis. © Carbon Leadership Forum*

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

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