THE CARBON FOOTPRINT OF ASPHALT PAVEMENTS

A REFERENCE DOCUMENT FOR DECARBONIZATION

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The Road Forward

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EXECUTIVE SUMMARY

Industry, pavement owners, and other stakeholders are developing ambitious goals to significantly reduce greenhouse gas (GHG) emissions. Efforts to achieve these climate related goals will affect all aspects of the U.S. economy, including a new focus on reducing the embodied carbon emissions associated with constructing and maintaining America's pavements and other infrastructure assets. Through the Infrastructure, Investment, and Jobs Act (IIJA) of 2021, the Inflation Reduction Act (IRA) of 2022, and other federal programs, unprecedented levels of federal funding will be used to reduce greenhouse gas (GHG) emissions throughout the U.S. economy. In the IRA, $4.5 billion is directed towards quantifying and reducing GHG emissions in the construction materials sector.

In 2022, NAPA released The Road Forward, a vision and long-range goal for the asphalt pavement community to achieve net zero greenhouse gas (GHG) emissions by 2050. This report supports The Road Forward by providing a reference document for decarbonizing asphalt pavements, covering the following topics:

- Understanding the sources and relative magnitude of GHG emissions throughout the entire life cycle of asphalt pavements.
- Exploring opportunities for agencies and industry to reduce GHG emissions using readily available technologies and practices.
- Identifying research needs to better quantify and further reduce GHG emissions associated with asphalt pavements toward an ultimate goal of achieving net zero GHG emissions.
- Providing an overview of key tools used to quantify GHG emissions and inform decision making.

This report focuses on specific actions that can be implemented by individual companies and agencies to reduce GHG emissions. The intended audience includes pavement engineers, asphalt mix producers, paving contractors, policy makers, and other stakeholders with an interest in reducing embodied carbon emissions associated with asphalt pavements.

Sources of GHG Emissions Throughout the Asphalt Pavement Life Cycle

This report provides a broad overview of the carbon footprint of asphalt pavements. It identifies the sources and relative magnitude of GHG emissions throughout the asphalt pavement life cycle including the following (Figure 1):

- Raw material manufacturing.
- Transportation of raw materials.
- Asphalt mixture production.
- Pavement construction.
- Use of pavements.
- Maintenance and rehabilitation.
- End-of-life.

For roadway pavements, tailpipe emissions from vehicle fuel consumption in the use stage (B1) can greatly exceed GHG emissions from all other life cycle stages combined, which explains why the majority of the legislative focus has been on reducing tailpipe emissions. However, with goals to reach net zero

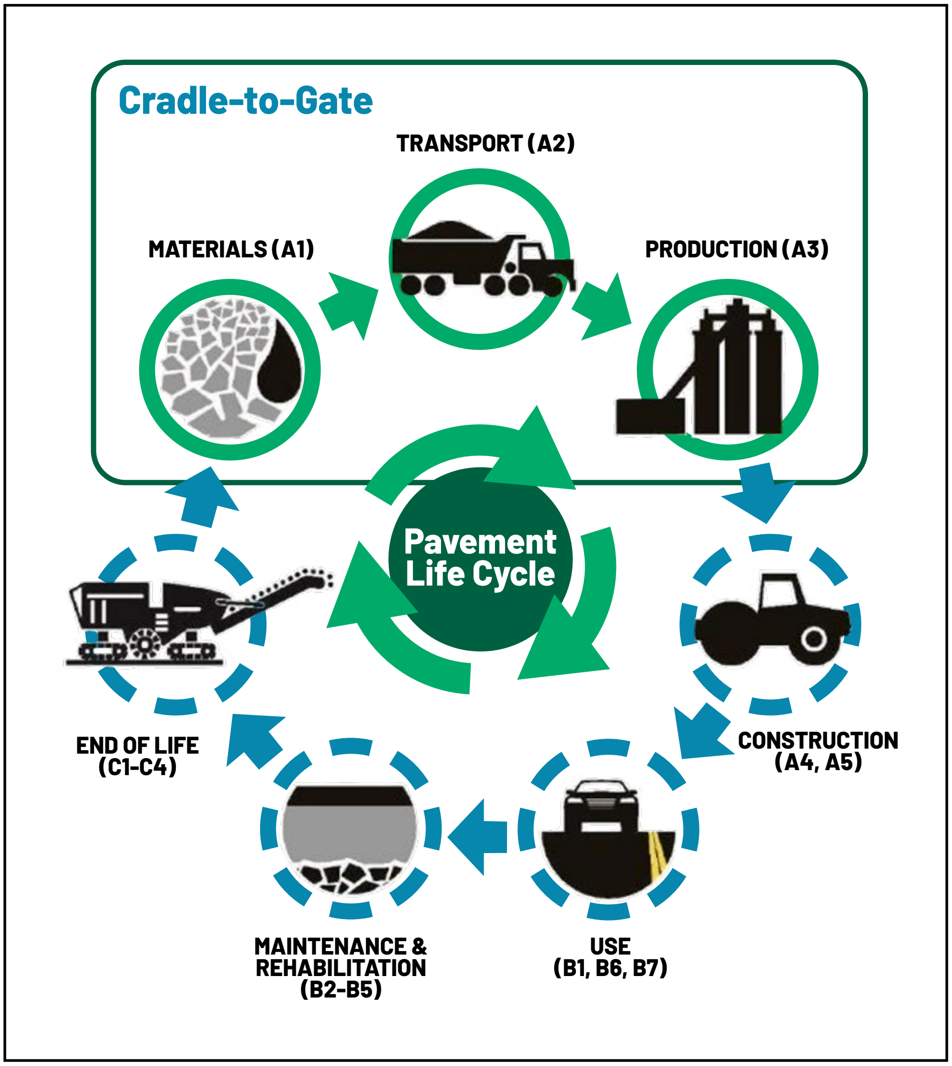


Figure 1. Key stages of the asphalt pavement life cycle with reference to the ISO 21930 life cycle information modules.

throughout the economy, there is a growing recognition that the embodied carbon of construction materials must also be addressed.

Embodied carbon is the GHG emissions associated with raw material extraction, transport, production, and construction of products used to build, maintain, and rehabilitate buildings and civil engineering works. The first three life cycle stages – material extraction, transport, and production (A1-A3) – are collectively referred to as the cradle-to-gate stages of a product's life cycle (Figure ES-1). Within the cradle-to-gate stages of asphalt mixture production, the two primary sources of embodied carbon emissions are upstream emissions associated with asphalt binder manufacturing and burner fuel consumption at asphalt plants.

In some cases, transportation of raw materials to the asphalt plant can also be a significant contributor to the emissions of the cradle-to-gate stages.

Emissions during the initial construction stage (A4 and A5) tend to be relatively low when compared to asphalt mixture production, but pavement design and construction practices can have a significant impact on emissions during other life cycle stages. Indeed, GHG emissions associated with future maintenance and rehabilitation (B2-B5) depend on a variety of factors that affect pavement life including pavement design, traffic loading, regional climate and weather conditions, subgrade conditions, and the type and frequency of maintenance treatments utilized. Excess fuel consumption caused by work zone congestion can also be a significant source of GHG emissions during maintenance and rehabilitation of existing roads. When asphalt pavements reach the end of their useful life (C1-C4), they are reused in new asphalt pavements, reducing future consumption of natural resources and associated GHG emissions.

Opportunities to Reduce GHG Emissions

With the ambitious goal of achieving net zero GHG emissions by 2050 (NAPA, 2022), one objective of this document is to identify the technologies and practices that can be readily adopted or expanded to reduce GHG emissions associated with asphalt pavements. These opportunities have been characterized as either industry-driven or agency-driven based on which party has the primary nexus of control, although many of the identified opportunities rely on industry and agencies working together.

Industry-Driven Opportunities

Industry-driven opportunities for emissions reduction associated with asphalt mix production and materials include the following:

- Increased use of reclaimed asphalt pavement (RAP) and other recycled materials to reduce the impacts of raw material manufacturing.
- Use of biobased materials that remove carbon dioxide from the atmosphere during the life of the feedstock material, then sequester biogenic carbon into the pavement.
- Adoption of energy efficiency initiatives, including the use of warm mix asphalt (WMA) and cold central plant recycling (CCPR) technologies to reduce mix production temperatures.
- Conversion of burner fuels with high carbon intensities to cleaner fuels such as natural gas and biofuels.

Although direct emissions from paving equipment during pavement construction tend to be low, construction practices can have a significant impact on GHG emissions. Industry-driven opportunities for emissions reduction associated with asphalt pavement construction and maintenance include the following:

- Improving density and smoothness during initial construction and maintenance activities to reduce future GHG emissions by extending the life of asphalt pavements.
- Improving the smoothness of asphalt pavements to reduce vehicle fuel consumption.
- Using trucks and paving equipment powered by alternative fuels, including compressed natural gas (CNG), renewable compressed natural gas (R-CNG), biodiesel, renewable diesel, hydrogen fuel cell electric vehicles (FCEV), and plug-in battery electric vehicles (BEV).
- Adopting flexible and rapid construction scheduling practices to reduce emissions associated with work zone congestion.

Agency-Driven Opportunities

Agency-driven opportunities to reduce GHG emissions include pavement design considerations, specifications, and pavement maintenance practices. The Perpetual Pavement design approach reduces life cycle GHG emissions by designing pavements to withstand the expected traffic loads without failing structurally, thereby reducing the frequency of future pavement maintenance activities. Specialty mixes such as polymer modified asphalt (PMA) and stone matrix asphalt (SMA) can reduce life cycle GHG emissions by extending the pavement service life. PMA can also allow for thinner pavement sections, thereby reducing embodied emissions.

Agencies can establish contract provisions and specifications that incentivize the use of materials and construction practices with lower embodied carbon emissions while allowing flexibility for contractors to innovate. For example, adoption of balanced mix design (BMD) specifications could enable contractors to use innovative materials, such as high RAP mix designs, without sacrificing pavement quality, if agencies relax volumetric requirements. Allowing contractors to schedule pavement maintenance activities to avoid peak travel times can reduce work zone congestion, significantly reducing congestion-related GHG emissions from vehicles.

For highway pavements with high traffic volume, one of the most significant opportunities to reduce life cycle GHG emissions is improving pavement smoothness to reduce vehicle fuel consumption. This can be accomplished by achieving smooth pavements during initial construction and by prioritizing pavement maintenance triggers as a function of smoothness and traffic volume. In this manner, pavement maintenance can be seen as a GHG mitigation measure that reduces emissions associated with vehicle fuel consumption. The preferential use of Thinlays as a pavement preservation treatment can achieve similar results, reducing vehicle fuel consumption and GHG emissions by enhancing pavement smoothness and reducing pavement macrotexture.

The Road Forward

Achieving net zero GHG emissions will require cooperation and partnerships between industry, agencies, and academia. While industry can drive innovation, there are limits to the pace and extent of adopting innovative practices and technologies without the cooperation of agencies, who play a critical role through agency specifications, contractual requirements, and pavement design and maintenance practices. Funding from government agencies is needed to accelerate the research, development, and deployment of new technologies and practices necessary to better quantify and reduce GHG emissions throughout the pavement life cycle. Academia can support this effort by conducting research and filling knowledge gaps.

Research is needed to quantify GHG emissions associated with several aspects of asphalt pavement design, production, construction, and maintenance, including:

- GHG emissions associated with various construction practices when asphalt pavement overlays are used to rehabilitate and reconstruct concrete pavements.
- GHG emissions associated with manufacturing asphalt additives, and life cycle emissions reductions associated with improved pavement performance from use of additives.
- The potential impact of biobased materials in asphalt pavements as a carbon dioxide removal, use, and sequestration strategy, and the development of innovative, carbon-sequestering, biobased binder technologies.
- The potential GHG emissions reductions that can be achieved by enabling innovation and improving mix performance through adoption of BMD.
- The life cycle GHG benefits of specialty asphalt mixes relative to their conventional counterparts.
- The impacts of initial pavement smoothness on the life cycle GHG emissions of asphalt pavements.
- The relationship between in-service pavement smoothness and life cycle emissions of pavements.

Lastly, coordinated research efforts are needed to refine GHG quantification methodologies for asphalt pavements, including:

- Methods to account for differential service lives when comparing LCA results of alternative pavement design and maintenance strategies.
- Further development and verification of work zone congestion modeling techniques for pavement LCA studies.
- Methods to accurately and consistently measure pavement rolling resistance to understand and optimize the combined effects of smoothness, texture, and stiffness on vehicle fuel consumption.

1. INTRODUCTION

Asphalt pavements serve as the backbone of America's surface transportation infrastructure with more than 94% of roads in the U.S. surfaced with asphalt (FHWA, 2020a). Pavement engineers choose this material due to a combination of its engineering properties and cost effectiveness. But the risk for any established market leader is that a disruptive technology will offer a superior attribute that upends the status quo. In the expected transition to a net zero economy, there is a growing awareness that legacy products and processes will be displaced by lower carbon alternatives.

In most sectors, efficiency gains will reduce the cost of decarbonized products. Other decarbonization efforts will be financed by a combination of carbon-pricing mandates and the customer's willingness to pay a premium for low carbon products (McKinsey, 2022). The Inflation Reduction Act of 2022 contains unprecedented levels of funding to decarbonize the U.S. economy and includes financial incentives for low embodied carbon construction materials, accelerating the transition to net zero.

The recent and growing adoption of Buy Clean policies is one such manifestation of changing priorities. Through Buy Clean and similar policies, there is a growing number of federal, state, and local agencies shifting their procurement and project delivery policies to account for the embodied carbon emissions associated with manufacturing construction materials such as asphalt, concrete, and steel. In this context, the risk to the asphalt pavement industry is the emergence of an alternative pavement material or technology that significantly reduces greenhouse gas emissions.

In 2022, NAPA launched The Road Forward, a set of industry goals to achieve net zero GHG emissions throughout the asphalt pavement life cycle (NAPA, 2022a). The driving force behind The Road Forward is a fundamental mission to engage, educate, and empower the U.S. asphalt pavement community to achieve net zero greenhouse gas emissions, preparing the asphalt pavement industry for the transition to a net zero economy.

To effectively reduce the carbon footprint of asphalt pavements, a holistic approach is needed to understand GHG emissions sources throughout the pavement life cycle and develop strategies to reduce those emissions. Low carbon pavement materials, coupled with technologies and practices that extend pavement life, provide an opportunity to reduce the embodied carbon of America's pavement system while improving overall system performance. Looking beyond the embodied carbon emissions of pavement materials, the impact of pavement properties on vehicle fuel consumption is a unique opportunity for pavement construction and maintenance practices to also reduce transportation related GHG emissions. The combined approaches of reducing asphalt pavement embodied carbon emissions and reducing vehicle operating emissions are important components of achieving long-term net zero emission goals.

1.1 Objectives of This Report

Currently, no single, comprehensive reference exists that describes and quantifies the sources of GHG emissions and opportunities to reduce emissions throughout the entire life cycle of asphalt pavements. This report has two primary objectives: The first is to identify the major factors that affect GHG emissions throughout the asphalt pavement life cycle; the second is to identify emissions reduction opportunities at various stages of the asphalt pavement life cycle to support an overall goal of achieving net zero GHG emissions.

This report provides a deep analysis of the carbon footprint of asphalt pavements. Chapter 1 sets the stage by briefly introducing the major frameworks for quantifying and categorizing GHG emissions, using the life cycle information modules defined in ISO 21930 (e.g., A1-A3, see Figure 1) to provide consistency in nomenclature and reduce potential confusion.

Chapter 2 of this report compiles publicly available research reports and LCA studies to identify the most significant sources of emissions. For asphalt mixture materials and production, GHG emissions were calculated based on realistic scenarios using the LCA model developed by Mukherjee (2021) to illustrate how key variables can influence cradle-to-gate GHG emissions. GHG emissions for the other life cycle stages presented in this report are based on published literature.

To identify emissions reduction opportunities, a high-level overview of readily deployable technologies and practices showcases the opportunities for industry (Chapter 3) and agencies (Chapter 4) to reduce GHG emissions throughout the asphalt pavement life cycle. Areas that need additional research to support GHG emissions reduction goals are also discussed. Chapters 3 and 4 focus on specific actions that can be implemented by individual companies and pavement owners/agencies to reduce GHG emissions. An overview of GHG quantification tools for pavements is provided in Chapter 5, with concluding thoughts presented in Chapter 6.

1.2 What Is a Carbon Footprint

GHGs trap heat in the earth's atmosphere. GHGs include compounds such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. Each GHG has a different global warming potential (GWP) based on its ability to absorb heat and the length of time it remains in the atmosphere. The global warming potentials of different GHGs are normalized to a common unit of carbon dioxide equivalents (CO_2e) to allow comparisons and simplify calculations.

A product's carbon footprint is a combination of the embodied carbon emissions associated with manufacturing, installing, and maintaining the product over its full life cycle and the operational emissions during use of the product. Carbon footprints are generally quantified using an LCA based methodology. This report provides a detailed analysis of the carbon footprint of asphalt pavements.

1.3 Overview of the Asphalt Pavement Life Cycle

Every manufactured product, from clothing to cell phones, has a life cycle divided into distinct stages. The ISO 21930 standard, which applies to construction products and services, further subdivides the major stages into information modules. The major life cycle stages (with information modules in parentheses) are: production (A1-A3); construction (A4, A5); use (B1, B6, B7); maintenance and rehabilitation (B2-B5); and end of life (C1-C4) (Figure 1).

A simplified diagram of the asphalt pavement life cycle is provided in Figure 1. The life cycle begins with the extraction and processing of raw materials (e.g., extraction of crude oil, which is then processed in a refinery and stored in tanks at an asphalt terminal), transporting raw materials to the plant, and asphalt mix production. Together, these stages are referred to as cradle-to-gate and collectively represent the production stage of the life cycle. Mix production is followed by construction, use, maintenance and rehabilitation, and end-of-life. The complete life cycle is referred to as cradle-to-grave. For materials that are typically recycled back into the same product system at end-of-life, such as asphalt pavements, the complete life cycle is inherently circular (see Sidebar).

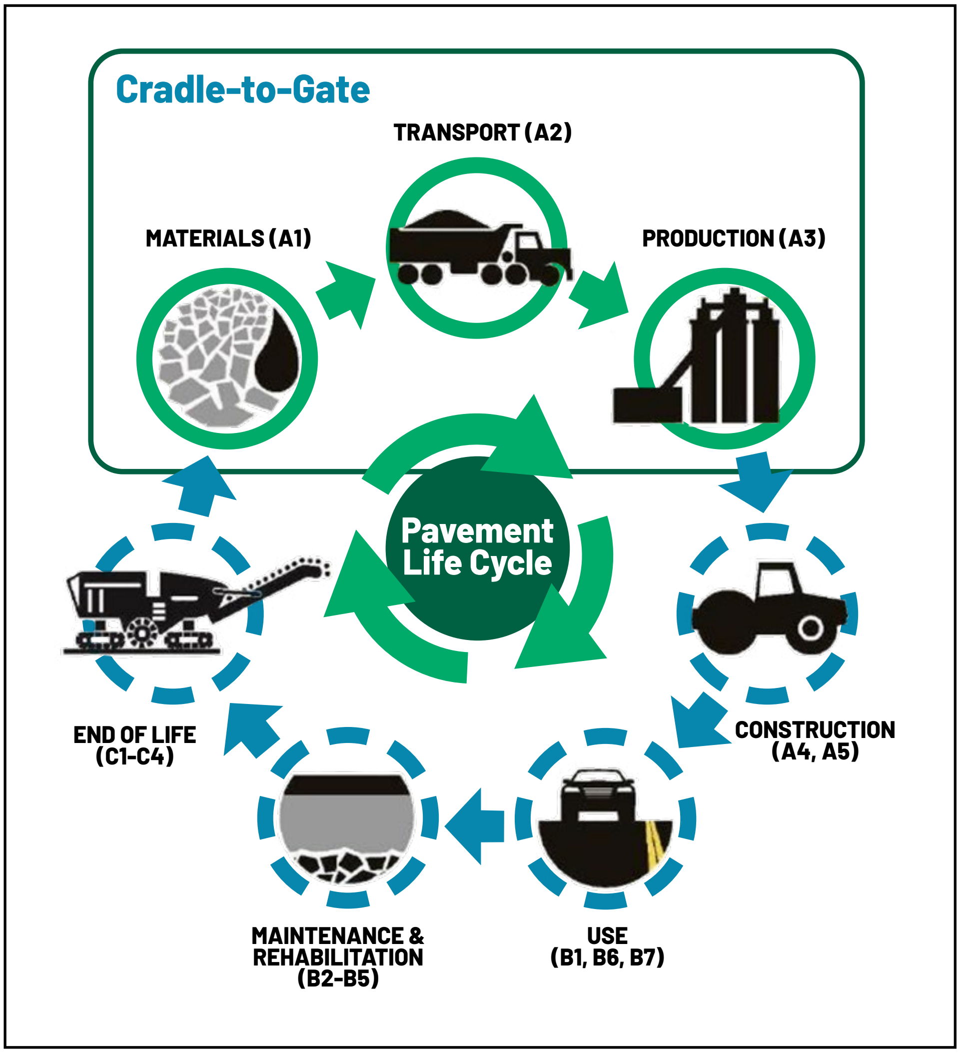


Figure 1. Key stages of the asphalt pavement life cycle with reference to the ISO 21930 life cycle information modules.

The ISO 14040/14044 series of standards, which is the most widely used standard for conducting an LCA, provides the principles, framework, requirements, and guidelines for conducting an LCA for any product system. The broad scope of the ISO 14040/14044 standards requires individual studies to clearly identify the goal and scope, which then informs the necessary system boundaries, life cycle stages, and other considerations. The Federal Highway Administration (FHWA) Pavement LCA Framework (FHWA, 2016) provides more specific guidance when conducting LCA of pavements and pavement materials.

LCA is not limited to GHG emissions. The methodology provides information regarding a variety of environmental impact indicators, resource use indicators, and waste materials, allowing for nuanced consideration of potential co-benefits and tradeoffs. This report focuses on GHG emissions using an LCA-based approach. LCA does not consider economic or social impacts, which can be investigated separately using frameworks such as life cycle cost analysis (LCCA) and social LCA, respectively.

1.4 Untangling LCA, EPDs, Embodied Carbon, and Operational Carbon

1.4.1 LCA Framework

LCA is an accounting method for quantifying GHG emissions throughout a product's entire life cycle.

Recycled Materials, the Circular Economy, and Asphalt Pavements. The circular economy is a concept that ensures products can be effectively recycled at end-of-life instead of the linear pattern of material production, consumption, and then waste at the end of life. Asphalt pavements support a circular economy through their recyclability. When an asphalt pavement reaches the end of its useful life, reclaimed asphalt pavement (RAP) is typically recycled into new asphalt mixtures through a process that reactivates the old asphalt binder, avoiding the need for new asphalt binder and aggregates, hence allowing significant upstream emissions reductions. Currently, RAP is recycled into manufactured products at a higher rate than any other construction and demolition material in America (U.S. EPA, 2020a).

1.4.2 Environmental Product Declarations (EPDs)

Environmental product declarations (EPDs) are transparent, verified reports developed by manufacturers to quantify and communicate GHG emissions and other environmental impacts associated with manufacturing construction materials (FHWA, 2020b). The environmental impacts reported in an EPD are calculated using a specific LCA methodology defined in the product category rules (PCR) for each product type. PCRs are developed through a transparent, consensus-based process defined in ISO 14025. Another standard, ISO 21930, serves as a core PCR for construction products and services. The PCR for Asphalt Mixtures, a subcategory PCR under ISO 21930, was developed and is maintained by NAPA (2022b). The PCR for Asphalt Mixtures defines the specific requirements for developing asphalt mixture EPDs. EPDs for asphalt mixtures produced in the U.S. can be developed using NAPA's Emerald Eco-Label tool, which is verified to ensure it meets all applicable requirements in the PCR for Asphalt Mixtures.

The life cycle stages reported in EPDs are defined in ISO 21930 (Figure 2). EPDs for asphalt mixtures report the cradle-to-gate (A1, A2, & A3) life cycle stages, as specified in the PCR for Asphalt Mixtures (NAPA, 2022b). It's common for EPDs for materials to only include the cradle-to-gate stages, since the environmental impacts in subsequent life cycle stages depend on factors outside the control of the manufacturer. For asphalt mixtures, these factors include the condition of existing road, base, and subgrade; climatic conditions; traffic loading; pavement design; construction specifications; and the pavement owner's maintenance program, among others. To account for these factors, EPDs can be used as a data source for whole pavement LCA when the applicable PCR meets the "Data Source" criteria in the PCR guidance toolkit established by the American Center for Life Cycle Assessment (ACLCA, 2022).

1.4.3 Embodied Carbon in the Context of EPDs and LCA

The term "embodied carbon" is not consistently used. Based on the life cycle stages in Figure 2,

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

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

Figure 2. Life cycle stages and information modules for construction products as defined in ISO 21930.

embodied carbon sometimes refers to production (A1-A3), production + construction (A1-A5), or more holistic assessments that include production (A1-A3), construction (A4-A5), maintenance and rehabilitation (B2-B5), and end-of-life (C1-C4). The only consistent concept is that none of these definitions include emissions from use (B1) or operational energy use (B6) as a component of embodied carbon (Adams et al., 2019; CLF, 2020).

EPDs for asphalt mixtures report the cradle-to-gate, or production stages, of the pavement life cycle. This represents a portion of the embodied carbon. When EPDs are used as a data source for LCA studies that include subsequent life cycle stages, such LCA studies may or may not include the use stage, also referred to as operational carbon, depending on the goal and scope of the study.

1.4.4 Negative Carbon Intensity vs Carbon Dioxide Removal

Negative carbon intensity and carbon dioxide removal are two terms related to carbon accounting that are often misunderstood.

Several states have established low carbon fuel standards (LCFS), which require fuel suppliers to conduct LCAs to determine the carbon intensity of transportation fuels sold in the state. Carbon intensity is a measure of the fuel's total carbon emissions throughout its entire life cycle. Negative carbon intensities occur when a process that normally emits methane is converted into a fuel and then combusted, releasing carbon dioxide. Because carbon dioxide emitted has a much lower global warming potential (GWP) than the avoided methane emissions, the overall process yields a net reduction in GWP. A common example of this is to utilize the manure pit in a dairy as the feedstock for renewable natural gas (RNG) production. The reduction in GWP from avoided methane emissions in the manure pit is larger in magnitude than the GWP of carbon dioxide emitted during fuel combustion, resulting in a negative carbon intensity even though carbon dioxide is not actually removed from the atmosphere. (California Natural Gas Vehicle Partnership, 2022). Fuels with negative carbon intensities are discussed in Section 3.3.1.

Carbon dioxide removal refers to the removal of carbon dioxide from the atmosphere and sequestering it into geological deposits, the ocean, or even into products. A variety of technologies can be used for carbon dioxide removal, such as direct air capture, soil carbon sequestration, biomass carbon removal and storage, enhanced mineralization, and afforestation/reforestation (U.S. Department of Energy, 2023). The use of biobased materials as a carbon dioxide removal strategy is discussed in Section 3.1.2.

2. SOURCES OF GHG EMISSIONS THROUGHOUT THE ASPHALT PAVEMENT LIFE CYCLE

GHG emissions occur during each stage of the pavement life cycle: production (A1-A3), construction (A4-A5), maintenance (B2-B5), use (B1, B6), and end of life (C2-C4). In general, the production stage (cradle-to-gate) tends to have the most significant contribution to a pavement's embodied carbon emissions. For moderate to high volume roads, operational emissions associated with vehicle fuel consumption during the use stage dominate the overall life cycle. Use stage emissions decrease in importance for low volume roads. For all roads, the relative importance of the use stage will decline as vehicles move toward zero-emission technologies.

Discussion of each life cycle stage is organized into the following sections of this report:

- Cradle-to-gate stages, including raw materials, transportation, and mix production, are covered in Sections 2.1 – 2.4.
- Pavement construction is discussed in Section 2.5.
- Use stage operational emissions are discussed in Section 2.6.
- Emissions during maintenance and rehabilitation are explored in Section 2.7.
- End-of-life considerations are discussed in Section 2.8.
- A brief summary of GHG emission sources throughout the asphalt pavement life cycle is provided in Section 2.9.

2.1 Overview of Cradle-to-Gate Stages (A1-A3)

Sources of GHG emissions in the cradle-to-gate stages include extraction and processing of raw materials (A1), transportation of raw materials to the asphalt plant (A2), and asphalt mix production (A3). Figure 3 shows the relative emissions in each of these life cycle stages for a virgin asphalt mixture with a 5% asphalt binder content produced at a typical asphalt plant that uses natural gas as a burner fuel.[1] This mixture is referred to as the baseline reference scenario throughout this report. Aggregates are assumed to be transported to the asphalt plant 21.5 miles by truck. Total cradle-to-gate emissions for the baseline reference scenario are 53.7 kg CO_2e/ton mix, of which 57% comes from raw materials (A1), 5% comes from transportation (A2), and 38% comes from mix production (A3). The results indicate that raw materials and plant operations dominate the cradle-to-gate emissions of asphalt mixtures, but transportation can become a significant driver when aggregates are sourced from long distances from the asphalt plant. Variables that affect each of these life cycle stages are explored in Sections 2.2 – 2.4.

To put the baseline emissions intensity of 53.7 kg CO_2e/ton mix into perspective, a typical passenger vehicle emits 4.6 metric tons of carbon dioxide per year (U.S. EPA, 2018). That means the production

[1] A complete list of assumptions for the baseline reference scenario is provided in Appendix A.

of about 85 tons, or about four truckloads of asphalt mixture, yields the equivalent annual emissions of one passenger vehicle.

The GHG emissions intensity of 53.7 kg CO_2e/ton mix for the baseline reference scenario is slightly higher than the national average emissions intensity published by Shacat et al. (2022), which was 51.4 kg CO_2e/ton mix in 2019. The two values are based on different underlying assumptions and datasets, the most significant being that the baseline reference scenario does not account for use of RAP. For any specific location or mix specification, both values may over- or under-estimate GHG and should not be considered targets or industry averages for policy purposes. Factors such as aggregate transport distance, fuels, use of recycled materials, agency specifications, and other variables significantly affect cradle-to-gate GHG emissions.

When GWP limits or benchmarks are required to implement Buy Clean policies, they should be established through a transparent methodology that accounts for the mix types specified by the agency and regional variability. To be clear, neither the baseline reference scenario reported here nor the national average emissions intensity published by Shacat et al. (2022) is appropriate for use as a GWP limit in a Buy Clean policy. Estimated industry averages for procurement of low embodied carbon asphalt mixtures under the Inflation Reduction Act will be provided in the industry benchmarking report published by NAPA (2024), which is based on data provided by hundreds of asphalt plants across the country.

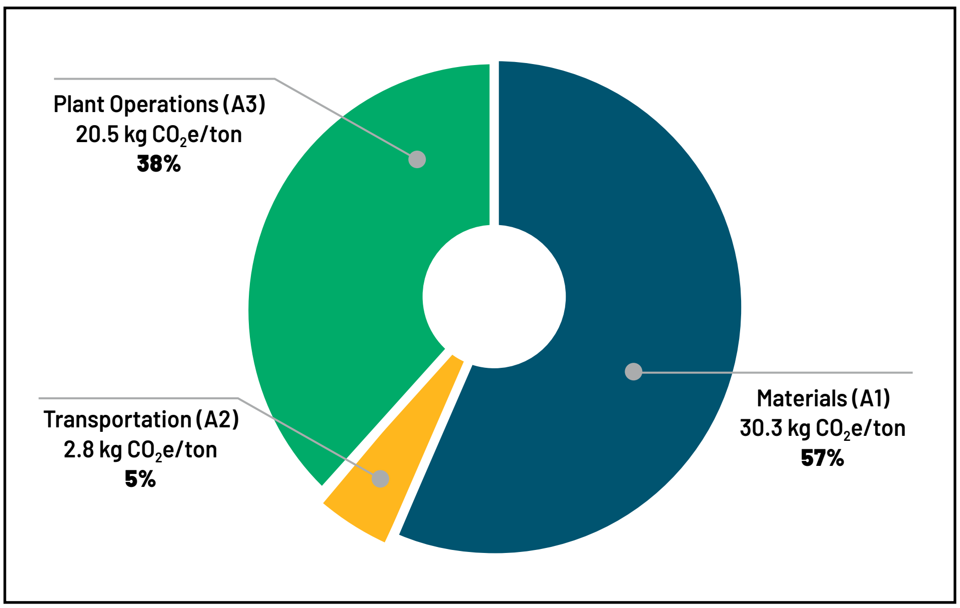


Figure 3. Cradle-to-gate GHG emissions (A1-A3) for the baseline reference scenario, which is a typical asphalt mixture with no recycled materials and average transportation distances produced at a plant that burns natural gas. The sum of individual life cycle stages does not equal the total of 53.7 due to rounding effects.

2.2 Upstream Production of Raw Materials (A1)

GHGs are emitted during the process of extracting, transporting, and manufacturing raw materials. The primary raw materials for asphalt mixtures are asphalt binder and aggregates such as crushed stone, sand, and gravel. Some asphalt mixtures also include additives to improve mixture quality and performance. These activities are grouped together as upstream production (A1). For the baseline reference scenario described in Section 2.1, GHG emissions from manufacturing of asphalt binder represent 94% of the carbon footprint of upstream production (A1), with aggregates representing the remaining 6% (Figure 4).

It's not uncommon for a single ingredient or process to dominate the cradle-to-gate GHG emissions of a product. For example, cement represents about 85% of the carbon footprint of a concrete mix, even though it only represents about 10-15% of the mix by weight (Cement Association of Canada, 2021). Similarly, upstream steel mill manufacturing represents about 92% of the carbon footprint of producing fabricated steel plate (American Institute of Steel Construction, 2021). Asphalt mixtures follow a slightly different path, with asphalt binder representing a little more than half of the cradle-to-gate emissions despite its significance in the raw materials (A1) stage for the baseline reference scenario.

2.2.1 Asphalt Binder

GHG emissions associated with asphalt binder production include emissions during crude oil extraction, transportation of crude oil to refineries,

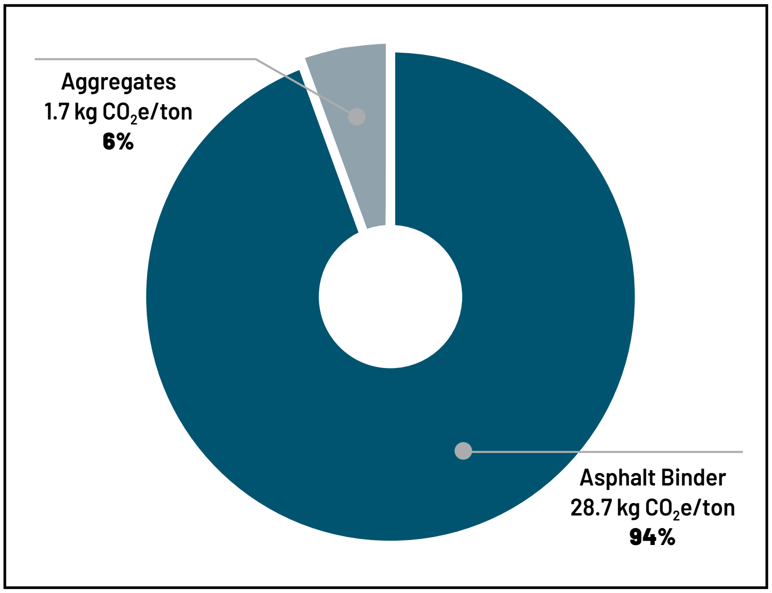


Figure 4. GHG emissions during upstream production of raw materials (A1) for a typical virgin asphalt mixture that contains 95% aggregates and 5% asphalt binder. The sum of individual materials does not equal the A1 total of 30.3 due to rounding effects.

refinery operations, transportation of asphalt binder to terminals, terminal operations, and upstream manufacturing of additives and modifiers. The complexity of the petroleum supply chain and refining process is a challenge for quantifying these emissions. With multiple co-products during refinery operations, there are various approaches to allocating the upstream impacts of asphalt binder manufacturing (including crude oil extraction, transportation to refineries, and refinery operations) depending on data availability and the allocation approaches selected (see Sidebar for more information).

GHG emission estimates for asphalt binder manufacturing in the U.S. range from 390 to 578 kg CO_2e per ton of asphalt binder (Mukherjee 2016 and Asphalt Institute 2019 respectively). The LCA model used to calculate the cradle-to-gate GHG emission scenarios in this report uses the Asphalt Institute (2019) dataset, which is the higher of these two values and considered the more conservative estimate. Asphalt binder is clearly the major contributor of GHG emissions associated with upstream production of raw materials. It represents 53% of GHG emissions in the cradle-to-gate (A1-A3) stages of the baseline reference scenario presented in Figure 3.

Feedstock Carbon

Feedstock carbon is a measure of the GHG emissions that would occur if the carbon-containing feedstock materials (namely, the asphalt binder) in an asphalt mixture were combusted. Although this is a potential source of emissions, asphalt binder is effectively never

Why Are The Asphalt Binder GHG Emissions Estimates So Different? The Asphalt Institute (2019) dataset was selected for this study because it is specific to the asphalt binder industry and is more complete than other available datasets, especially since it's the only available dataset that includes terminal operations. But there are significant differences between asphalt binder datasets, both in terms of the methodology and the results. It's helpful to understand why they are so different from each other.

Mukherjee (2016) used publicly available national data (the USLCI) for crude sources and refinery operations and applied an economic/mass balance allocation factor to each co-product using an approach developed by Yang (2014). This promotes a consistent allocation method for all co-products of refinery operations, minimizing the potential for double-counting or omitting impacts throughout the entire system of petroleum products. This is particularly beneficial since many fuels used during asphalt mix production and asphalt binder are all co-products of refinery operations. Mukherjee (2016) did not include transportation of asphalt binder to terminals or terminal operations due to a lack of publicly available data.

More recently, Asphalt Institute (2019) used a more granular approach by limiting the scope of their study to the specific crude slates and refinery operations associated with asphalt binder production in North America. They used different allocation approaches than Mukherjee (2016) for electricity inputs (mass allocation), crude oil extraction and transportation (energy content allocation), thermal energy (subdivision calculated as sensible heat of asphalt, accounting for inefficiencies), and direct emissions (allocated based on thermal energy use). The Asphalt Institute (2019) study also included transportation of asphalt binder to terminals and terminal operations. However, there are some limitations to the Asphalt Institute (2019) study. The limited participation (12 refineries and 10 terminals) and scope (only looking at crude slates and refinery operations during asphalt binder production), combined with the use of different allocation approaches compared LCAs for other petroleum products, creates the potential for double-counting or omitting some aspects of the petroleum product system as a whole. Another limitation of the study is the geographical representativeness of the dataset, which is heavily weighted toward the Gulf Coast region (PADD 3) based on participating refineries' asphalt binder production capacity and has no representation in the East Coast region (PADD 1).

The crude slate in the Asphalt Institute (2019) LCA is substantially more carbon-intensive than the North American national average petroleum crude slate because the companies that participated in the Asphalt Institute's LCA study reported a higher proportion of carbon intensive crude sources for asphalt binder production than the overall North American average crude slate. When combined with the inclusion of terminal operations, this yields an increased carbon intensity for asphalt binder production and distribution when compared to other datasets. If the asphalt binder dataset from Mukherjee (2016) were used for this report, the carbon intensity of the baseline reference scenario would drop by 17%, from 53.7 to approximately 44.5 kg CO_2e per ton of mix.

combusted during the asphalt pavement life cycle, including end-of-life. This attribute is reflected in the Inventory of U.S. Greenhouse Gas Emissions and Sinks, which assigns Asphalt and Road Oil a storage factor of 1.00, meaning that GHG emissions from combustion of asphalt binder are negligible. (U.S. EPA, 2021).

2.2.2 Aggregates

Aggregates have a much lower carbon footprint than asphalt binder on a mass basis, approximately 1.8 kg CO_2e per ton of aggregate for material extraction and processing (A1) according to the U.S. Life Cycle Inventory (USLCI) database. Based on a typical aggregate content of 95% for a virgin mixture, this equates to GHG emissions of 1.7 kg CO_2e per ton of mix. For a simple mix with no recycled materials and a 5% binder content, manufacturing of **aggregates represents only 6% of the carbon footprint of the materials stage (A1) of an asphalt mixture (Figure 4) and 3% of the cradle-to-gate (A1-A3) GHG emissions, even though aggregates represent 95% of the mix by mass.**

2.2.3 Recycled Materials

Recycled materials such as reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), and ground tire rubber (GTR) can replace new materials in asphalt mixtures. Emissions from recycled materials are typically evaluated using the cut-off approach, meaning that they enter the current product system's life cycle burden-free with the system boundary typically established at the point where recycled materials arrive at the central processing or storage location (ISO 21930). For RAP, this effectively means that activities before arriving at the RAP stockpile (e.g., milling and transport) are not included in the cradle-to-gate stages of a new asphalt mixture. Only the energy and emissions associated with transporting those materials from the central collection or storage area and processing them (e.g., RAP crushing and screening) are included. Thus, recycled materials tend to reduce the carbon footprint of an asphalt mixture by replacing new materials and avoiding the upstream emissions associated with extracting, transporting, and manufacturing the new materials they replace.

RAP and RAS

Mukherjee (2016) found that the energy associated with processing RAP is 0.1 gallons of diesel fuel per ton of material processed. This translates to A1 emissions of approximately 0.7 kg CO2e per ton of RAP processed, which is a small fraction of the emissions associated with raw materials extraction and processing for a typical mix. Similarly, emissions from processing RAS are approximately 3.2 kg CO_2e per ton of RAS processed. Since the A1 emissions for a mix without any RAP or RAS are 30.3 kg CO_2e per ton of mix (Figure 3), **using RAP and RAS can significantly reduce the cradle-to-gate GHG emissions (A1-A3) of asphalt mixtures by offsetting the use of virgin asphalt binder and aggregates in the mix.** End-of-life emissions for milling operations (C1) and transport of RAP to the initial storage location (C2) are discussed in Section 2.8.1. GHG emissions reductions from use of RAP and RAS are explored in Section 3.1.1.

Other Recycled Materials and Industrial Byproducts

Other recycled materials and industrial byproducts that may be used in asphalt mixtures include steel slag, blast furnace slag, GTR, recycled fibers, and coal combustion products. As shown in Table 1, these materials are generally used in relatively small quantities and therefore offer a limited opportunity to reduce the embodied emissions of asphalt mixtures at an industry-wide level at this time. No data is currently available regarding the upstream impacts associated with processing steel slag, blast furnace slag, or recycled fibers. As reported by Farina et al. (2023), several LCA studies have been published for asphalt mixtures that contain GTR, but the results are complicated due to the wide diversity of GTR applications in asphalt mixtures (wet process, dry process, and engineered crumb rubber) and consideration of different allocation processes (cut-off method, economic allocation, and system expansion). A thorough analysis of these materials is not included in this report.

2.2.4 Additives

Additives can be used in asphalt mixtures and asphalt binders to improve performance. Common additives include polymers for improved binder elasticity and rutting resistance; anti-stripping agents to reduce moisture susceptibility; warm-mix additives to reduce mix production temperatures and improve workability; recycling agents to improve the quality of mixes with high RAP or RAS contents; cellulose fibers to prevent binder draindown in specialty mixtures; and aramid fibers to improve mix performance.

Table 1. Use of recycled materials and industrial byproducts in asphalt mixtures in 2021. From Williams et al. (2022).

Material	Typical Function	Consumption in Ashalt Mixtures (tons)[1]
RAP	Aggregate and asphalt binder replacement	94,600,000
RAS	Aggregate and asphalt binder replacement	630,000
Steel Slag	Aggregate replacement	526,295
Blast Furnace Slag	Aggregate replacement	792,502
GTR	Mixture/binder modifier (wet process) or aggregate replacement (dry process)	14,000
Recycled Fibers	To prevent drain-down in open-graded mixes	2,482
Coal Combustion Products	Mineral Filler	1,700

[1] Values for RAP and RAS are estimated national totals. Values for all other materials are as reported.

When additives are used, they tend to be in relatively small amounts (less than one percent of total mix, by weight). The publicly available data on the upstream GHG emissions of asphalt additives are presented in Table 2. The information in Table 2 only provides data on upstream GHG emissions and does not reflect the emissions reductions that can be achieved in subsequent life cycle stages through the use of additives.

Even at a low percentage by weight of total mixture, GHG emissions of some additives can be significant. For example, hydrated lime, which is required by numerous agency specifications as an antistripping agent, can increase the cradle-to-gate GWP of the baseline reference scenario by about 23%, from 53.7 to 66.3 kg CO_2e/ton of mix. Generally, the increase in emissions from these additives is offset by extended pavement life, resulting in an overall reduction in life cycle GHG emissions (Schlegel et al., 2016).

Biobased additives can actually have a negative carbon footprint because they contain biogenic carbon. Asphalt mixtures are not typically combusted at

Table 2. GHG emissions associated with additive manufacturing (A1 of the asphalt mixture life cycle) based on nominal content in an asphalt mixture.

Material	Function	Upstream GHG Emissions (kg CO_2e/ton material)[5]	Nominal Content in Asphalt Mixture[6]	Nominal Contribution to Asphalt Mixture GHG Emissions (kg CO_2e/ton mix)	Reference
Hydrated Lime[1]	Anti-strip	1,260	1%	12.6	USLCI
SBS[2]	Binder Modification	3,869	0.18%	6.8	Asphalt Institute (2019)
GTR[3]	Binder Modification	396	0.40%	1.6	Asphalt Institute (2019)
PPA[4]	Binder Modification	3,662	0.03%	0.9	Asphalt Institute (2019)
Aramid Fibers	Cracking Resistance	6,134 to 7,820	0.01%	0.7 to 0.8	Surface Tech (2022 and 2023)
Rejuvenator, Soy Oil Based	Cracking Resistance	-839	0.06%	-0.5	Cargill (2023b)
WMA Additive, Soy Oil Based	WMA	-888	0.03%	-0.2	Cargill (2023a)
WMA Additive, Tall Oil Based	Reguvenator	-118 to 2,404	0.05%	-0.1 to 1.2	Ingevity (2022 and 2023)

Notes:

[1]Lime, or quicklime, is used as a proxy for hydrated lime. Hydrated lime is typically combined with aggregates and water in a pugmill. The energy needed to evaporate this additional moisture during asphalt mix production is not accounted for in this estimate.

[2]Styrene-butadiene-rubber (SBR) is used as a proxy for styrene-butadiene-styrene (SBS) at a dosage rate of 3.5% by weight of binder by Asphalt Institute (2019).

[3]GTR is ground tire rubber for terminal blend application with no additional polymers, coatings, or extender oils, used at a dosage rate of 8% by weight of binder by Asphalt Institute (2019).

[4]PPA is polyphosphoric acid, used at a dosage rate of 0.5% by weight of binder by Asphalt Institute (2019).

[5]Includes biogenic carbon. See Section 3.12 and Table 4 for more information about biogenic carbon accounting.

[6]Nominal contents may vary significantly depending on the mix design and application. Data provided here are for illustrative purposes only.

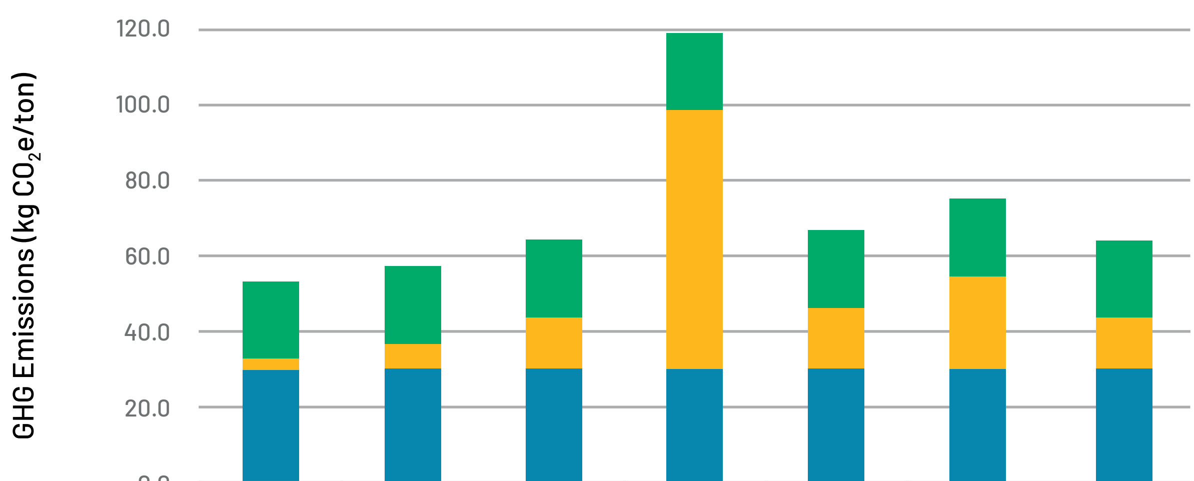
end-of-life and the components do not readily break down. Thus, the use of biobased materials in asphalt mixtures offers a unique opportunity to sequester GHG emissions. Biogenic carbon is explored in more detail in Section 3.1.2.

Public data are not available for many additives, and the performance benefits from using additives can be difficult to quantify, making precise tradeoffs difficult to quantify. **The need for reliable information on the upstream GHG emissions and other environmental impacts of additives continues to grow.**

2.3 Transportation (A2)

GHG emissions from raw material transportation to the asphalt plant depends on the distance and transport mode (truck, rail, barge, etc.) from the material suppliers. Mukherjee (2016) found average transportation distances of 21.5 and 3.9 ton-miles/ton for aggregates and asphalt binder, respectively. Based on these values, transportation adds 2.8 kg CO_2e per ton, 5% of the cradle-to-gate GHG emissions in the baseline reference scenario (Figure 3). In this case, transportation emissions are small, but in some cases when transportation of aggregates is more than 100 miles by truck or 1000 miles by barge, the transportation emissions will be more significant.

Figure 5 shows the results of a sensitivity analysis for transportation stage (A2) GHG emissions using various material transportation scenarios. **Transportation of mix ingredients to the asphalt plant can be a significant factor in the cradle-to-gate stages, depending on the transportation distance and mode** – increasing the distance to 50 miles increases the cradle-to-gate emissions by more than 7% when compared to the average truck scenario. These impacts can be mitigated by switching to a more efficient transportation mode such as train or barge when available, as seen in the comparison when transporting mix ingredients 500 miles via different transportation modes.



	Average Truck	50 Miles Truck	100 Miles Truck	500 Miles Truck	500 Miles Train	500 Miles Inland Barge	500 Miles Ocean Vessel
Total (A1-A3)	53.7	57.7	64.6	119.5	67.2	75.3	64.4
Mix Production (A3)	20.5	20.5	20.5	20.5	20.5	20.5	20.5
Transportation (A2)	2.8	6.9	13.7	68.7	16.3	24.5	13.6
Raw Materials (A1)	30.3	30.3	30.3	30.3	30.3	30.3	30.3

Figure 5. Impact of transport distance on transportation related (A2) GHG emissions. The Average Truck scenario assumes transport distances of 21.5 miles for aggregates and 3.9 miles for asphalt binder (Mukherjee, 2016). The sum of individual life cycle stages may not equal the total due to rounding effects.

It should be noted that the average transport distances reported by Mukherjee (2016) are based on a relatively small dataset (fewer than 20 plants). Generally, plants are located relatively close to the aggregate supply for logistical and economic reasons. In regions with limited adequate-quality aggregates, transportation (A2) can have a major impact on cradle-to-gate GHG emissions, in some cases overwhelming the emissions associated with raw materials (A1) and production (A3). For example, aggregates are routinely transported more than 2,000 miles by ship to some markets in Florida and Hawaii, both of which have limited supplies of adequate-quality aggregates for asphalt mixtures. GWP emissions for transporting aggregates 3,000 miles by ship would more than double the total cradle-to-gate emissions in the baseline reference scenario.

2.4 Mix Production (A3)

GHG emissions during asphalt mix production include direct emissions from on-site fuel consumption and indirect emissions from upstream electricity production. Production-related emissions sources include fuel consumption for the burner, hot oil heater, on-site generator, as well as mobile equipment such as loaders and trucks, and other fuel-burning equipment that may support asphalt plant operations.

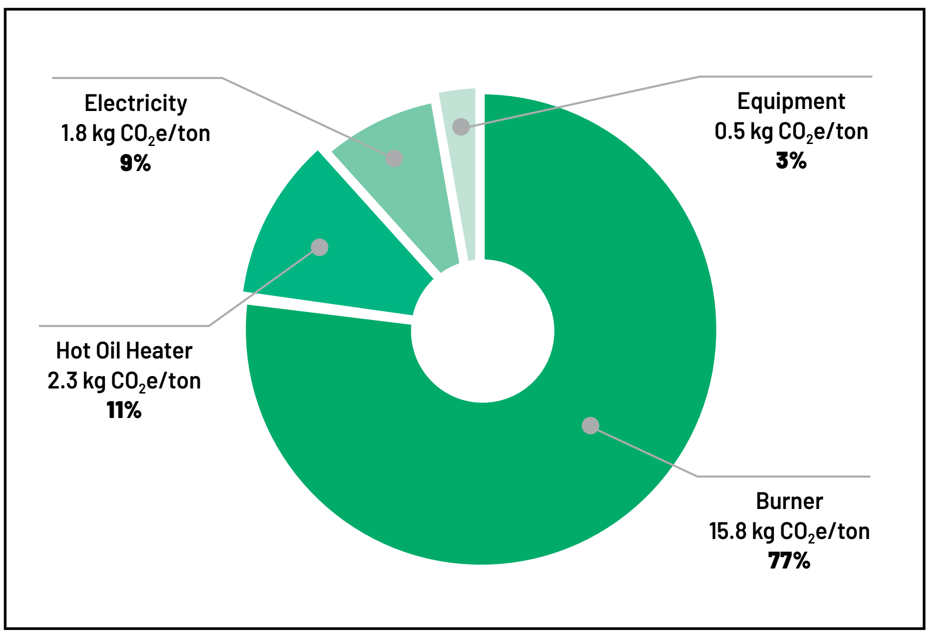


Figure 6. Mix production related GHG emissions (A3) for a typical asphalt plant with grid-supplied electricity that consumes natural gas for the burner and hot oil heater and diesel fuel for mobile equipment. Data inputs are provided in Appendix A. The sum of individual unit processes does not equal the A3 total of 20.5 due to rounding effects.

The largest single source of GHG emissions during mix production is burner fuel consumption (Figure 6). Opportunities to reduce GHG emissions during asphalt mix production are discussed in Section 3.2.

2.5 Pavement Construction (A4-A5)

Initial pavement construction activities include construction of new roads or additional lanes on existing roads. GHG emissions during construction of asphalt pavements include fuel consumption during transportation of pavement materials to the jobsite (A4) and fuel consumption associated with paving operations (A5). Quantifying GHG emissions during initial pavement construction is relatively straightforward as this stage of the pavement life cycle does not typically involve impacts to the traveling public such as work zone congestion or changes to pavement smoothness and texture. In general, **construction related GHG emissions for asphalt pavements are relatively low, typically around ten percent or less of the cradle-to-gate (A1-A3) emissions associated with mix production** (Butt et al. 2019).

While A4 and A5 emissions tend to be low relative to the cradle-to-gate stages, there is a notable exception when asphalt mixtures are transported long distances from the asphalt plant to the jobsite. To illustrate the potential impacts of transporting mix to the jobsite, picture a scenario in which two separate plants produce the same asphalt mix under the baseline reference scenario of 53.7 kg CO_2e/ton mix. If one plant is located 5 miles from the jobsite and another plant is located 50 miles from the jobsite, the cradle-to-jobsite emissions (A1-A4) would be 54.4 and 60.5 kg CO_2e/ton mix, respectively. The difference of 6.1 kg CO_2e/ton mix is 11% higher for the plant located 50 miles from the jobsite, even though the cradle-to-gate emissions from both plants are identical.

Transportation of asphalt mixtures from the plant to the jobsite is an important consideration in the context of Buy Clean policies that require or incentivize "low carbon" asphalt mixtures.

Pavement maintenance, rehabilitation, and reconstruction of existing roads can be viewed through the lens of pavement construction (A4-A5) at the individual project level, but they can also be viewed through the lens of maintaining an existing asset (B2-B5) from a network or whole pavement LCA perspective. Maintenance, rehabilitation, and reconstruction are covered in detail in Section 2.7.

2.6 Use of Pavements (B1 and B6)

Pavement use falls under two life cycle stages. Use (B1) covers environmental impacts connected to the normal use of products (ISO 21930). In the context of a whole pavement LCA, B1 should include emissions from vehicles that drive on the pavement. Operational energy use (B6) covers the operation of integrated technical systems for a product (ISO 21930). The most common example of B6 activities for a pavement is electricity use for lighting. The remainder of this section focuses on vehicle emissions (B1).

LCA studies rely on models to estimate emissions during the use stage of pavements, whereas cradle-to-gate emissions are typically based on activities that have already happened (or, at the very least, have significant less uncertainty). Predictive models are based on parameters such as expected traffic loading, vehicular fuel efficiency, and the carbon intensity of surface transportation fuels, all of which have significant uncertainty. This uncertainty in use stage models is an important consideration.

Chappat and Bilal (2003) identified that GHG emissions from vehicle operations are 10 to 400 times greater than the emissions associated with materials, construction, and maintenance of the roads that vehicles drive on. Roads with high traffic volume have the greatest differential. A study conducted by the Virginia Transportation Research Council (VTRC) found that GHG emissions from vehicle operations during the use stage accounted for approximately 98% of total life cycle emissions, about a factor of 50 greater than emissions associated with materials, construction, and maintenance for several highways in Virginia (Amarh et al., 2021). The VTRC study found that vehicle type can affect use stage emissions, with large trucks traveling on low-volume roads sometimes causing significant emissions.

2.6.1 Impact of Pavement Rolling Resistance on Vehicle Fuel Consumption

Small changes to a pavement's rolling resistance can affect vehicle fuel consumption and significantly impact life cycle GHG emissions. Estimates to quantify the effect of pavement rolling resistance on vehicle emissions vary. One estimate suggests that rolling resistance accounts for 4-7% of gasoline powered vehicle fuel consumption (U.S. Department of Energy and U.S. EPA, 2021). The Minnesota Road Research Facility (MnROAD) estimated that rolling resistance contributes to 10-13% of the total fuel consumed by a heavy-duty truck (Paterlini et al., 2015), suggesting that rolling resistance has a greater impact on the fuel economy of heavy trucks than passenger cars.

The rolling resistance of pavements is controlled by three properties – smoothness, texture, and stiffness. The relative impact of these properties on pavement rolling resistance and vehicle fuel consumption was reviewed by Willis et al. (2015), who found general consensus in the literature that smoothness and texture have the most significant effects on pavement rolling resistance. For example, the Missouri DOT found that improving the international roughness index (IRI) of a road from 130 in/mile to 60 in/mile improved vehicle fuel efficiency of dump trucks by 2.46% (Amos 2006). FHWA (2000) reported that rehabilitation of an accelerated pavement test facility improved the fuel efficiency of heavy trucks by 4.5 percent.

Surface macrotexture is a measure of variations in the pavement surface profile with a wavelength between 0.5 and 5 mm. Ullidtz et al. (2010) found that a 0.5 mm increase in the mean profile depth (MPD), a measure of the pavement surface macrotexture, would increase the pavement rolling resistance by about 10 percent. For reference, dense graded asphalt pavements have a typical MPD of 0.5-1.4 mm (Henault and Bliven, 2011). Effectively, this means that doubling the MPD from

0.5 to 1.0 mm increases the rolling resistance by 10 percent. NASEM (2012) found that pavement surface texture has a significant impact on fuel consumption only for heavier trucks traveling at low speed. It's important to note that some pavement texture is good – microtexture contributes directly to skid resistance, and macrotexture helps clear the water from under the tire (National Academy of Science, 1972).

The effect of pavement stiffness (also referred to as deflection or structural response) on rolling resistance and vehicle fuel consumption is more complex. Computational models of excess fuel consumption from pavement deflection disagree on the magnitude of this effect and generally have not been validated or calibrated through published field studies, although the relative impact of pavement deflection appears to be lower than smoothness and texture (Gu et al., 2020; Greene et al., 2013).

Computational models do not always predict real-life results, which is why field studies are important. Some models suggest that the structural response of different pavement types (stiff vs. flexible) can affect vehicle fuel consumption, but the main influence is limited to heavy trucks traveling at slow speeds (less than 35 miles per hour) during summertime conditions (Zaabar and Chatti, 2012). A comprehensive field test designed to determine the effect of pavement deflection on vehicle fuel consumption found that "the magnitude of a pavement structure type's influence on fuel consumption… is too small for meaningful conclusions about the effect of pavement type" (Butt et al., 2022). However, the field test conducted by Butt et al. (2022) does not settle the science because it did not assess all potentially relevant scenarios, such as heavy trucks moving at slow speeds (less than 35 miles per hour).

Additional research is needed to validate and calibrate computational models of the impact of pavement stiffness on vehicle fuel consumption, integrate these models into LCA studies, and identify context-sensitive best practices for optimizing pavement rolling resistance to reduce vehicle fuel consumption.

2.6.2 Impact of Traffic Flow Conditions on Vehicle Fuel Consumption

When modeling the use stage of a pavement, it's also important to use realistic traffic flow conditions to account for increased emissions associated with idling, acceleration, and deceleration that occurs when roads are congested. For example, Haslett et al. (2019) demonstrated that modeling realistic traffic flow conditions increased GHG emissions during the use stage (B1) by 6.4% in comparison to baseline conditions for a section of I-495 in Massachusetts. In contrast, traffic conditions are typically modeled using a steady state traffic flow for simplicity.

2.7 Maintenance, Rehabilitation, and Reconstruction (B2-B5)

Periodic maintenance of asphalt pavement surface layers is required to repair distresses such as cracking and rutting and to maintain acceptable ride quality. Maintenance also prevents damage to the underlying structural pavement layers and the base, prolonging the service life of the road before rehabilitation or reconstruction is required.

Navigating the Maze of Information Modules Assigning maintenance, rehabilitation, and reconstruction activities to specific life cycle stages can be challenging because the information modules were not developed with pavements in mind. For example, with a simple 1.5-inch mill-and-inlay project, should the milling activity be classified as part of the maintenance operations (B2-B5) or as end-of-life removal (C1-C4)? The answer depends on the system being studied. If the focus is on asphalt mixtures as a product, milling would likely be classified as an end-of-life activity (C1-C4). A whole pavement LCA, on the other hand, would classify routine milling expected to occur in the future as part of a maintenance activity (B2-B5). If that's not confusing enough, the maintenance stages (B2-B5) inherently include the product (A1-A3), construction (A4-A5), and end-of-life (C1-C4) stages within the context of each maintenance activity. To add further confusion, agencies sometimes use different nomenclature for the same activities. It's important to clearly state which activities are assigned to which stages and to be sure not to omit any relevant activities.

Maintenance, rehabilitation, and reconstruction activities (B2-B5) include a variety of technologies and practices. Pavement preservation technologies, which include crack seals, sealcoats, slurry seals, chip seals, thinlays, and others, are applied to roads in good condition to preserve and extend their service life. For roads in fair condition, rehabilitation activities include overlays on top of existing pavements with minimal surface preparation or milling of surface pavement layers followed by overlays. Reconstruction of the pavement structure is often necessary for roads in poor condition. These terms are collectively referred to as "maintenance" throughout the rest of this report for simplicity. In most cases, capacity expansion (e.g., adding travel lanes) would be considered a new construction activity altogether and would not be classified under maintenance (B2-B5).

2.7.1 Direct GHG Emissions During Maintenance Activities

Direct GHG emissions during maintenance activities include production and installation of materials used to maintain roads (A1-A5), including temporary infrastructure used during construction (e.g., additional travel lanes or strengthening of shoulders to handle traffic to accommodate lane closures); excess vehicle emissions caused by work zone congestion (A5); and end-of-life considerations (C1-C4) for RAP and other materials that are removed during maintenance activities.

Most studies that quantify GHG emissions associated with asphalt pavement maintenance focus on milling and overlays. For this type of maintenance activity, GHG emissions associated with materials and construction would be similar to emissions during initial construction as outlined in Sections 2.1 – 2.5 for the A1-A5 life cycle stages. Typically, material quantities are less for maintenance activities than initial construction. Emissions associated with milling operations are described in Section 2.8.1.

Work zone congestion causes excess vehicle emissions, an additional source of GHG emissions during maintenance activities. The magnitude of these emissions is context sensitive and depends on traffic volume as well as the scheduling of maintenance activities. GHG emissions from work zone congestion are negligible for low volume rural roads (Wang et al., 2014a). On the other hand, emissions from work zone congestion can be significant for roads with high traffic volumes, potentially exceeding the emissions from materials and construction (A1-A5) by as much as a factor of five when work is conducted during peak travel hours (Inti et al., 2016). Practices that can mitigate the impacts of maintenance work include using pavement materials that allow for rapid construction schedules, scheduling maintenance work to avoid peak travel hours, and designing perpetual pavements that require less maintenance. **The ability to schedule maintenance activities for high volume roads during periods that avoid peak traffic conditions can significantly reduce GHG emissions.** This should not be construed as a recommendation to pave everything at night, as full weekend closures and other alternative scheduling practices can sometimes be advantageous.

2.7.2 Indirect GHG Emissions Associated with Maintenance Activities

The primary sources of indirect GHG emissions associated with pavement maintenance and rehabilitation include the impact of changes to pavement surface properties (e.g., smoothness and texture) on vehicle fuel consumption and the impact of construction quality on pavement life and future maintenance-related emissions. These impacts can be significant, demonstrating that attention to initial construction quality and maintenance activities can have a significant impact on life cycle GHG emissions. This concept is explored in Section 4.3 of this report.

2.8 End-of-Life (C1-C4)

GHG emissions during end-of-life are caused by combustion of equipment fuel during pavement removal (C1), material transportation from the jobsite to the processing or disposal site (C2), waste processing (C3), and waste disposal (C4). As discussed in Section 2.8.1, direct GHG emissions during pavement removal are relatively low for asphalt pavements. In addition, asphalt pavements typically are not completely removed at end of life. A portion of the old pavement is often reused as part of the reconstructed pavement structure. Section 2.8.2 discusses how to account for remaining service life of existing pavement layers.

2.8.1 Direct Emissions During End of Life

When an asphalt pavement reaches the end of its useful life, the asphalt layers are often removed with a milling machine, transported to the asphalt plant, processed, and recycled into new asphalt mixtures. During maintenance and rehabilitation activities, only the upper 1-2 inches of pavement is removed. During pavement reconstruction, the entire pavement structure is removed down to the unbound aggregate base. While several LCA studies include milling operations within their scope, most are not granular enough to distinguish milling emissions from overall construction related GHG emissions. Based on fuel consumption data provided in the FHWA Pavement LCA Framework, milling of asphalt pavements (C1) emits approximately 2.7 kg CO_2e/ton of RAP removed (Table 3).

GHG emissions associated with transport of RAP from the jobsite to the asphalt plant or central stockpile location for recycling (C2) depends primarily on the distance traveled. An industry survey conducted by NAPA found the average distance from the milling site to the asphalt plant or stockpile location to be 33 miles (Shacat, 2024). This equates to approximately 4.5 kg CO_2e/ton RAP.

In 2021, more than 97% of the 101.3 million tons of RAP returned to asphalt mix producers was recycled or beneficially reused (Williams et al., 2022). Most of this material, about 95 million tons, was recycled directly into new asphalt mixtures. Only 0.1% of the RAP was landfilled. The remainder, about 2.1% of collected RAP, was stockpiled for future use. These results are consistent with the previous ten years of data collected through NAPA's industry survey of recycled materials and warm-mix technologies (Williams et al., 2022) and demonstrate the significant contribution of the asphalt pavement industry to a circular economy.

According to the cut-off method for use of recycled materials, processing of RAP for recycling is included in the Raw Materials stage (A1). Therefore, the Waste Processing stage (C3) and Disposal of Waste stage (C4) are negligible. Emissions associated with processing RAP for asphalt mixtures are discussed in Section 2.2.3. For the small amount of RAP that does go to a landfill, the EPA's Waste Reduction Model (WARM) recognizes that RAP generates zero emissions from landfill methane because it does not contain biodegradable carbon. The WARM model assigns a value of 20 kg CO_2e/ton RAP for transporting RAP to the landfill (20 miles) and use of landfill equipment (C2-C4) (U.S. EPA, 2020b).

Table 3. Fuel Consumption and GHG Emissions Associated with Milling Asphalt Pavement

Parameter	Value	Units	Notes
Productivity, yd^3/hr	50	yd^3 RAP/hr	1
Unit Weight, Asphalt Pavement	2.0	ton/yd^3	2
Productivity, ton/hr	100	ton RAP/hr	= Unit Weight x Productivity, yd^3/hr
Fuel Consumption - Milling	19.8	gal/hr	1
Fuel Consumption - Broom	2.3	gal/hr	1
Fuel Consumption - Total	22.1	gal/hr	= Milling + Broom
Fuel Intensity	0.221	gal/ton	= Fuel Intensity / Productivity, ton/hr
GHG Emission Factor (Well to Wheels)	12.16	kg CO_2e/gal diesel	3
GHG Emissions	2.7	kg CO_2e/ton RAP removed	= Fuel Intensity x GHG Emission Factor

Notes:
1. FHWA (2016), Table 4-11
2. NAPA (2021a)
3. Derived from Deru and Torcellini (2007)

2.8.2 Accounting for Remaining Service Life in Comparative LCA

It's rare for an entire asphalt pavement structure to be completely removed. In most cases, only the surface layers are removed during routine maintenance activities. The underlying layers are reused as part of the new pavement structure.

To compare pavement design alternatives, each design might have a different remaining service life at the end of the analysis period. The cut-off method allocates benefits and impacts of recycled materials, but does not account for design alternatives with different remaining service lives. Importantly, it does not address how to account for lower pavement layers that remain in-place at the end of the analysis period.

Few LCA studies discuss how the remaining service life for different design alternatives is accounted for. A common approach is to express all emissions as an annualized value and pro-rate maintenance treatments that extend beyond the analysis period (Wang et al. 2013). For example, if a mill-and-overlay with a ten-year expected life is applied at year 30 of a 35-year analysis, only half of the emissions are considered in the LCA. While this approach may be reasonable in some cases, it infers that the pavement structure has no value at the end of the analysis period.

Asphalt pavements are rarely reconstructed at the end of their service life. As observed by Musselman and West (2020), only the upper pavement layers are milled and resurfaced. The lower pavement layers remain intact and provide structural support for the pavement beyond the analysis period. Thus, lower pavement layers have a residual value that should be accounted for. Although Musselman and West (2020) focused their research on life cycle cost analysis (LCCA), the same concepts can be applied to LCA. For instance, it may be appropriate to annualize GHG emissions associated with lower pavement layers (in addition to the last maintenance treatment) over a period that extends beyond the analysis period to reflect their actual useful life, and only include the annualized emissions that fall within the analysis period. Additional research is needed to better understand and account for differential remaining service lives when comparing LCA results of alternative pavement designs.

2.8.3 Emissions Associated with Reconstructing Other Pavement Materials

Asphalt pavements are often placed on concrete pavements that have reached the end of their useful life. Various techniques are used, including direct overlays that may or may not include geotextiles or crack attenuating intermediate layers, rubblization, crack and seat, or break and seat of existing concrete pavements. There are few LCA studies of these practices. One study conducted by Weiland and Muench (2010) found that replacing the existing concrete pavement with a full depth asphalt pavement or treating the concrete pavement with crack and seat followed by an asphalt pavement overlay reduced life cycle GHG emissions by 32% and 62% (respectively) relative to reconstructing with new concrete pavement. However, the scope of their study did not include vehicle emissions during use or work zone congestion and the only upstream dataset available at the time was based on European data. Additional research is needed to characterize GHG emissions of asphalt pavement overlays used to rehabilitate concrete pavements.

2.9 Summary of GHG Throughout the Asphalt Pavement Life Cycle

As presented in Section 2, GHG emissions during the cradle-to-gate stages of asphalt mix production (A1-A3) are strongly influenced by burner fuel consumption and upstream impacts of asphalt binder production. In some cases, transport of aggregates can also be significant when aggregates are sourced from long distances. Emissions during construction activities (A4-A5) tend to be relatively small compared to the cradle-to-gate stages, but transportation to the jobsite (A4) can be significant in some cases. Design and construction processes can significantly impact future emissions. Increased frequency of maintenance and rehabilitation (B2-B5) caused by inadequate design or poor construction quality and increased fuel consumption caused by pavement roughness (B1) will increase GHG emissions in the life cycle. For roadway pavements with moderate to high traffic volumes, emissions from vehicle fuel consumption (B1) can far outweigh emissions during all other life cycle stages.

Chapters 3 and 4 explore industry and agency driven opportunities to reduce GHG emissions throughout the asphalt pavement life cycle.

3. INDUSTRY DRIVEN OPPORTUNITIES TO REDUCE GHG EMISSIONS

Numerous opportunities exist to reduce GHG emissions throughout the life cycle of asphalt pavements. Many of the emissions reduction practices described in this report require cooperative involvement of industry and agencies for successful implementation. In each case, however, the primary nexus of control belongs to either industry or agencies. Chapter 3 explores the GHG emission reduction opportunities that are primarily under the asphalt paving industry's control (viz., asphalt mix producers, paving contractors, and upstream material suppliers). Industry-driven activities include the use of recycled materials, use of biobased materials, energy efficiency during mix production, use of alternative fuels, and pavement construction considerations.

While the activities in Chapter 3 are primarily under industry's control, it's important to acknowledge that agencies influence many of these activities through agency specifications and contractual requirements. For example, asphalt mix producers can only increase RAP content to the extent that specifications allow, and some agencies retain ownership of the RAP, precluding any opportunity for the mix producer to recycle it back into the mix.

Economics also plays an important role in implementation. Some GHG reduction practices can decrease construction costs, creating a "win-win" situation in which reducing emissions costs less. Other practices may increase construction costs, making it difficult for contractors to implement in a low-bid environment unless financial incentives or contractual requirements apply to all contractors.

3.1 Asphalt Mixture Materials

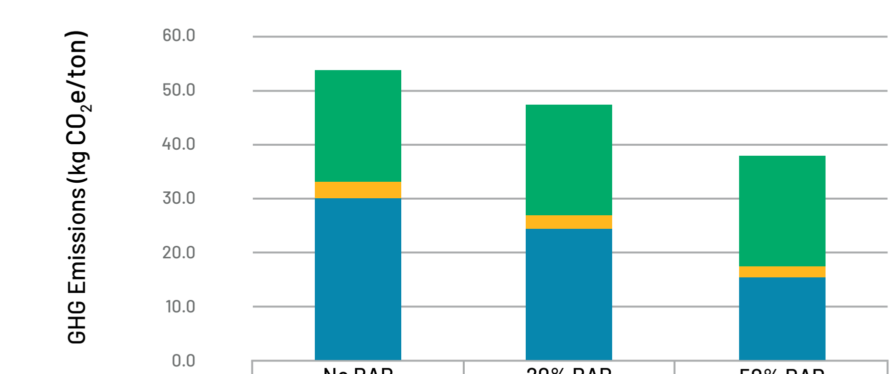
One of the most effective ways to reduce the cradle-to-gate GHG emissions of asphalt mixtures is through use of recycled materials such as RAP and RAS. The carbon footprint of these materials is much lower than new aggregate or asphalt binder. With the ability to recycle RAP directly into new asphalt pavements, RAP is the foundation of a truly circular economy. Other material considerations include feedstock carbon and use of biobased materials.

3.1.1 Recycled Materials

Emissions Reduction from Use of RAP

Figure 7 shows the reduction in cradle-to-gate GHG emissions for a mix with no RAP, 20% RAP, and 50% RAP. The mix with no RAP is the same baseline reference scenario presented in Section 2.1. Input parameters for the other scenarios are provided in Appendix A. All scenarios assume the same plant operational energy intensity (A3), although this may vary in practice depending on the plant configuration and operational parameters. Materials related emissions (A1) decrease as the RAP content increases because emissions associated with processing RAP are much lower than the emissions from sourcing new aggregates and asphalt binder (see Section 2.2.3). Transportation emissions (A2) may also decrease if RAP is transported a shorter distance than virgin aggregates (see Appendix A). **The mixes with 20% and 50% RAP contents reduce cradle-to-gate (A1-A3) emissions by 12% and 29%, respectively, relative to the mix without any RAP.**

Although use of RAP is provided here as an industry-driven opportunity, the industry's ability to use RAP is often controlled by agency decisions. For example, the Federal Aviation Administration (FAA) generally does not allow the use of RAP on airfield P-401 surface mixtures, although the P-403 specifications allow RAP in base courses and airfield shoulders at the engineer's discretion. Some municipal agencies and state DOTs have similar prohibitions on the use of RAP. Other agencies allow the use of RAP, but don't allow the contractor to maintain possession of the millings, instead keeping the RAP for agency use such as shoulder dressing.



	No RAP	20% RAP	50% RAP
Total (A1-A3)	53.7	47.4	37.9
Mix Production (A3)	20.5	20.5	20.5
Transportation (A2)	2.8	2.5	1.9
Materials (A1)	30.3	24.4	15.5

Figure 7. Impact of RAP on cradle-to-gate (A1-A3) GHG emissions of an asphalt mixture. Total asphalt binder content for each mix is 5%. RAP is assumed to also have a 5% asphalt binder content and to offset the virgin binder content accordingly (e.g., a mix with 20% RAP would have a virgin binder content of 4% and a recycled binder content of 1%). Units in the data table are in kg CO_2e/ton of mix. The sum of individual life cycle stages may not equal the total due to rounding effects.

The average RAP content in the U.S. increased rapidly from 2009 to 2014, from 15.7% to 20.4%. After 2014, the average RAP content increased slowly, reaching 21.9% in 2021 (Figure 8). Williams et al. (2022) estimated that use of RAP provided more than $3.4 billion in economic savings and net GHG emissions reduction of 2.6 MMT CO2e in 2021, demonstrating that use of RAP can reduce economic costs as well as GHG emissions.

Emission Reductions from Use of RAS

Recycled asphalt shingles (RAS) fall under two categories, manufacturing waste asphalt shingles (MWAS) and post-consumer

Impacts of Transporting RAP. Transport of RAP and other recycled materials contributes to both A2 emissions and C2 emissions. For the A2 stage, Shacat (2024) found that 82% of asphalt plants in the U.S. process their RAP on-site (within 2 miles of the asphalt plant). The remaining 18% of asphalt plants transport RAP from another processing or storage site located an average of 31 miles from the asphalt plant. These distances were used to conduct a sensitivity analysis of the impact of RAP transport distance for a mix with a nominal RAP content of 20%. The short-haul RAP transport scenario of 2 miles resulted in a value of 2.3 kg CO_2e per ton of mix for A2 emissions, which is similar to the value of 2.5 kg CO_2e per ton of mix for the weighted average transport distance used for the 20% RAP scenario in Figure 7. The long-haul RAP transport scenario of 31 miles increased the A2 emissions to 3.1 kg CO_2e per ton of mix for the 20% RAP scenario.

For the C2 stage, Shacat (2024) found that the average distance from the pavement maintenance jobsite to the initial processing or storage location is 33 miles. For the 20% RAP and 50% RAP mixes, the C2 transportation emissions from the previous pavement life would be approximately 0.9 and 2.3 kg CO_2e per ton of mix produced, respectively.

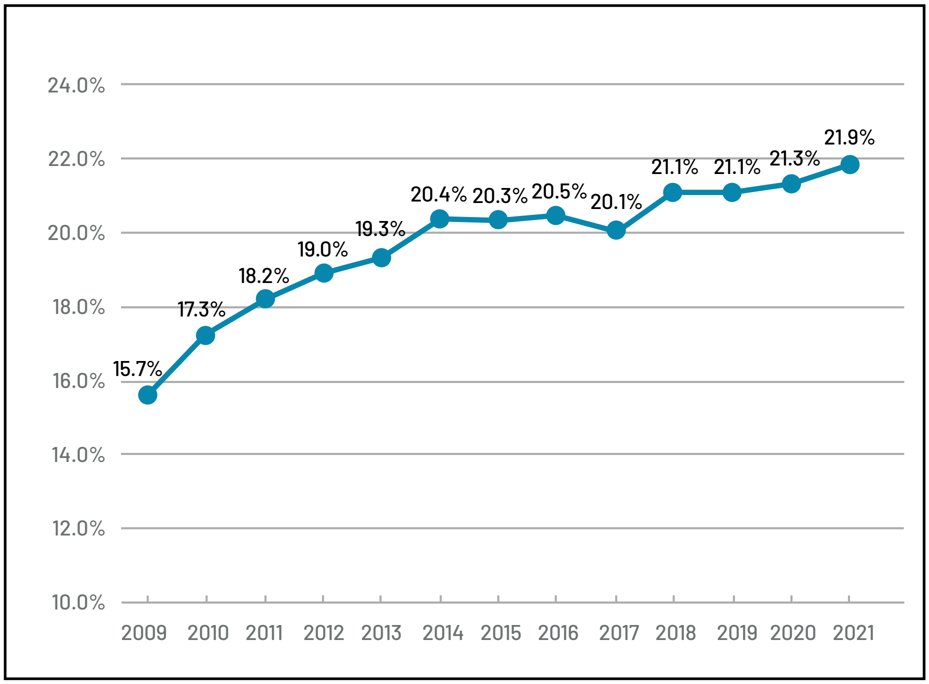
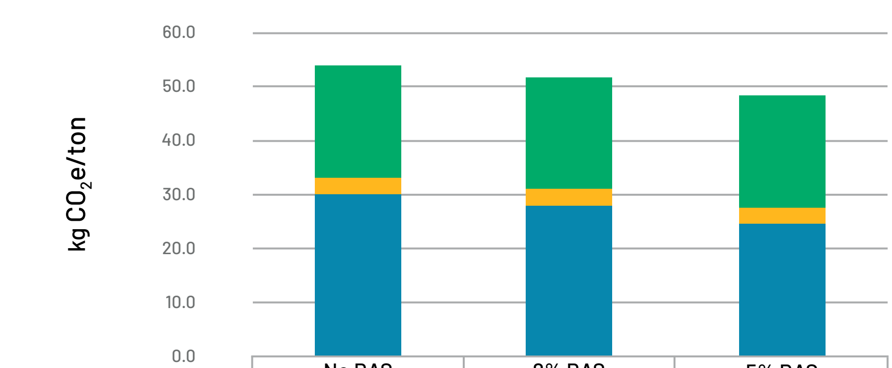


Figure 8. Average RAP content of new asphalt mixtures, 2009-2021. From the IS-138 series (e.g., Williams et al. 2022).

asphalt shingles (PCAS). Both are commonly used in asphalt mixtures, with 25 states reporting use of RAS in 2021 (Williams et al., 2022). The asphalt binder content of RAS is relatively high, typically 15% or more, although it's a much stiffer grade of binder than is normally used in paving materials. Use of RAS is limited by factors including regional availability, restrictions by state and local environmental agencies, and specifications.

Stiffness of the asphalt binder can be addressed through the use of softer binders and performance testing under a balanced mix design framework (Wang et al., 2020). Still, additional research is needed to ensure acceptable performance of asphalt mixtures that contain RAS and understand how use of RAS affects life cycle GHG emissions.

Figure 9 shows the reduction in cradle-to-gate GHG emissions for a mix with no RAS, 2% RAS, and 5% RAS. The mix with no RAS is the same baseline reference scenario presented in Section 2.1. The 2% and 5% RAS mixes have recycled binder ratios (RBRs) of 8% and 20%, respectively. Input parameters for the scenarios are provided in Appendix A. The mixes with 2% and 5% RAS contents reduce cradle-to-gate (A1-A3) GHG emissions by 4% and 10%, respectively. These emissions reductions do not account for avoided burdens associated with not sending end-of-life shingles to landfill, which requires a consequential LCA to evaluate. Consequential LCA is discussed in Section 5.4.



	No RAS	2% RAS	5% RAS
Total (A1-A3)	53.7	51.5	48.3
Plant Operations (A3)	20.5	20.5	20.5
Transportation (A2)	2.8	2.9	3.1
Materials (A1)	30.3	28.1	24.7

Figure 9. Impact of RAS on cradle-to-gate (A1-A3) emissions of an asphalt mixture. Total asphalt binder content for each mix is 5%. RAS is assumed to have a 20% asphalt binder content and to offset the virgin binder content accordingly (e.g., a mix with 5% RAS would have a virgin binder content of 4% and a recycled binder content of 1%). Units in the data table are in kg CO_2e/ton of mix. The sum of individual life cycle stages may not equal the total due to rounding effects.

3.1.2 Biobased Materials

GHGs can also be removed from the atmosphere and stored in biobased materials. Biobased materials used in asphalt mixtures include liquid anti-strips, WMA additives, recycling agents, and alternative asphalt binders. These materials are inert (they don't decompose in landfills) and offer an opportunity to sequester biogenic carbon, permanently removing it from the atmosphere. For example, Pett-Ridge et al. (2023) found that substituting 10% of asphalt binder consumption in the U.S. with bio-asphalt could account for 13-15 million metric tonnes of carbon dioxide removal and sequestration per year by 2050.

There are several different methods to quantify GHG emissions and uptakes associated with biogenic carbon (Hoxha et al., 2020), creating confusion and the potential for misinterpreting results. However, ISO 21930 provides a consistent approach for evaluating the impacts of biogenic carbon. Under ISO 21930, biogenic carbon enters the product system during managed agricultural activities (e.g., growing soybean feedstock for soy oil-based additives) or when it is harvested from natural systems (e.g., harvesting pine trees for tall oil-based additives). When biogenic carbon enters the product system it is assigned a value of -1 kg CO_2e/kg CO_2 of biogenic carbon, recognizing that atmospheric carbon dioxide has been sequestered into biobased material. Wood must originate from sustainably managed forests for this negative flow of biogenic carbon to be included. Note that 1 kg of biogenic carbon (as an element in a biobased material) is equivalent to 44/12 kg CO_2 to account for the molecular weights of carbon dioxide and elemental carbon in the chemical reaction that occurs during photosynthesis.

When biogenic carbon is emitted (e.g., through combustion of biofuels), it's assigned a value of +1 kg CO_2e/kg CO_2 of biogenic carbon. ISO 21930 also requires emissions of biogenic carbon to be accounted for when emitted at the end of life for products and packaging (e.g., during decomposition in a landfill). Methane emissions (e.g., from a landfill) must be characterized as CO_2e, implying that biogenic carbon uptake and emissions will not always balance mathematically when expressed as CO_2e. Finally, ISO 21930 requires GHG emissions from land-use change to be included in the calculations, with wood from sustainably managed forests assigned a value of zero emissions from land use change.

Since asphalt mixtures are not typically combusted at end of life, the biogenic carbon from asphalt additives is assumed to be sequestered indefinitely. Table 4 provides a list of asphalt additives with published EPDs that account for biogenic carbon. These additives have a small but noticeable impact on the cradle-to-gate emissions of an asphalt mixture when biogenic carbon is accounted for. For example, applying a dosage rate of 1.5% by weight of total binder to Rejuvenator 1 in Table 4 translates to 0.075% by weight of total mixture for a mix with a 5% total binder content, resulting in a GWP contribution of -0.63 kg CO_2e/ton of asphalt mixture. If this were applied to the 50% RAP scenario in Figure 7, cradle-to-gate emissions for that mix would reduce from 37.9 to 37.3 kg CO_2e/ton of asphalt mixture.

Biobased binders and binder extenders are another opportunity to sequester biogenic carbon in asphalt pavements. Shacat et al. (2022) discussed various feedstocks that have been investigated for development of biobased binders and binder extenders,

Table 4. Carbon footprint of asphalt additives with available data to account for biogenic carbon removals.

Product Type	GWP (not including biogenic carbon)	Biogenic carbon content	Emissions from land use and land use change	GWP (including biogenic carbon)	Reference
	kg CO_2e/ton product	kg CO_2e/ton product	kg CO_2e/ton product	kg CO_2e/ton product	
Rejuvenator	584	-1,434	11	-839	Cargill (2023b)
WMA 1	723	-1,623	12	-888	Cargill (2023a)
WMA 2	1,896	-2,014	0.3	-118	Ingevity (2023)
WMA 3	3,475	-1,070	0.1	2,404	Ingevity (2022)

Note: Data from the source EPDs have been converted to consistent units for this table.

including animal fat, palm oil, lignin, and swine manure. Pett-Ridge et al. (2023) explore the potential for biobased binders as a carbon dioxide removal strategy in more detail. Significant research is needed to develop these technologies, assess their life cycle GHG emissions, and bring them to market.

3.2 Asphalt Mixture Production

Numerous opportunities exist to reduce energy consumption and GHG emissions during asphalt mix production, including warm-mix asphalt (WMA) technologies to reduce mix production temperature, energy efficiency practices such as stockpile moisture control, and changing the burner fuel type. Cold recycling is a process that offers significant emissions reduction potential by producing asphalt mixtures with very high RAP contents at ambient temperature, although the potential application of cold recycling technologies may be limited. These practices and technologies are explored in more detail in this section.

3.2.1 Warm Mix Asphalt

WMA technologies allow asphalt mixtures to be produced at reduced temperature, typically about 25-50°F lower than conventional hot-mix asphalt (HMA). Temperature reductions as high as 90°F have been documented. In fact, WMA was initially developed in Europe because countries wanted to reduce emissions in response to the Kyoto Protocol. The GHG-related benefits of WMA include reduced burner fuel consumption and reduced stack emissions (NASEM 2014). NASEM (2014) found average energy savings of 1,100 Btu/°F/ton of mix produced using WMA technologies. Data shown in Figure 10 uses a lower assumption of 1,000 Btu/°F/ton. Plant GHG emissions (A3) are reduced 9-16% for a typical asphalt plant that burns natural gas with temperature reductions of 30° and 50°F, respectively (Figure 10). This translates to potential cradle-to-gate (A1-A3) emissions reductions of 3.6-6.0% using WMA technologies. Not included in this evaluation are upstream emissions from the WMA additives or reduced electricity for baghouse air handling.

WMA technologies can also be used without reduced temperature, in which case they are a compaction aid providing improved workability and, sometimes, antistrip properties. In this case WMA technologies extend pavement life, resulting in reduced life cycle GHG emissions. Reduced life cycle GHG emissions from increased pavement life is discussed in Section 3.3.2. In 2021, about 41% of asphalt mixtures produced in the U.S. used WMA technologies, and 53% of that was produced with a temperature reduction of at least 10°F (Williams et al., 2022).

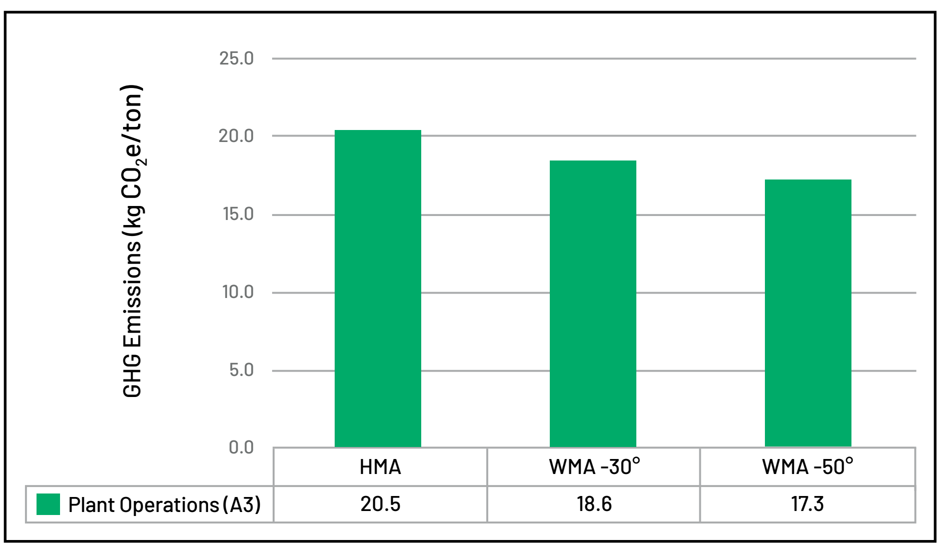


Figure 10. Potential reductions in GHG emissions from use of WMA technologies to reduce mix production temperature. HMA is hot-mix asphalt produced at a typical plant using natural gas for the baseline reference scenario presented in Section 2.1. WMA scenarios assume a reduction in burner fuel consumption of 1,000 Btu/°F/ton.

Another application of WMA is during production of stone matrix asphalt (SMA). While a typical SMA mix uses cellulose fibers to reduce drain-down of the asphalt binder, several states have piloted the use of WMA technologies to eliminate the fiber (Steger, 2018). One company found a 25% reduction in burner fuel consumption while reducing the mix production temperature by 40-50°F. As an added benefit, they were able to reduce the asphalt binder content of the fiberless SMA mix from 6.7% to 6.4% (Lender, 2022).

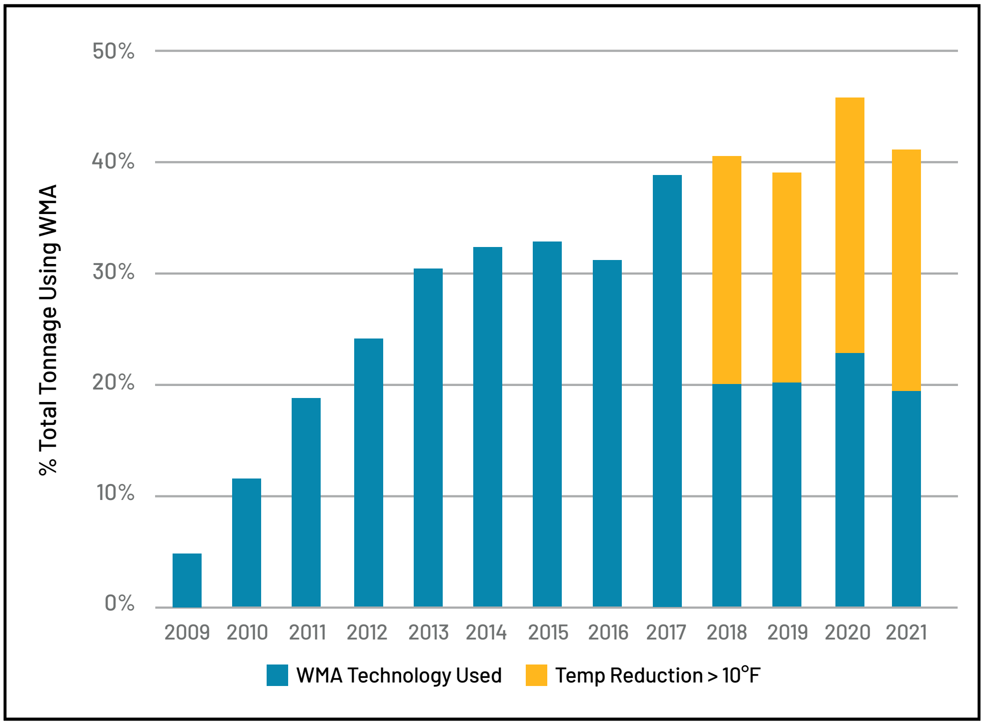


Figure 11. Percent of total tonnage produced using WMA technologies, 2009-2021. Data prior to 2018 did not differentiate between WMA production and WMA production with a temperature reduction. From Williams et al. (2022).

Figure 11 shows WMA technology use has grown substantially from about 5% of total mix production in 2009 to 41.1% of total mix production in 2021. Williams et al. (2022) estimated that reducing mix production temperature through the use of WMA technologies resulted in a total GHG emission reduction of 0.08 MMT CO_2e in 2021, equivalent to the annual emissions of 17,000 passenger vehicles.

The rapid adoption of WMA technologies was supported by focused research and deployment activities by state agencies, FHWA, and the academic research community. Close collaboration and a common objective between industry and other stakeholders accelerates new technology implementation.

3.2.2 Other Energy Efficiency Opportunities

Other energy efficiency measures include reducing aggregate moisture content, insulating hot equipment, routine burner tuning to improve combustion efficiency, flight adjustment to improve drying efficiency with reduced exhaust gas temperatures, and electrical efficiency upgrades (Young, 2007 and Young, 2023).

Aggregate moisture content has a significant impact on fuel consumption. Asphalt plants are designed at a nominal aggregate moisture content of 5%. At this moisture content, the energy needed to evaporate the aggregate moisture in an asphalt plant is approximately half the total heat demand for mix production. Decreasing the aggregate moisture content from 5% to 4% reduces burner fuel consumption by about 10%. Electricity consumption is also lower since the volume of air and steam handled by the baghouse fan is decreased (Young, 2007).

The ENERGY STAR program for industrial facilities offers several resources to reduce energy consumption. Generic tools developed by the U.S. EPA provide a framework to develop an energy management program. Additional tools specific to the asphalt mix production industry are being developed by the Asphalt Plant Energy Performance Peer Exchange (APEX) Program (NAPA, 2022c).

3.2.3 Burner Fuel

Asphalt plants can burn several different fuels. The most common are natural gas, diesel fuel, and used oil (EIA 2021). The chemical composition of natural gas allows the lowest amount of CO_2 to be generated for an amount of heat energy (EIA 2020). In addition, upstream emissions from extracting, processing, and transporting natural gas are lower than other fossil fuels (Deru and Torcellini 2007). As a result, natural gas has the lowest cradle-to-gate emissions when compared to other fossil fuels as shown in Figure 12. Plant operation emissions (A3) for a mix produced using natural gas are 26% lower than a mix using diesel fuel as the burner fuel. For cradle-to-gate emissions (A1-A3) this equates to a reduction of 12%.

Table 5. Average blend of fuels consumed by the U.S. asphalt industry. HGL is hydrocarbon gas liquids, which is assumed to be propane for simplicity. Derived from EIA (2013, 2017, & 2021).

Fuel Type	Percentage of Total Fuel Consumption		
	2010	2014	2018
Residual Fuel Oil	5%	4%	2%
Diesel Fuel	20%	9%	14%
Natural Gas	64%	78%	69%
Propane (HGL)	2%	2%	5%
Used Oil and Other	10%	7%	10%

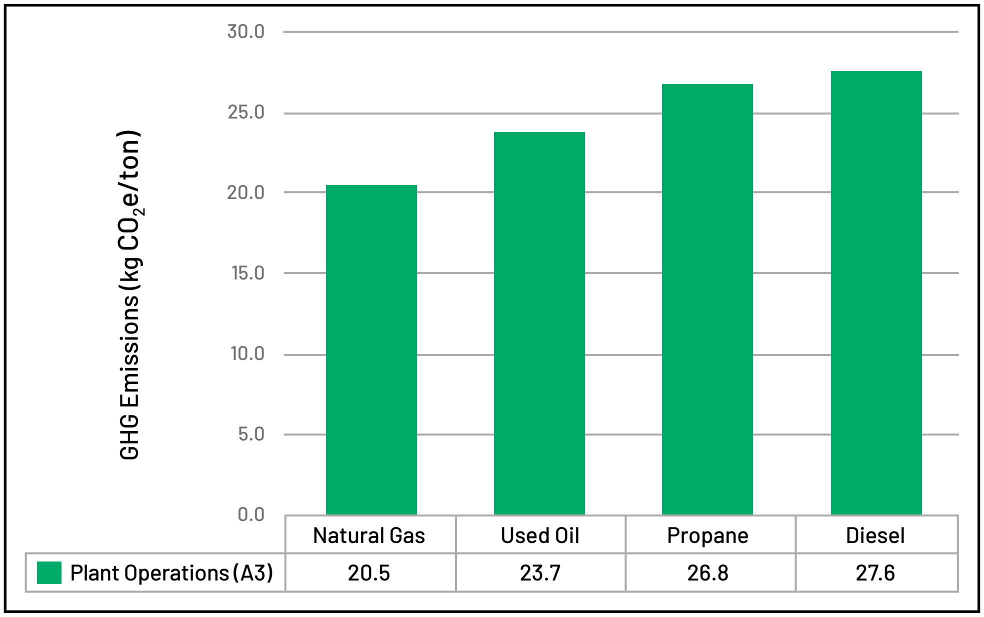


Figure 12. GHG emissions from plant operations (A3) for asphalt mixtures produced using various fuels on an equivalent Btu basis.

In 2018, more than two thirds of the fuel consumed by asphalt plants in the U.S. was natural gas. The other third was a combination of diesel fuel, used oil, propane, and residual fuel oil (RFO) (Table 5). This blend of burner fuels used by the asphalt industry as compared to the blend of fuels consumed by the overall U.S. industrial sector in 2019 resulted in 0.4 MMT of avoided CO_2e emissions (Shacat et al., 2022).

3.2.4 Cold Central Plant Recycling (CCPR)

CCPR is a process in which the RAP is blended at ambient temperatures with either emulsified asphalt binder or foamed asphalt binder. Virgin aggregates up to about 15% and portland cement up to about 1% are sometimes included in CCPR mixtures. CCPR is typically produced in a purpose-designed pugmill style plant, although Bowers and Powell (2021) demonstrated the ability to produce CCPR in a conventional asphalt plant with the burner turned off.

A combination of the high recycled material content and the ability to produce CCPR mixes without heating and drying the RAP and aggregates offers a significant opportunity for GHG emissions reduction. Gu et al. (2019) found that mixes produced using CCPR technologies had a 39-40% lower cradle-to-gate carbon footprint than a conventional hot-mix asphalt with 20% RAP. Their research also found significant cost savings through the use of CCPR. Similarly, FHWA (2020c) found significant emissions reductions and cost savings when CCPR was used in conjunction with cement-treated recycled base and full depth reclamation for two interstate highways in Virginia.

3.3 Pavement Construction, Maintenance, and Rehabilitation

Opportunities to reduce construction GHG emissions (A4-A5) fall under two categories. The first is direct reduction of GHG emissions from paving equipment (Section 3.3.1) and by reducing work zone congestion (Section 4.3.2). The second category is indirect emissions reductions from extending pavement life through improved construction practices (Section 3.3.2), and reducing vehicle fuel consumption in the use phase through smoother roads (Section 3.3.3).

Maintaining roads in a state of good repair can significantly reduce vehicle fuel consumption and GHG emissions.

3.3.1 Paving Operations

Use of alternative fuels can reduce GHG emissions from trucks (A4) and paving equipment (A5). For trucking operations, alternative fuels currently available in some markets include compressed natural gas (CNG), renewable compressed natural gas (R-CNG), biodiesel, and renewable diesel. Additional power sources that are expected to be available in the next five to ten years include hydrogen fuel cell electric vehicles (FCEV) and plug-in battery electric vehicles (BEV). Most of the published research on alternative fuel heavy duty vehicles is focused on trucks. Similar principles may be applicable to construction equipment – the U.S. Department of Energy is funding research to decarbonize construction equipment and other non-road engines (U.S. Department of Energy, 2022).

CNG offers reduced tailpipe emissions, but overall life cycle GHG emissions (from a well-to-wheel perspective) are slightly higher than diesel fuel emissions, primarily due to methane leakage in the natural gas supply chain and reduced fuel efficiency of natural gas vehicles (Cai et al. 2017). R-CNG, on the other hand, is sourced from renewable sources such as landfill gas and anaerobic digesters at agricultural operations, wastewater treatment plants, or food waste composting facilities. Life cycle carbon intensities of various R-CNG feedstocks are compared to diesel fuel and battery electric fuel in Figure 13. R-CNG can substantially reduce life cycle GHG emissions compared to diesel fuel, and for some feedstock pathways it can actually generate negative carbon intensities when sourced from feedstocks that would otherwise release methane to the atmosphere (Argonne National Laboratory, 2020).

Note that the negative carbon intensity value for dairy waste-derived R-CNG is based on an overall reduction in global warming potential when the system boundary is expanded to include avoided emissions from feedstocks that would otherwise release methane into the atmosphere. Negative carbon intensity values are not the same as carbon dioxide removal, which occurs when carbon dioxide is removed from the atmosphere.

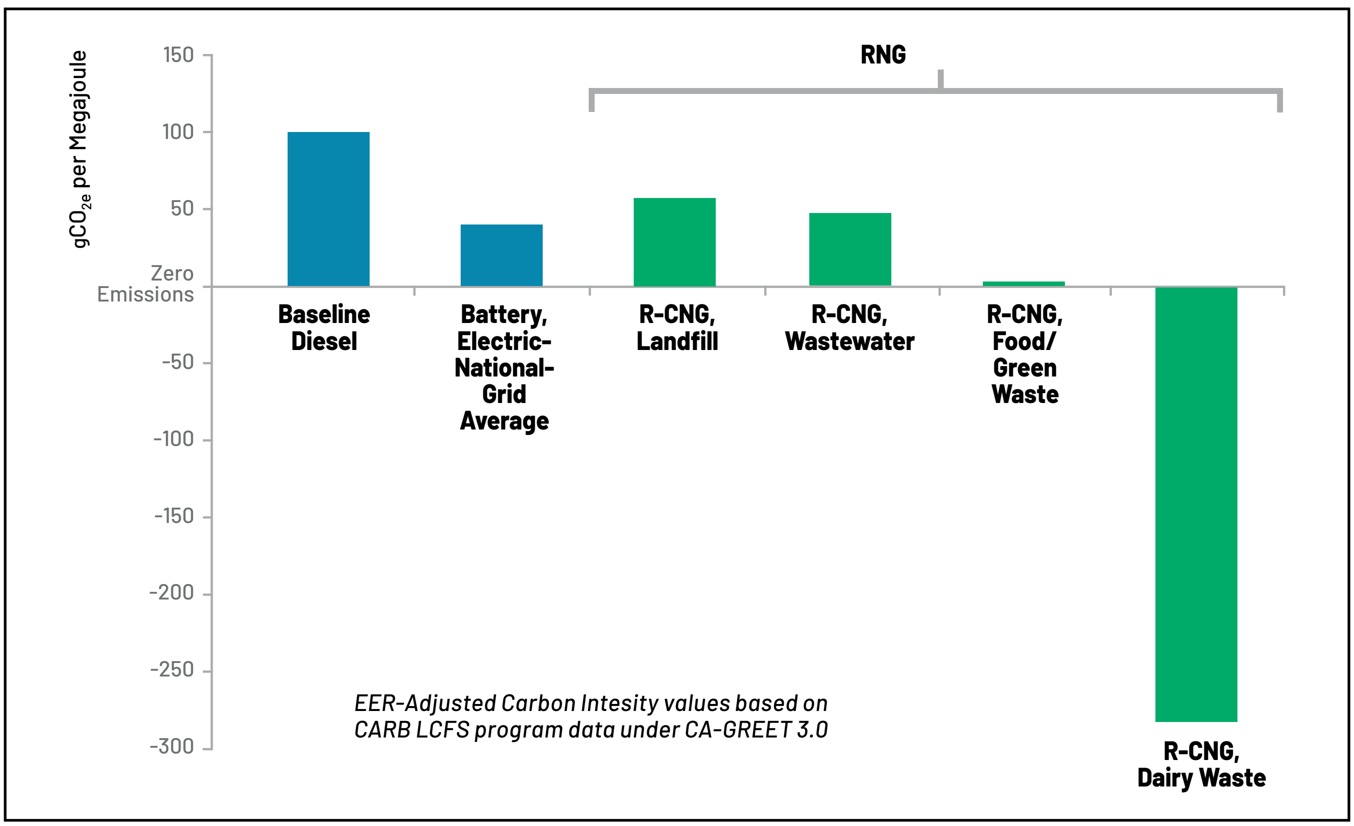


Figure 13. Life cycle carbon intensity (CI) values for CNG as a transportation fuel sourced renewable sources (R-CNG). R-CNG feedstocks have low or even negative CI scores because they capture emissions that would otherwise be released to the atmosphere. From NGVAmerica (2019).

Biodiesel and renewable diesel are biobased fuels that can be used in diesel engines to reduce GHG emissions. Their carbon intensities are similar to each other, and both are about 70% lower than diesel fuel (EIA, 2018a). The advantage of renewable diesel (compared to biodiesel) is that it meets the same specification and has the same chemical makeup as petroleum-based diesel, which allows it to be used as a drop-in replacement without the negative side effects that are sometimes experienced with biodiesel, such as fuel filter clogging and deposits on fuel injectors (Ciolkosz, 2013). Use of renewable diesel is growing in California due to financial incentives offered by the state's low carbon fuel standard (LCFS). Some companies in the asphalt paving industry are starting to utilize renewable diesel to reduce GHG emissions (e.g., Granite Construction, 2021).

Availability and affordability of R-CNG, renewable diesel, and other renewable fuels as a transportation fuel is generally limited to states with low carbon fuel standards (LCFS) for renewable fuel production and consumption, such as California, Oregon, and Washington (Kriha and Lafferty, 2023). Also, LCFS programs target transportation fuels and generally do not apply to off-road or stationary equipment.

Another development on the horizon for reducing transportation emissions is the anticipated availability of heavy duty fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV). Emissions reduction estimates for these developing technologies vary. For example, a comparative LCA study indicates that heavy duty BEV and FCEV may reduce life cycle GHG emissions by 30% and 45%, respectively, with more significant reductions possible depending on the carbon intensity of the electricity grid and the hydrogen feedstock (ATRI, 2022). Results from a scenario analysis developed by ATRI (2022) are presented in Figure 14. While these results are encouraging as a potential future technology that may be adopted, it's important to note that FCEV and BEV technologies are not yet widely available for heavy-duty trucks (Mehta, 2022).

3.3.2 In-Place Density

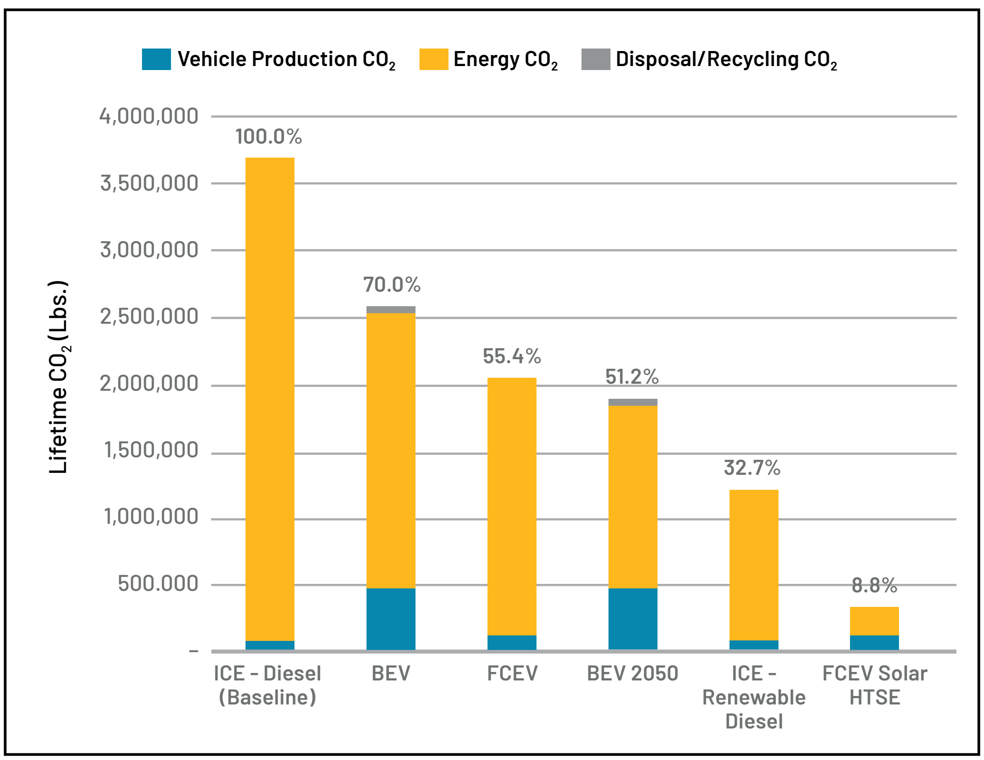


Figure 14. Scenario analysis of life cycle GHG emissions for various heavy-duty vehicle technologies. ICE is internal combustion engine, BEV is battery electric vehicle, BEV 2050 uses the Energy Information Administration (EIA) projected grid mix of energy supply for the year 2050, FCEV is fuel cell electric vehicle, and FCEV Solar HTSE assumes that the hydrogen is generated using solar powered high-temperature steam electrolysis. From ATRI (2022).

Increasing in-place density of asphalt mixtures increases pavement life which reduces the frequency of maintenance treatments and reduces life cycle GHG emissions. This relationship depends on factors such as mix type, mix gradation, initial (baseline) density, and the relationship between air voids and permeability.

Tran et al. (2016) showed that a 1% reduction in in-place air voids can extend the service life of surface pavements by 10%. This relationship between in-place density and pavement service life is based on data from the New Jersey DOT's pavement management system that was compiled and published by Wang et al. (2015),

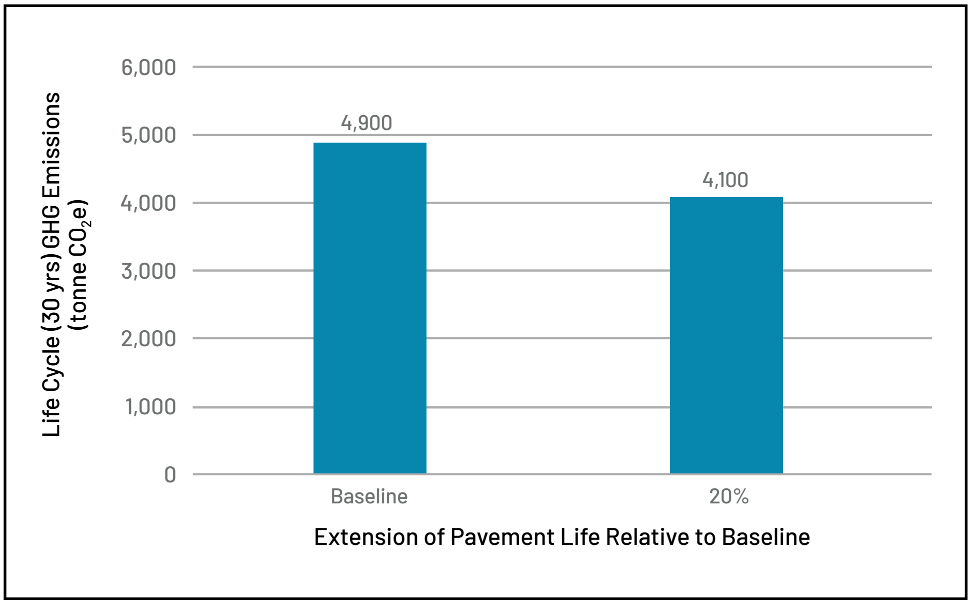


Figure 15. Potential reduction in total GHG emissions for materials, construction activity, and maintenance over a 30-year period by extending the life of an airfield pavement through increased density. Adapted from Butt et al. (2019).

Density can be increased by using intelligent compaction technologies, infrared monitoring of mat temperature, and ensuring adequate lift thickness (Muench and Hand, 2019). Other sustainable construction practices to extend pavement life include improving the density of longitudinal joints, achieving more uniform density, reducing density differentials, and improving inter-layer cohesion through proper use of tack coats (NASEM, 2019).

who found a stronger correlation between air voids and service life for surface pavements than intermediate layers. Wang et al. (2015) also found that reducing the standard deviation in air voids resulted in longer service life, underscoring the importance of consistency in achieving in-place density. An analysis of FHWA's long term pavement performance (LTPP) database concluded that increased density during construction generally improved pavement performance, "but the effect is not consistent between pavement demographics (climate, traffic, and pavement structure), types of pavements (new construction and rehabilitation), and measures of performance (rutting, fatigue cracking, thermal cracking, and ride)" (NASEM, 2021).

The potential impact of in-place density was evaluated in an LCA scenario developed by Butt et al. (2019) for airfield pavements. They show that longer pavement life from increased density can reduce life cycle carbon emissions (Figure 15). The authors assumed that a 2% density increase would extend the pavement life by 20% which resulted in 16% less GHG emissions from materials, construction, and maintenance over a 30-year life cycle. While the exact relationship between in-place density and service life may vary depending on a variety of factors, this analysis demonstrates the reduction in life cycle GHG emissions that can be achieved by extending pavement life.

3.3.3 Smoothness

As discussed in Section 2.6, the use stage emissions from vehicle fuel consumption (B1) is substantially greater than the GHG emissions from pavement materials, construction, and maintenance. Smoother pavements reduce rolling resistance, reducing life cycle GHG emissions. Importantly, roughness from initial construction (or reconstruction) accelerates deterioration throughout the pavement life, while smoother pavements increase pavement life (Smith et al., 1997).

Many factors affect asphalt pavement smoothness, including surface preparation, paver speed consistency, mix temperature, grade control, compaction, and transverse joint construction (Merritt et al., 2015). Additional research would allow agencies to more precisely quantify the impacts of initial pavement smoothness on the life cycle GHG emissions of asphalt pavements, although it's clear that initial pavement smoothness has a significant impact on GHG emissions. Pavement network smoothness optimization as an agency-driven opportunity to reduce emissions is discussed in Section 4.2.1.

4. AGENCY DRIVEN OPPORTUNITIES TO REDUCE GHG EMISSIONS

Agencies can play a significant role in reducing the carbon footprint of asphalt pavements through design practices including pavement structural design, mix design requirements for contractors, mix type selection, and pavement type selection. Agencies also control scheduling and selection of pavement maintenance activities, which also affects GHG emissions. This chapter describes how each of these activities can be leveraged by agencies to reduce the carbon footprint of asphalt pavements. Similar to the considerations for industry-driven opportunities presented in Chapter 3, agency activities do not operate in a vacuum, since agencies depend on paving contractors and materials suppliers to construct and maintain roads. However, agencies have the primary nexus of control for the activities presented in Chapter 4.

4.1 Material Specifications

4.1.1 Rethinking the Recipe

Most agency specifications have requirements related to the types of materials that can be used in asphalt mixtures. These requirements are generally based on a combination of the agency's experiences with various materials (both good and bad) and application of good engineering principles to ensure pavement performance. In the vast majority of cases, the carbon footprint of pavement materials was not taken into account when these requirements were established.

As agencies begin to look at the embodied carbon emissions as an added dimension of a material's engineering properties, there is an opportunity to review and potentially reconsider their specifications to allow for materials that result in a lower carbon footprint without sacrificing performance.

One example of an agency-driven alternative material strategy that can reduce emissions is allowing or encouraging the use of locally sourced aggregates. For example, the Illinois DOT is conducting research to evaluate the use of locally sourced aggregates for its stone matrix asphalt (SMA) mixes. The goal is to reduce the cost and environmental impacts of transporting aggregates from nearby states. The challenge is that imported aggregates, which are currently required by the agency for SMA mixes, tend to be stronger and have better skid resistance properties than the locally available dolomite, limestone, and gravel, so any updates to the agency specifications and supporting documents will need to account for these properties (Macomber, 2023). Noting the significance of transportation-related emissions in the cradle-to-gate stages of asphalt mixture production (Figure 5), the effort to allow the use of locally sourced aggregates for SMA mixes in Illinois could be beneficial from an emissions reduction perspective. There are numerous opportunities across the country for agencies to take a fresh look at material specifications through the lens of embodied carbon emissions as a GHG mitigation strategy.

4.1.2 Balanced Mix Design

Asphalt mix design is the process of selecting the appropriate asphalt binder content to provide sufficient coating and bonding of aggregates to meet the aggregate gradation and required specifications. The mixture design process can have significant impacts on GHG emissions by influencing raw material selection and pavement performance.

Conventional mix design methods, such as Superpave, rely primarily on volumetric properties of materials to optimize the blend of materials in the asphalt mixture. Although the Superpave mix design method originally envisioned the adoption of mix performance tests for moderate and high volume roads, the Superpave performance tests were not practical for routine mix design acceptance and production quality assurance/ quality control needs (NCAT, 2018). As asphalt mixtures become more complex through high recycled material contents and other novel materials, volumetric properties alone do not properly address potential performance aspects (Yin and West, 2021). There is a growing trend among agencies to develop balanced mix design (BMD) specifications to address concerns with conventional mix design processes and ensure acceptable field performance of asphalt mixtures. BMD uses performance tests to optimize mix performance in terms of both rutting and cracking. Yin and West (2021) identify four approaches to BMD that are differentiated from each other by the degree to which volumetrics are augmented or replaced by performance tests. In general, more innovation is possible when volumetric requirements are relaxed in lieu of performance testing, with the greatest opportunity for innovation when a truly performance-based design approach is adopted without volumetric constraints.

Powell et al. (2021) demonstrated a simplified BMD approach developed for county agencies in Alabama that enabled contractors to increase RAP quantities to 35%, resulting in reduced bid costs and impressive early performance of mixes. Although GHG emissions reductions were not quantified for this effort, the increased RAP contents likely resulted in reduced GHG emissions as described in Section 3.1.1. This study is a great example of using BMD to maximize the use of recycled materials without negatively affecting pavement performance, in accordance with FHWA's Recycled Materials Policy (FHWA, 2015).

Agency adoption of BMD is critical to accelerating the increased use of RAP, RAS, and other novel materials without sacrificing mix quality and performance. Agencies should consider implementing BMD specifications that enable innovation by relaxing or even eliminating volumetric requirements in lieu of appropriate performance tests. Additional research is needed to quantify the potential GHG emissions reductions that can be achieved by enabling innovation and improving mix performance through adoption of BMD.

4.1.3 High Performance Specialty Mixes

Another design consideration is the use of specialty asphalt mixture types, including polymer modified asphalt (PMA), highly polymer modified asphalt (HP Asphalt), stone matrix asphalt (SMA), and high modulus asphalt mixtures, to improve pavement performance. These specialty mixes can effectively extend pavement life or reduce pavement thickness, both of which can yield net life cycle benefits. While there are few studies that directly compare the life cycle GHG benefits of specialty mixes to their conventional counterparts, several of the key specialty mixes with the greatest potential for performance optimization are discussed here as potential tools to reduce life cycle GHG emissions. It should be noted that specialty mixes are not always necessary or appropriate and are no substitute for good engineering practices with respect to pavement design. NAPA's Mix Type Selection Guide (NAPA, 2023) is an excellent reference for selecting appropriate mixture types for different pavement applications.

Polymer Modified Asphalt (PMA)

The performance of asphalt pavements can be enhanced by using polymer modified asphalt (PMA) binders. A number of different polymers are commercially available, but the most common are SBS and GTR. A review of more than three dozen pavement sections found that PMA enhances both the rutting performance and the fatigue resistance of asphalt pavements, extending the service life of pavements by five to ten years (von Quintus et al., 2007).

However, the carbon footprint of PMA binder with a 3.5% SBS content is about 20% higher than unmodified asphalt binder (Asphalt Institute, 2019). This translates to a 13% increase in the cradle-to-gate (A1-A3) emissions of the baseline reference mix discussed in Section 2.1. Thus, a comparable extension of pavement life would be needed to compensate for the increased upfront emissions associated with the polymer. Extending the pavement life by two to three years would exceed break-even threshold from a life cycle perspective in most cases.

For a simple example, assume that a pavement is constructed with unmodified binder and has an expected service life of 15 years. For a baseline reference scenario mix (53.7 kg CO_2e/ton), this corresponds to an annualized rate of 3.6 kg CO_2e/ton/yr. A comparable polymer modified mix would have a cradle-to-gate carbon footprint of 60.5 kg CO_2e/ton. With a five-year extension of service life, the low end of the range observed by von Quintis et al. (2007), the annualized cradle-to-gate emissions would be 3.0 kg CO_2e/ton/yr, a 16% reduction compared to the unmodified mix. Over the life of the pavement, extending the time between maintenance operations should also reduce emissions associated with construction activities.

While this analysis is illustrative, reality is more complex. PMA is sometimes used for the full depth of the pavement, and sometimes only for the surface wearing course. These factors and others should be evaluated through project-level or network-level whole pavement LCA studies. As discussed in Section 2.8.2, any extension in the service life of lower pavement layers, if applicable, should be considered separately from the extension in service life for the surface wearing course to appropriately account for the remaining service life when conducting an LCA study to compare the environmental impacts of unmodified vs. PMA mixes.

Highly Polymer Modified Asphalt (HP Asphalt)
Highly polymer modified asphalt (HP Asphalt) is essentially PMA with a higher polymer content, typically around 7% SBS by weight of binder. The additional polymer content increases both the stiffness and the elasticity of the asphalt binder.

Habbouche et al. (2021) found that HP Asphalt overlays constructed on top of concrete pavements (composite pavements) extended the service life of overlays in Virginia by 34% when compared to a more conventional PMA overlay. The HP Asphalt overlays effectively reduced the onset of reflective cracking for composite pavements.

Stone Matrix Asphalt (SMA)
SMA is a durable, rut-resistance asphalt pavement mixture that is used as a surface wearing course or an intermediate course on projects with high traffic volumes. A recent study of agencies who use SMA found that it has equivalent or better performance than dense graded PMA Superpave mixes, with predicted extensions in pavement life ranging from 1 to 13 years (Yin and West, 2018). Although Vavrik (2018) found that extension of pavement life and reduction of rolling resistance are the most significant life cycle benefits of SMA, there are no published studies that directly compare life cycle GHG emissions of SMA pavements to pavements constructed using other asphalt mixture types.

High Modulus Asphalt Mixtures
High modulus asphalt mixtures are designed to ensure that they are both high modulus and fatigue resistant. These mixtures can be used to reduce overall pavement thickness in conventional pavement structures. When applied in a perpetual pavement design, high modulus asphalt mixtures can be used as a single mix design for both the base and intermediate layers, simplifying the pavement structure and construction process (Newcomb et al, 2020).

While the traditional high modulus mixture (originally developed in France) uses a highly modified binder (e.g., HP Asphalt) to increase the stiffness of the pavement without the use of recycled materials, Leiva-Villacorta et al. (2017) found that PMA mix designs with high recycled material contents (e.g., 35% RAP or more) yielded comparable performance as HP Asphalt mixes. This demonstrates the potential of high RAP mix designs to reduce the virgin asphalt binder content as well as the polymer content for high modulus asphalt mixtures, allowing for significant reductions in cradle-to-gate GHG emissions without sacrificing performance.

4.2 Pavement Design Considerations

4.2.1 Perpetual Pavement Design

The most significant opportunity to reduce life cycle GHG emissions during the pavement design process is to design pavements using the Perpetual Pavement design approach, which eliminates the need for structural pavement repairs. Although roads with more traffic generally require thicker pavements, overdesigning pavements is not efficient fiscally or environmentally. For example, constructing a pavement two feet thick would be a waste of materials and money if a 14-inch thick pavement can handle the expected traffic loads. Perpetual Pavements are designed to optimize each layer of the pavement structure to resist distresses and limit any necessary maintenance treatments to periodic milling and replacement of the surface wearing course, greatly reducing life cycle costs (Newcomb et al., 2020).

FHWA (2020d) conducted an LCA for a Perpetual Pavement project in Iowa that showed a 20% reduction in life cycle GHG emissions (Figure 16). That study also found the perpetual pavement design option reduced life cycle costs by 17-28 percent, depending on the discount rate used. Other studies have found that Perpetual Pavements reduce the agency's life cycle economic cost when compared to conventional asphalt pavement designs (Timm and Newcomb, 2007) and when compared to continuously reinforced concrete pavements (Lee et al., 2018). **The combined LCCA and LCA results of these studies indicates that adoption of the Perpetual Pavement design approach is a significant opportunity for agencies to cost-effectively reduce life cycle GHG emissions.**

4.2.2 Pavement Type Selection

An important consideration for pavement type selection with respect to GHG emissions is the impact of pavement smoothness on vehicle fuel consumption over the life of the pavement. Robbins and Tran (2019) analyzed field performance of asphalt and concrete pavements using FHWA's long term pavement performance (LTPP) database to evaluate the use of IRI as a criterion for determining the initial service life of pavements. They determined the 95% confidence interval of the mean IRI at the time of first intervention was between 1.64 m/km and 1.91 m/km for asphalt pavements and between 1.88 and 2.19 m/km for concrete pavements. In other words, asphalt pavements are typically smoother than concrete pavements when they are rehabilitated. Due to the link between pavement smoothness and vehicle fuel consumption (see Section 2.6.1), **the sustained smoothness benefit of asphalt pavements throughout their life offers a distinct advantage in terms of reducing GHG emissions associated with vehicle fuel consumption.**

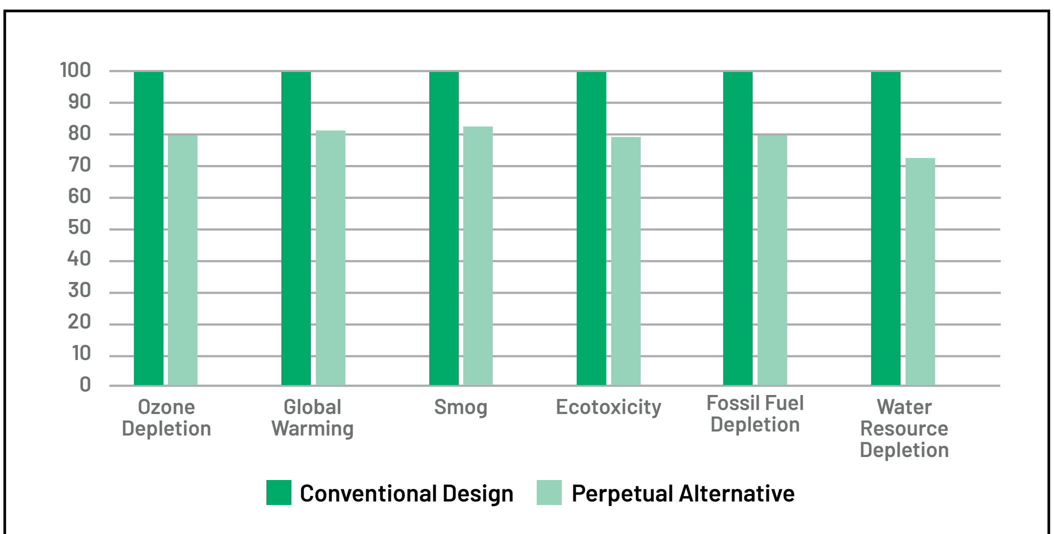


Figure 16. LCA results for a conventional design and perpetual alternative for an Iowa highway over a 50-year analysis period. Values for the conventional design were established as the baseline, set at 100 percent. From FHWA (2020d).

An important research gap related to pavement smoothness is the accuracy of IRI models that are commonly used during pavement design. For example, Hasan et al. (2020) found that the IRI model in the AASHTOWare mechanistic empirical (M-E) pavement design software overestimated the IRI of asphalt pavements relative to field measurements of IRI by 185 – 205%.

Thus, LCA studies that compare the use stage emissions of asphalt and concrete pavements should rely on empirically derived IRI deterioration models rather than the IRI degradation model embedded in AASHTOWare. Additional research is needed to improve IRI prediction models for pavement design and integrate those models into LCA studies.

Another consideration for pavement type selection is the impact of work zone congestion on GHG emissions. As discussed in Sections 2.7.1 and 4.3.2, comparative LCA studies for different pavement types need to account for the impacts of any differences in the construction and maintenance schedules related to different pavement materials and how the different schedules affect work zone congestion.

4.3. Maintenance

4.3.1 Pavement Smoothness Optimization

A significant volume of work has been done by the University of California Pavement Research Center (UCPRC) to quantify how smoother roads benefit GHG emissions reductions by optimizing maintenance intervals. For example, Wang et al. (2014b) evaluated the potential GHG emissions reductions that could be achieved by Caltrans if the agency were to optimize maintenance intervals based on a combination of traffic levels and pavement smoothness. They found the optimal IRI trigger for road maintenance for the Caltrans pavement network to range from 101 to 152 in/mile (1.6 to 2.4 m/km), depending on the traffic volume. Higher volume roads (in excess of 34,000 daily passenger car equivalents) would have the lowest IRI trigger (Figure 17). When compared to the agency's existing IRI trigger of 170 in/mile, the optimization scheme would yield a net GHG emission reduction of 1.38 million metric tonne (MMT) per year at an agency cost of \$416/tonne CO_2e. The cost does not account for the decrease in vehicle user cost due to reduced fuel consumption. The authors estimated that including the user cost benefit would yield a total cost effectiveness of –\$710 to –\$1,610/tonne CO_2e, offering an opportunity to reduce emissions and economic costs.

It should be noted that low volume roads (in this analysis, roads with fewer than 2,517 daily passenger car equivalents) never achieve a net GHG emission reduction through optimization of smoothness because the reduction in vehicle emissions (B6) is not sufficient to offset the direct emissions from pavement materials and maintenance activities (B2-B5). **For low volume roads, policies that focus on reducing the embodied carbon of pavement materials are likely to be more effective as a GHG mitigation measure than optimizing the timing of maintenance activities.**

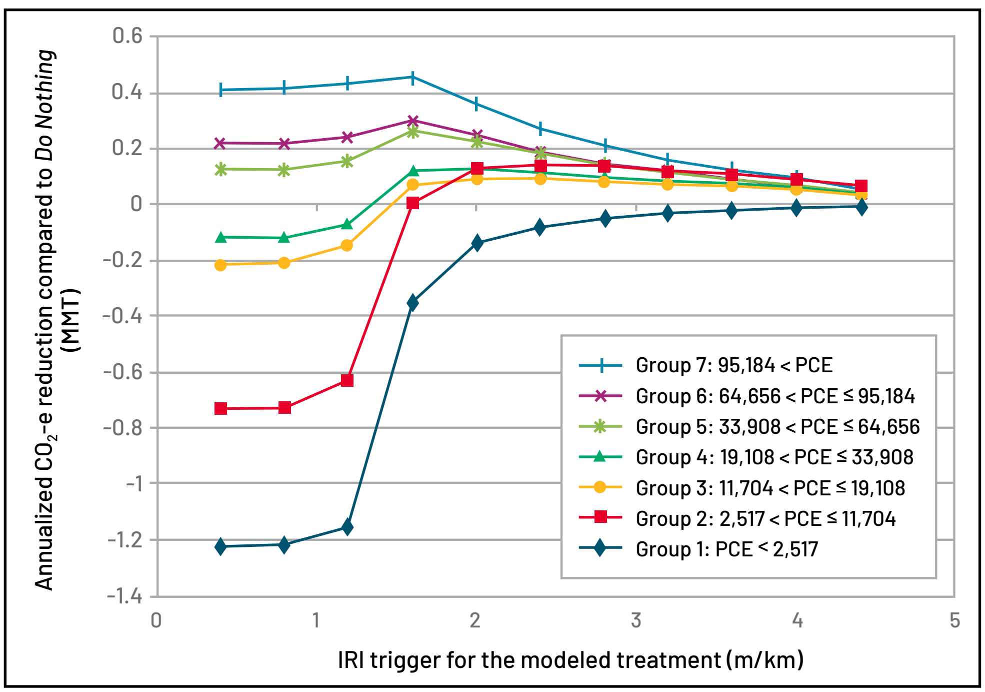


Figure 17. Annualized CO_2e reductions versus IRI trigger for different traffic levels over a 10-year analysis period for the entire Caltrans pavement network compared to maintaining the network at approximately its current roughness and macrotexture. The optimal IRI trigger is lower for high volume roads. Low volume roads (Group 1) never achieve a net GHG emission reduction. PCE is daily passenger car equivalents. From Wang et al. (2014b).

The UCPRC pavement maintenance optimization study indicates that increasing the maintenance frequency for moderate- to high-volume roads can be viewed as a GHG mitigation measure with a net economic benefit to society.

This is a profoundly important conclusion. It shows that road maintenance can actually yield a net decrease in GHG emissions, since emissions from maintenance of asphalt pavements are offset by net reductions in emissions from vehicles driving on roads with moderate to high traffic volumes. It also demonstrates the importance of including user cost benefits when conducting economic analysis of pavement maintenance activities, since the user cost benefit can significantly outweigh the agency cost of road maintenance. Lastly, this study highlights the importance of including all life cycle stages when assessing the potential environmental impacts associated with pavement maintenance activities. **Pavement maintenance for high-volume roads is an energy efficiency measure that reduces GHG emissions and saves money.**

4.3.2 Work Zone Congestion

Asphalt pavements can be constructed rapidly and have a short curing (cooling) time. Work zone congestion can be reduced by paving during low traffic times and reopening to traffic after each shift. In one example, an Iowa interstate pavement was closed rather than restricted due to flood damage in 2019. The repair using asphalt pavement was completed quickly and the contractor received a financial incentive of $10.6 million (Bowers and Gu, 2021). This amount reflects the economic value of a highway being accessible. Although the GHG emission benefits were not quantified, the case study demonstrates reduced user cost that can be achieved by rapid construction.

As discussed in Section 2.7.1, work zone congestion can significantly affect GHG emissions for high volume roads depending on the time of day that construction occurs. Although tools are available to model work zone traffic congestion and excess emissions, most LCA studies use simplistic assumptions regarding work zone traffic flow. Modeling techniques that account for realistic traffic flow patterns have been applied to the use stage (e.g., Haslett et al., 2019), but they have not been applied to studies of work zone congestion.

Although contractors are ultimately responsible for project scheduling and execution, the agency's project specifications typically define the requirements and any available options related to project schedules (e.g., night-time work, weekend closures, and incentives and penalties related to the project schedule).

There is a need for further development and verification of work zone congestion modeling techniques for LCA studies. **GHG emissions associated with work zone congestion should be considered when comparing emissions from different pavement design and maintenance alternatives, particularly when maintenance of high-volume roads requires different timing and scheduling practices for different pavement materials or maintenance practices.**

4.3.3 Thinlays for Pavement Preservation

Thinlays are thin-lift asphalt pavements that are used as a pavement preservation treatment for roads in good to fair condition. Their inherent properties can repair minor structural issues and result in a smoother road that lasts longer than other pavement preservation techniques (Heitzman et al., 2018).

One of the few available LCA studies of pavement preservation, conducted by Wang et al. (2019), found that Thinlays yield greater net reductions in life cycle GHG emissions than chip seals or crack seals. Net emissions reductions for Thinlays ranged from 0.2 to 0.4 million kg CO_2e per lane-mile depending on the average annual daily truck traffic (AADTT) and the duration between initial construction and application of the Thinlay (Figure 18). Net emissions reductions also depend on the initial smoothness (IRI) of the pavement. Generally, the greatest net reductions were observed for pavements with higher IRI and AADTT values.

The reduction in vehicle fuel consumption caused by smoother roads more than compensates for the GHG emissions from the materials and construction of Thinlays by a factor of 10 to 20 in the analysis conducted by Wang et al. (2019), depending on the scenario. The results of this study support the notion that using Thinlays as a pavement preservation technique can be seen as an effective GHG mitigation measure.

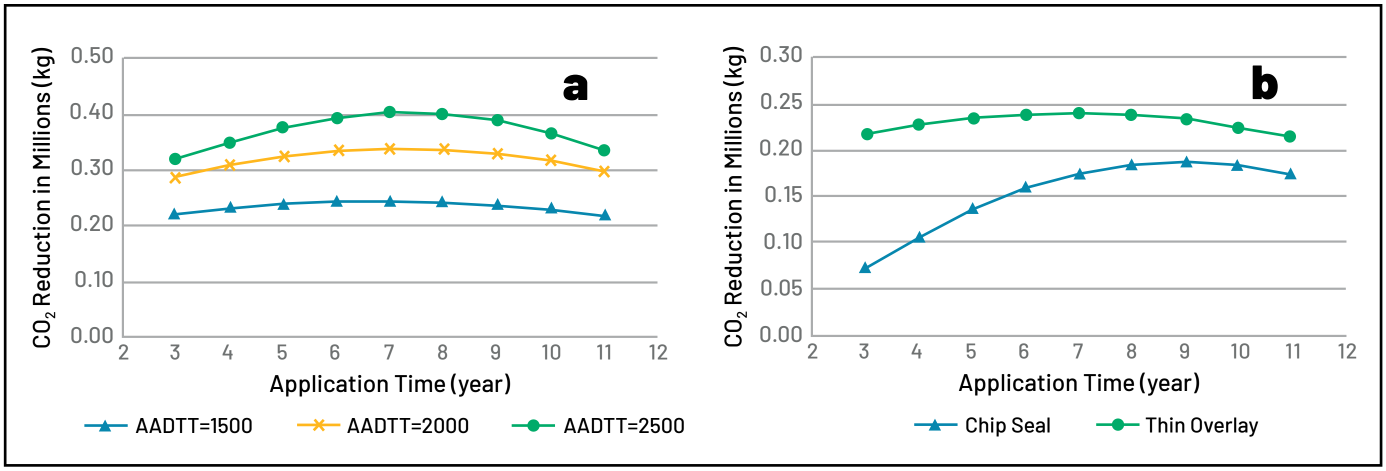


Figure 18. **(a) Net CO_2 emission reductions for different AADTT values and application times in the production, construction, and use stages of Thinlays. (b) Comparison of net CO_2 reductions for Thinlays and chip seals with AADTT of 1500 ESALs. For both graphs, Initial IRI = 1.0 m/km. For each point, the analysis was conducted for one lane-mile of asphalt pavement with a speed limit of 65 mph from application of the thin overlay until IRI reached a terminal value of 2.714 m/km. The inflection point in each AADTT curve represents the optimal application time for achieving net CO2 reductions. From Wang et al. (2019).**

No other pavement preservation technique has the same potential to improve smoothness. Many other techniques use highly modified asphalt products that use ingredients for which currently no upstream data is available. Thinlays also have a lower surface macrotexture than other pavement preservation techniques like chip seals (FHWA, 2019), which can affect vehicle fuel consumption (Ullidtz, 2010; NASEM, 2012). However, the interaction between surface macrotexture and vehicle fuel consumption for thinlays and other pavement preservation technologies has not been studied.

5. TOOLS TO QUANTIFY GHG EMISSIONS AND INFORM DECISION MAKING

Several tools are available to quantify GHG emissions at various stages of the pavement life cycle. Each tool has its own purpose, scope, system boundaries, upstream datasets, and allocation procedures. It's critical that users understand the assumptions and limitations of each tool. In most cases, direct comparisons of the outputs from different tools should be avoided due to inconsistencies in upstream datasets, assumptions, and allocation methodologies.

Another consideration with respect to LCAs and EPDs is that the upstream datasets and industry practices are constantly evolving. In some cases, such as the transition to renewables in the electricity grid, reduced environmental impacts are expected over time. In other cases, the reported upstream emissions can increase over time as data gaps get filled and industry-wide average data are replaced with product-specific EPDs.

5.1 Environmental Product Declarations (EPDs)

EPDs are verified reports that quantify the GHG emissions and other environmental impacts associated with manufacturing a product. Several agencies at the federal, state, and local level have adopted Buy Clean policies that require paving contractors to submit EPDs for asphalt mixtures and other pavement materials. Several of these agencies are planning to use the EPDs collected to inform development of pavement design, maintenance, procurement, and project delivery policies to reduce embodied carbon emissions. NAPA (2024) established industry averages that can be used for identifying low embodied carbon asphalt mixtures for projects funded under the FHWA Low-Carbon Transportation Materials Grant Program.

Emerald Eco-Label is NAPA's web-based software for developing and publishing verified plant- and product-specific EPDs. Emerald Eco-Label is the only software tool that has been verified to meet the requirements of the PCR for Asphalt Mixtures (NAPA, 2022b). The scope of the tool and the EPDs it generates is cradle-to-gate (A1-A3). The tool's consistent use of common upstream datasets, allocation procedures, and other considerations established in the PCR for Asphalt Mixtures enhances the comparability of EPDs generated by different plants and companies. In contrast, a recent review of concrete EPDs found that comparability of EPDs for mixes produced by different companies was diminished due to variability in upstream data sources and data quality (Rangelov et al., 2021). The Emerald Eco-Label tool is available at https://asphaltepd.org/.

The Emerald Eco-Label software includes an Optimizer function, which allows users to easily develop scenarios to evaluate emissions reductions that can be achieved through operational improvements. The Optimizer also provides a detailed, granular analysis of emissions at the unit process level (rather than aggregating emissions into the A1, A2, and A3 stages), and enables easy comparison of different mix designs and plant scenarios within the user's library of plant variants and mixes.

5.2 LCA Software

While EPDs can be used to compare asphalt mixtures with comparable performance, LCA software is needed to compare asphalt mixtures and pavement designs that are expected to perform differently. Several LCA software packages are commercially available. Generally, these require advanced user knowledge and experience. They offer flexibility by allowing users to choose different upstream datasets, some of which must be purchased separately, as well as different impact assessment methodologies. Generally, results from different LCA tools should not be directly compared to each other unless the system boundaries, upstream data, impact assessment methodologies, and other parameters have been carefully reviewed and harmonized.

LCA Pave is FHWA's Excel-based software tool designed for agencies and other stakeholders to conduct LCAs for pavements. The scope of the tool is cradle-to-grave, although the scope does not include use stage emissions (B1 and B6). With the cradle-to-grave scope, LCA Pave is appropriate for studies that compare asphalt pavement designs, mix designs, and maintenance practices that have different performance expectations. The tool uses publicly available upstream inventories for energy and materials that are available through the Federal LCA Commons. Users can create custom libraries of materials, mix designs, pavement sections, equipment, and other parameters. EPDs can also be used as data inputs, allowing the user to incorporate EPDs into project-level LCAs.

EPDs for asphalt mixtures use the same upstream datasets as FHWA's LCA Pave software, which reduces potential alignment issues between Emerald Eco-Label EPDs for asphalt mixtures and LCAs developed using LCA Pave. This means users can rely on EPDs to characterize the cradle-to-gate emissions of asphalt mixtures and feed the data into LCA Pave to assess additional life cycle stages such as construction, maintenance, and end-of-life. The importance of aligning upstream datasets cannot be overstated – different background datasets for common processes such as electricity production can vary significantly.

In general, LCA Pave should not be used to compare different pavement types (e.g., asphalt and concrete) for decision-making purposes. Upstream datasets for asphalt and concrete have not been harmonized, and LCA Pave does not include use stage emissions, which should be accounted for when the smoothness and other rolling resistance factors for different pavement types are not equivalent. The LCA Pave software tool was released in 2021 (Ram et al., 2021) and is available for free at https://www.fhwa.dot.gov/pavement/lcatool/.

5.3 The Supply Curve Approach

Agencies, industry, and other decision-makers who want to reduce GHG emissions are often faced with the challenge of prioritizing which projects or activities to focus their limited financial and human resources on. For example, this report identifies numerous opportunities to leverage the sustainable attributes of asphalt pavements to reduce GHG emissions. With so many options on the table, it can be difficult to decide how to achieve GHG emissions reduction goals in a cost-efficient manner. One method for comparing and prioritizing projects is the supply curve approach, which is a simple visual analysis that ranks GHG mitigation measures by their cost-effectiveness and GHG mitigation potential.

Harvey et al. (2019) used the supply curve approach to evaluate the cost effectiveness of six different GHG mitigation strategies under consideration by Caltrans. The scope of their analysis focused on agency costs, meaning that strategies with a negative cost effectiveness are expected to reduce agency costs and strategies with a positive cost effectiveness will require additional agency expenditures. Using this approach, **Harvey et al. (2019) found that, among the six strategies under consideration to reduce GHG emissions, the most cost-effective was increasing RAP use** (Figure 19). They also found that pavement roughness and maintenance prioritization to reduce vehicle emissions was the most effective in terms of cumulative GHG emissions reduction potential, although it had a slight positive cost effectiveness.

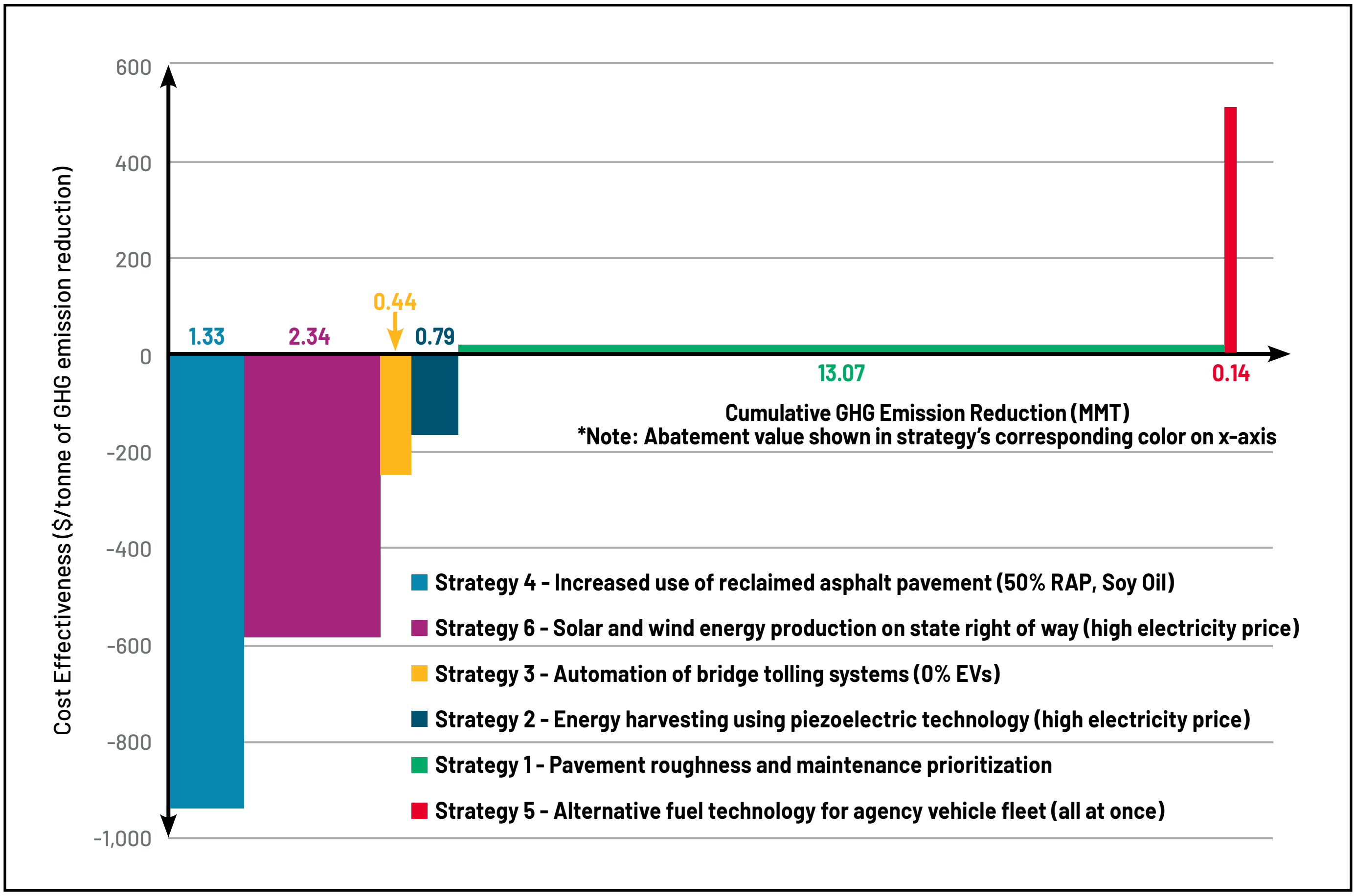


Figure 19. Supply curve for six pilot case studies for optimistic scenarios considering both GHG and cost-effectiveness. Strategy 4, increased use of RAP, was the most cost effective. Strategy 1, pavement roughness and maintenance prioritization, had the greatest cumulative GHG emission reduction potential with 13.07 MMT CO_2e. Emission reductions for Strategy 1 represent the overall Caltrans pavement network over a 35-year analysis period. From Harvey et al. (2019).

Because Harvey et al. (2019) only considered agency costs in their analysis, the slight positive cost effectiveness value for the pavement maintenance optimization does not account for the user cost reductions associated with increased fuel efficiency from smoother pavements.

5.4 Attributional versus Consequential LCA

There are two broad categories of LCA – attributional and consequential. An attributional LCA uses a clearly defined system boundary and allocates environmental impacts to the product system in a manner that reflects the physical relationship between products (Agusdinata and Zhao, 2014). For example, in their LCA of asphalt binder production, Asphalt Institute (2019) allocates the impacts of crude oil extraction to asphalt binder and other refinery co-products based on the energy content (net calorific value) of each co-product.

The vast majority of LCA studies related to asphalt pavements are attributional in nature. EPDs are also based on attributional LCA, as required by ISO 14025. When evaluated using an attributional LCA, decreasing asphalt binder consumption results in a decrease in environmental impacts, as has been demonstrated in this report.

Consequential LCA uses an expanded system boundary to investigate the consequences of changing the demand for a given product. Consequential LCA is intended to assist with policy decisions in a manner that addresses the complex nature of product systems with multiple co-products that may either substitute or compete with each other (Agusdinata and Zhao, 2014). For example, many refineries can choose to use a coking process to produce gasoline or other fuels as a substitute for asphalt binder production based on economic supply and demand considerations.

If there is less demand for asphalt binder, the refinery could choose to produce more gasoline. Alternatively, the refinery might choose to change its crude slate in response to changing demand for asphalt binder and other co-products of refinery operations. This decision would likely be based on a combination of economic, supply chain, refinery configuration, and product demand considerations. Consequential LCA provides a window into how changes to refinery operations in response to a change in demand for asphalt binder might affect environmental impacts.

The decision to use attributional vs. consequential LCA is important because, in some cases, the two methods can yield significantly different results. For example, a consequential LCA for petroleum production in Europe found that reducing production of asphalt binder at the refinery by one unit of production would increase emissions if production of all other products and the makeup of the incoming crude slate are held constant (Concawe, 2017). This reflects the underlying situation in which a refinery would increase its output of lighter products (such as gasoline) in response to reduced demand for asphalt binder if all other parameters are held constant, which consumes more energy than producing asphalt binder. While this may seem to imply that asphalt binder production will result in a reduction in GHG emissions, the reality depends on a complex interaction between factors such as changes in demand for all other refinery co-products, chemical and physical properties of available crude sources, the refinery's technological capabilities, and economic considerations, among others. For this reason, interpreting the results of a consequential LCA requires careful consideration of the assumptions, system models, and other parameters considered in the study.

Due to the potentially contradictory results from attributional and consequential LCAs, policy decisions based on either type of LCA should be mindful of the inherent challenges of modeling complex systems and take into account broader trends that affect the supply and demand of materials within a product system and related co-products. For example, if decreased demand for asphalt binder (due to increased use of RAP) coincides with an economy-wide decrease in demand for other petroleum products (due to widespread adoption of electric vehicles), consequential LCA results would likely track more closely with those of an attributional LCA.

6. CONCLUDING THOUGHTS

6.1 Significant Emission Reductions Are Readily Achievable

Numerous technologies and practices are readily available to significantly reduce GHG emissions throughout the life cycle of asphalt pavements. Some of the key opportunities discussed in this report include the following:

- Increasing the use of RAP and other recycled materials in asphalt mixtures to reduce upstream GHG emissions.
- Energy efficiency measures, including use of WMA technologies to reduce mix production temperatures, burner fuel consumption, and GHG emissions during mix production.
- Improving construction quality, such as smoothness and density, to extend the life of pavements and reduce vehicle fuel consumption, both of which can reduce life cycle GHG emissions.
- Using specialty mixes to reduce life cycle emissions by improving pavement performance or allowing for thinner pavement sections.
- Adopting the Perpetual Pavement design approach to improve pavement durability and reduce life cycle GHG emissions.

Another important consideration for asphalt pavements is the maintenance of existing roads with moderate to high traffic volumes, which accounts for a significant portion of asphalt mix produced, yields a net reduction in GHG emissions by improving smoothness and reducing vehicle fuel consumption. In other words, **road maintenance can in many cases be viewed as a GHG mitigation measure that is conceptually no different from purchasing energy efficient appliances for a home kitchen.** The upfront emissions associated with asphalt pavement materials and construction can be offset by a reduction in vehicle emissions through smoothness-related reductions in vehicle fuel consumption, yielding a net reduction in GHG emissions. This approach should not be applied blindly – it requires verification and analysis by pavement owners to ensure that context-specific variables such as pavement design and materials, traffic volume, and construction practices are accounted for.

Increased funding of transportation infrastructure that focuses on maintenance and repair of the existing network of roads and highways has the potential to significantly reduce overall U.S. GHG emissions while reducing user costs associated with vehicle operation, maintenance, and repair. There are numerous co-benefits to accelerating road maintenance funding, including the following:

- Economic stimulation of local economies through purchasing of locally sourced materials and construction jobs.
- Equal sharing of reduced user costs, both directly to individual motorists and indirectly through reduced freight transportation costs.
- Reduced life cycle agency costs through preventive maintenance.

6.2 The Importance of Partnerships Between Agencies, Industry, and Other Stakeholders

Future progress toward reducing GHG emissions associated with asphalt pavements relies heavily on effective partnerships between industry, agencies, and the academic research community. Examples of key areas where collaborative efforts are needed include the following:

- Adoption of BMD policies that rely on performance tests rather than volumetrics to enable innovation and use of mix designs with high RAP content and other novel materials while maintaining or even improving pavement performance.
- Continued focus on training pavement engineers, inspectors, and contractors on best practices in pavement design, mix design, mix production, and paving operations to improve pavement performance.
- Industry participation in the ENERGY STAR APEX program to help asphalt plants improve energy efficiency.
- Development of Buy Clean policies that are sensitive to regional and application-specific variability in cradle-to-gate GHG emissions.
- Adoption of pilot programs to conduct LCAs that inform the development of pavement design and project delivery policies that reduce GHG emissions.

6.3 Research Needs

Coordinated research efforts are needed to refine GHG quantification methodologies for asphalt pavements, including:

- Methods to account for differences in the remaining service life of lower pavement layers when comparing LCA results of alternative pavement designs.
- Further development and verification of work zone congestion modeling techniques for pavement LCA studies.
- Methods to accurately and consistently measure pavement rolling resistance to understand and optimize the combined effects of smoothness, texture, and stiffness on vehicle fuel consumption.

Additional research is needed to quantify GHG emissions associated with several aspects of asphalt pavement design, production, construction, and maintenance, including:

- GHG emissions associated with various construction practices when asphalt pavement overlays are used to rehabilitate and reconstruct concrete pavements.
- GHG emissions associated with manufacturing asphalt additives, along with life cycle emissions reductions associated with improved pavement performance from use of additives.
- The potential GHG emissions reductions that can be achieved by enabling innovation and improving mix performance through adoption of BMD.
- The life cycle GHG benefits of specialty asphalt mixes relative to their conventional counterparts.
- The impacts of initial pavement smoothness on the life cycle GHG emissions of asphalt pavements.
- The relationship between in-service pavement smoothness and life cycle emissions of both asphalt and concrete pavements.

Lastly, there is a need to develop innovative, carbon-sequestering, biobased binder technologies, assess their life cycle GHG emissions, and bring them to market.

6.4 The Road Forward

As the nation strives to significantly reduce GHG emissions, numerous technologies and practices are immediately available to reduce emissions associated with asphalt pavements in the near term. Over the long term, substantial research, technology transfer, and implementation efforts will be necessary to achieve greater emissions reductions. This will require strengthening and expanding the existing partnerships between industry, government agencies, and other stakeholder groups.

Considerations related to LCA-based GHG quantification of asphalt pavements as discussed throughout this report need to be integrated into pavement design, production, construction, and maintenance activities, including procurement and project delivery. This will require a significant workforce development effort to train existing material suppliers, contractors, and pavement engineers, and also develop a pipeline of students who are prepared to tackle the challenge of achieving net zero GHG emissions.

The U.S. asphalt pavement community has adapted to challenges in the past and is poised to continue on the path toward achieving net zero GHG emissions while providing durable, cost-effective solutions for pavement owners.

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APPENDIX A. ASSUMPTIONS FOR GHG EMISSION CALCULATIONS

GHG emissions were calculated using the LCA model developed by Mukherjee (2021).

The heating values and other conversion factors used for converting from energy consumption in MMBtu to quantities of fuel are provided in Table A-1.

Table A1. Energy conversion factors used in this report. MMBtu is million Btu, MCF is thousand cubic feet, HGL is hydrocarbon gas liquid and is assumed to be propane for simplicity.

Parameter	Value	Units	Reference
Diesel Fuel	0.1375	MMBtu/gal	Derived from EIA (2018b)
Electricity	3.412E-03	MMBtu/kWh	
Natural Gas	1.039	MMBtu/MCF	
Propane/HGL	0.09133	MMBtu/gal	
Residual Fuel Oil (RFO)	0.1497	MMBtu/gal	
Used Oil	0.14	MMBtu/gal	

The input parameters for the baseline reference scenario are provided in Table A-2. For electricity consumption, the national average grid mix was used rather than specifying a regional balancing authority.

Table A2. Inputs and assumptions for baseline reference scenario.

Parameter	Value	Units	Source
Plant Data (Typical Plant)			
Total Mix Production	100,000	tons	Assumption
Electricity	3.32	kWh/ton	Mukherjee (2016)
Total Fuel Consumption	0.289	MMBtu/ton	Mukherjee (2016)
Hot Oil Heater (Natural Gas)	3600	MMBtu/yr	Assumption
Mobile Equipment (Diesel)	600	MMBtu/yr	Assumption
Burner Fuel Consumption (Natural Gas)	24,700	MMBtu/yr	Assumption
Mix Data (no RAP)			
Aggregate Content	95%		Assumption
Asphalt Binder Content	5%		Assumption
Transportation Distances (Average Distance)			
Aggregates	21.5	ton-miles/ton	Mukherjee (2016)
Asphalt Binder	3.9	ton-miles/ton	Mukherjee (2016)

The input parameters for the RAP and RAS scenarios discussed in Section 3.1.1 are provided in Tables A-3 and A-4.

Table A3. Input parameters for the RAP scenarios.

Parameter[1]	Scenario[2]		
	No RAP	20% RAP	50% RAP
Aggregate Content	95.0%	76.0%	47.5%
RAP Content	0.0%	20.0%	50.0%
Asphalt Binder Content	5.0%	4.0%	2.5%

[1] See Table A-2 for other input parameters.
[2] Scenarios assume that RAP has a 5% binder content.

Table A4. Input parameters for the RAS scenarios.

Parameter[1]	Scenario[2]		
	No RAS	2% RAS	5% RAS
Aggregate Content	95.0%	93.4%	91.0%
RAS Content	0.0%	2.0%	5.0%
Asphalt Binder Content	5.0%	4.6%	4.0%

[1] See Table A-2 for other input parameters.
[2] Scenarios assume that RAS has a 20% binder content and is transported 7.2 miles.

Input parameters for the WMA scenarios discussed in Section 3.2.1 are provided in Table A-5.

Table A5. Input parameters for the WMA scenarios.

Parameter[1]	Scenario[2]		
	HMA	WMA -30°F	WMA -50°F
Burner Fuel, MCF Natural Gas	23,773	20,885	18,961

[1] See Table A-2 for other input parameters.
[2] Scenarios assume fuel savings of 1,000 Btu/°F/ton.

Input parameters for the burner fuel scenarios discussed in Section 3.2.3 were calculated by multiplying the burner fuel consumption value in Table A-2 by the appropriate thermal energy conversion factor in Table A-1.