Infrastructure Carbon Estimator, version 2.2

Final Report and User's Guide

May 5, 2023

Transportation Pooled Fund Study TPF-5(362)

State Departments of Transportation: Minnesota (lead), California, Colorado, Iowa, New York, Texas, Washington, and the Federal Highway Administration

Infrastructure Carbon Estimator, version 2.2 (ICE2.2) Final Report and User's Guide

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This project developed the second iteration of the Infrastructure Carbon Estimator tool (ICE2). This document is the User Guide for the final tool, ICE version 2.2.

ICE is a lifecycle greenhouse gas (GHG) emissions and energy consumption estimation tool for transportation infrastructure. ICE was created to solve the problem of "planning level" estimation of embodied carbon emissions in transportation infrastructure. Without the need for engineering studies, ICE estimates the amount carbon and energy associated with building, modification, maintenance, and/or use of a transportation project. ICE provides users the ability to easily develop simple but comprehensive lifecycle estimates of "embodied carbon emissions". ICE also includes vehicle operating emissions on roads. Such estimates are suitable for the early, planning stage of a project or plan. ICE is a nearly complete tool for addressing sketch-level, lifecycle emissions from construction and maintenance of transportation infrastructure. It addresses most project lifecycle phases and many common infrastructure types. ICE may be used in conjunction with transportation planning and NEPA processes, before details about specific facility dimensions, materials, and construction practices are known.

This project modernized the ICE tool (first released in 2013) in several ways, including by revising its interface to a user-centered design approach, updating the lifecycle factors and available project types, modernizing avaialble mitigation measures, making the tool compliant with Section 508 of the Rehabilitation Act, including state-specific electricity factors, and numerous other changes. This document details those changes, summarizes the ICE tool, and provides a User's Guide for and additional information on ICE2.2.

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2. Executive Summary

Energy and greenhouse gas (GHG) emissions associated with the construction and maintenance of transportation systems are an important part of the total environmental impact of transportation. Assessments of energy and GHG emissions from transportation typically focus on the energy and fuel used by vehicles in travel. However, some state Departments of Transportation (DOTs) and metropolitan planning organizations (MPOs) consider construction and maintenance emissions associated with their long-range transportation plans and of individual projects for inclusion in Environmental Impact Statements (EIS). With over four million miles of highways and over 16,000 miles of bridges in the U.S., overlooking infrastructure can exclude a significant portion of total impacts.[1]

ICE was created to solve the problem of "planning level" estimation of embodied carbon emissions in transportation infrastructure. Without the need for engineering studies, ICE helps answer this question: How much carbon and energy is associated with the building, modification, maintenance, and/or use of this transportation project (or group of projects)? ICE is designed to allow users to create pre-engineering, "ballpark" estimates of lifecycle energy and GHG emissions using limited data inputs. It generally avoids requiring detailed data that would be derived from engineering documents and construction plans. This approach allows the tool to be used in conjunction with transportation planning and NEPA processes, before details about specific facility dimensions, materials, and construction practices are known.

ICE is intended to be used primarily by state DOTs and MPOs for planning level analysis to help answer the following types of questions:

1. *Planning and Programming:* What is the total energy and emissions impact of maintaining the current regional transportation system? What is the scale of impact of constructing projects included in a long-range plan, transportation improvement program, or corridor plan? Are there alternative plans or projects considered that would result in fewer construction emissions? What is the relative contribution by different project types in the plan?
2. *Evaluating the net energy and GHG impacts of individual projects:* If a project is intended to reduce operational energy and GHG emissions, how do these savings compare to emissions generated from the construction and maintenance of the infrastructure itself? What is the payback period for the project to generate a net reduction in emissions?
3. *Mitigation Strategies:* What types of strategies are most effective to reduce energy use and GHG emissions from materials, construction, preservation, and both facility maintenance and pavement preservation? How much can mitigation measures reduce emissions relative to the total? What is the impact of planned mitigations beyond standard agency practices?

ICE is a spreadsheet model that estimates lifecycle energy and GHG emissions from transportation infrastructure. The tool provides a screening-level lifecycle assessment (LCA) of energy and GHG

[1] Office of Highway Policy Information. Highway Statistics 2012 (Report). Federal Highway Administration. https://www.fhwa.dot.gov/policyinformation/statistics/2012/.

emissions, based on deterministic infrastructure prototypes. Specifically, ICE combines prototype models of various components of transportation related infrastructure and national-scale emission and energy use factors for materials and construction activities to calculate cumulative greenhouse gas (GHG) emissions and energy use. ICE is based on data collected from state DOTs, a nationwide database of construction bid documents, a survey of commercial environmental product declarations (EPDs), and consultation with transportation engineers and lifecycle analysis experts.

ICE is not a detailed engineering tool, does not generally address state-by-state variations in material energy and emissions, and relies on a fixed pavement surface mix design to remain "pavement material-neutral". These fixed proportions of asphalt and concrete used as pavement surface assumptions are derived from the representative sample of projects including both asphalt and concrete pavement types. ICE is also prescriptive for most operations and maintenance activities. ICE should not be used to inform engineering analysis and pavement selection.

This project developed the second iteration of the Infrastructure Carbon Estimator (released along with this User Guide as ICE2). ICE2.0, released November 2019, updated ICE1.0 in several ways. ICE2.0 was developed by relying on a user-centered design approach. ICE2.0 was redesigned to incorporate a wide variety of functions but display only the input fields the users need, facilitating its use by different types of users, such as planners and engineers. ICE2.0 incorporated an updated database of lifecycle emission factors and an updated list of available project types developed by Arizona State University's (ASU') Transportation Life Cycle Assessment Laboratory. The approach to mitigation was updated to include new data on certain mitigation measures, notably alternative fuels. ICE2.0 also updated the logic for calculating the effect of mitigation measures, to help avoid inappropriate or incompatible mitigation measures being selected. Vehicle use phase energy and emissions were updated to incorporate updated information from US EPA's MOVES2014b model. The model interface and summary of results in ICE2.0 also incorporated several new infrastructure types that were prioritized by the Pooled Fund Oversight Group and updated the calculation method for several existing infrastructure types. It was also designed to incorporate input from external LCA models.

ICE2.1, released August 2020, updated ICE2.0 primarily by modifying the functionality to be compliant with Section 508 of the Rehabilitation Act. This version of the tool includes a toggle that activates features making the tool accessible to people using assistive technology. The corresponding version of the User's Guide was also updated to be e compliant with Section 508. The general structure and calculations are identical to that of ICE2.0.

This version of ICE, ICE2.2, continues the improvements in ICE2. It includes the following major categories of improvements:

1) The addition of interchanges as a new infrastructure category,

2) Improved functionalities for estimating vehicle operating emissions,

3) The incorporation of updated lifecycle energy and GHG emissions factors for transportation fuels from the Greenhouse gases, Regulated Emissions and Energy Use Technologies (GREET) model coupled with energy consumption rates determined with the EPA's MOVES3 model,

4) The incorporation of state-specific energy consumption and emissions rates for electricity,

5) A new method for evaluating roadway rehabilitation,

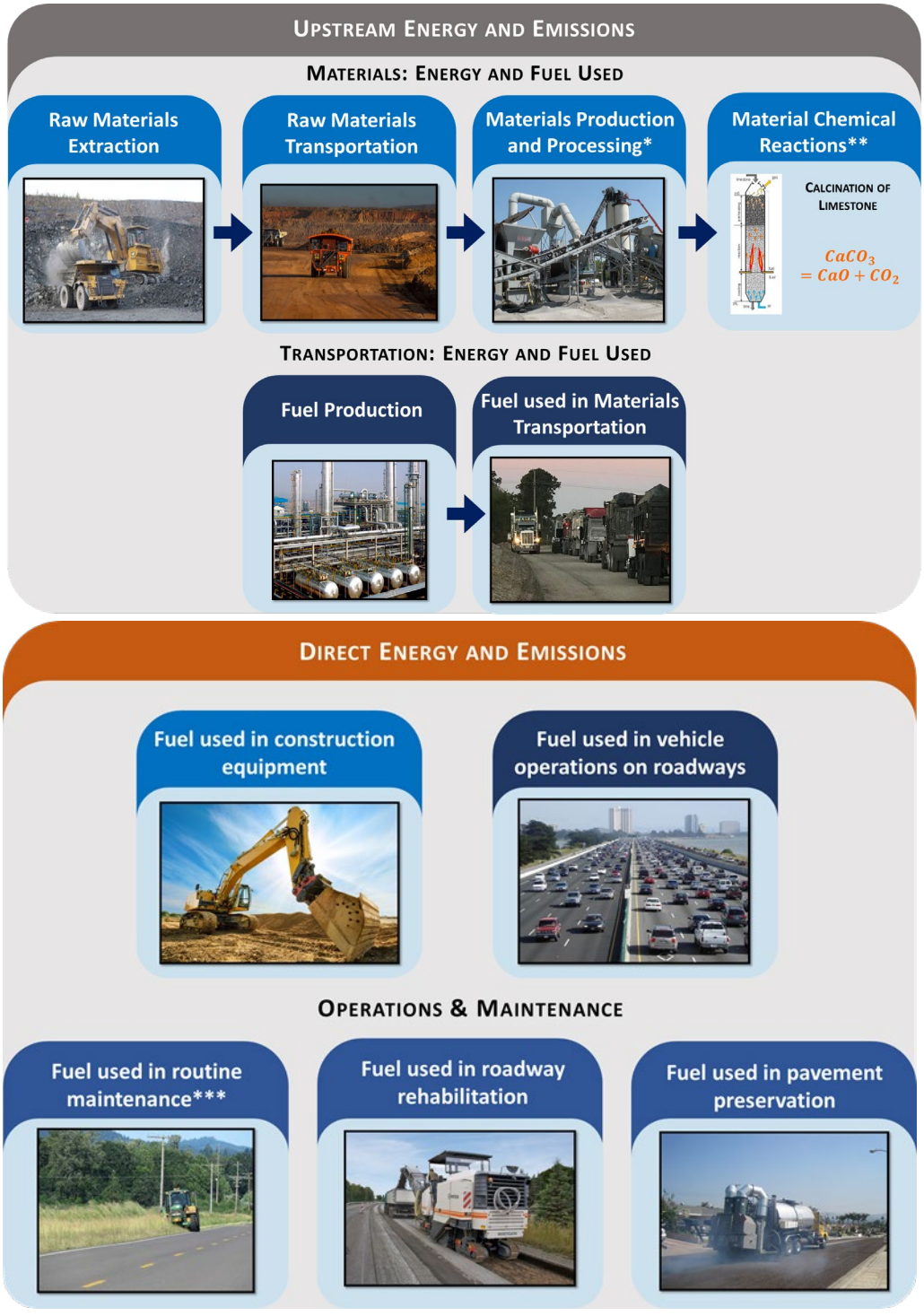
6) A new method for evaluating construction delay,

7) Internal changes to address issues identified in ICE 2.1, and

8) Updates to the model interface, including additional graphics and background information, and the reorganization of summary results.

ICE takes a lifecycle approach to accounting for energy use and emissions. The lifecycle analysis for materials used in projects is based on a cradle-to-gate scope. The lifecycle of infrastructure use includes vehicles using the infrastructure, routine maintenance, rehabilitation and preventative maintenance. Figure ES1 shows the upstream and direct activities included in the factors used to estimate impacts.

Figure ES-1 Life Cycle Stages of Construction and Maintenance Activities



* e.g., crushing of aggregate, asphalt batch plants
** e.g., CO2 emitted from calcination of limestone
*** activities include sweeping, striping, bridge deck repair, litter pickup, and maintenance of appurtenances

Included activities and emission sources are:

- *Construction/Rehabilitation:* Construction of a new facility or rehabilitation of an existing facility, including reconstruction and resurfacing .
  - Materials – Embodied energy and emissions associated with the extraction, transportation, and production of materials.
  - Construction equipment and transportation – Fuel use on site in construction and routine maintenance equipment, as well as fuel used to transport materials to the site.
  - Traffic delay – Excess fuel consumption by vehicles using existing facilities due to delays caused by construction activity.
- *Routine Maintenance:* Periodic maintenance activities including vegetation and snow management, sweeping, restriping, and (optionally) pavement preservation activities.
  - Construction equipment and transportation – Fuel used in maintenance equipment.
- Infrastructure Use:
  - Roadway vehicle use of the facility (excluding special facilities such as rail and BRT).

Table ES-1 provides a complete list of infrastructure and project types included in ICE2.1. Figure ES-2 shows examples of each of the types of facilities in ICE2.1.

Figure ES-2 Examples of ICE2.1 Infrastructure Types

Table ES-1: Infrastructure Types and Activities Included in ICE

Category	Infrastructure Type	Project Type
Bicycle	Off-Street Paths On-Street Bicycle Lanes	New Construction Resurfacing Restriping (On-Street Only)
Bridges and Overpasses	Single-span Two-span Multi-span (over land) Multi-span (over water)	New Construction Reconstruction Lane Addition
Bus Rapid Transit (BRT)	BRT Lane or Right-of-Way BRT Station	New Construction Convert/Upgrade Lane
Culverts	Single Box Culvert Double Box Culvert Pipe Culvert	New construction of small, medium, large, or custom facility
Custom Pavement	Infrastructure with pavement type other than that specified in ICE	Custom pavement analysis from external data sources
Interchanges	Cloverleaf highway interchanges	New Construction
Lighting	Street lighting	HPS or LED Lights on Vertical, Vertical and Vertical with Arm, or High Mast configurations
Parking	Surface Parking Structured Parking	New Construction
Pedestrian	Off-Street Paths On-Street (Sidewalks)	New Construction Resurfacing (Off-Street Only)
Rail	Light Rail Heavy Rail Rail Station	New Construction, Underground (hard rock, soft soil) New Construction, Elevated New Construction, at Grade Convert/Upgrade Existing Facility (Light Rail Only)

Roadways	Rural Interstates
	Rural Principal Arterials
	Rural Minor Arterials
	Rural Collectors
	Urban Interstates/Expressway
	Urban Principal Arterials
	Urban Minor Arterials/Collectors
		Roadway Construction
		  New Infrastructure
		  Re-alignment
		  Construct Additional Lane
		  Lane Widening
		  Shoulder Improvement
		With or without Roadway Rehabilitation (Pavement reconstruction or resurfacing)
		Within difficult terrain or not

Category	Infrastructure Type	Project Type
Existing Roadway Rehabilitation	Rural Interstates Rural Principal Arterials Rural Minor Arterials Rural Collectors Urban Interstates/Expressway Urban Principal Arterials Urban Minor Arterials/Collectors	Stand-alone pavement reconstruction or resurfacing activities on existing roadways only
Signage	Roadway signage	New installation of small, medium (regulatory and warning), or large (overhead guidance highway) signs
Vehicle Operations	Roadways	Additional emissions due to construction delay Vehicle emissions from roadway use Options to: Import custom values, or Use internal calculations

In addition to estimating baseline energy and emissions from construction and maintenance activity, the tool can estimate the impact of a variety of mitigation strategies that reduce energy use and GHG emissions in construction and maintenance. These include:

1. Alternative Fuels and Vehicle Hybridization
2. Vegetation Management
3. Snow Fencing and Removal Strategies
4. In-place Roadway Recycling
5. Warn-mix Asphalt
6. Recycled and Reclaimed Materials
7. Pavement Preservation

This document provides a step-by-step guide to using the Infrastructure Carbon Estimator, version 2.2 (ICE2.2). It is meant to accompany the detailed instructions and explanations of key input parameters also provided in the tool itself.

3. Infrastructure Carbon Estimator, version 2.2: An Introduction

Transportation system energy use and greenhouse gas (GHG) emissions are important to many transportation planners and decision makers. Simultaneously, there is increasing recognition that comprehensive analyses are necessary to understand the full range of contributors to such emissions, and that quantified, lifecycle assessments (LCA) of the energy and GHG emissions associated with infrastructure is necessary to support that understanding and begin to address the full lifecycle impacts of transportation projects and plans.

Climate action plans (CAPs) routinely analyze the potential to reduce fuel use and GHG emissions from on-road transportation as well as other modes. Several state departments of transportation (DOTs) and metropolitan planning organizations (MPOs) have goals to reduce energy and GHG emissions from transportation. Until recently, transportation agencies addressed these impacts by focusing exclusively on tailpipe energy and GHG emissions from vehicles traveling on the network. However, transportation infrastructure also requires energy and has associated GHG emissions. Infrastructure materials (including aggregate, asphalt, concrete, and steel) require energy to extract, process, and transport. Construction equipment burns diesel and other fuels in the processes of grading, laying road base, building bridges and rail lines, and paving. These processes must be considered to account for the transportation system's impacts. However, addressing these impacts is uncommon in long-range planning and NEPA analysis, which typically focus on changes in energy use and emissions once operational without addressing impacts associated with transportation projects themselves.

Traditional transportation air quality analysis may include construction equipment and may only consider short-lived, localized impacts of pollutants like particulate matter. The impacts of these pollutants only last for the duration of the construction project, as carbon monoxide and other criteria pollutants break down relatively quickly in the atmosphere compared to CO_2. In contrast, GHG emissions' impacts are cumulative. GHG emissions persist in the atmosphere for decades to centuries. The location of GHG emissions (of which carbon dioxide is the most common) is not important. It is the total amount of GHG emissions in the atmosphere that determines their effect on the Earth's temperature and weather patterns. It is worth noting that several states now require analysis of GHG emissions associated with projects' environmental assessments in addition to the traditional air pollutants. However, these may not consider the full lifecycle emissions.

ICE1.0 was released in 2013. ICE was created to solve the problem of "planning level" estimation of embodied carbon emissions in transportation infrastructure. Without the need for any engineering studies, ICE helped answer this question: How much carbon will be embodied in the building, modification, and/or maintenance of this transportation project (or group of projects)? Since its release, an increasing number of transportation agencies have begun implementing sustainability practices in their activities and projects. Such efforts may target sustainable pavements, GHG inventories, and other sustainability metrics. The growing efforts to quantify sustainability benefits have led to advancements in infrastructure lifecycle analysis. Many of the advancements related to transportation infrastructure LCA are captured in FHWA's 2016 report, *Pavement Life-Cycle Assessment Framework* (FHWA-HIF-16-014). Beginning in the mid-1990s, LCA was used to compare

the environmental impacts of roadway alternatives much in the same way lifecycle costing analysis had been used to determine the economic costs of alternatives. The early work was largely developed by researchers and academics and tended to focus on evaluating different impacts between different material selections. As the field has matured, practitioners have adopted the practice and additional factors have been assessed including the impacts associated with carbonation, albedo, pavement vehicle interaction, recycled materials and the impact of differing traffic loadings. Another advancement is a shift from attributional style of early LCAs (footprinting) to consequential LCAs (future forecasting to measure the effects of policies and decisions). Finally, there has been a recent emergence of pavement LCAs focused on alternative materials and practices, accounting for new and emerging technologies. In addition to the improvements made in sustainability practices and infrastructure lifecycle assessments there is also a growing number of sustainability experts in place at transportation agencies across the country.

ICE1.0 provided agencies and individuals the ability to develop simple LCA estimates of energy use and GHG emissions but it lacked sophistication in its design and a systematic approach to underlying data that led to challenges when it was applied to the purposes driving the use of LCAs today, such as identification of opportunities to reduce impacts in various lifecycle stages. ICE1.0's user challenges stemmed from having been tasked with serving a variety of overlapping and sometimes conflicting, purposes. While ICE was conceived as a solution to the question of "planning level" estimation of embodied carbon emissions, it was also asked to do much more, such as estimating the impact of mitigation efforts, pavement preservation programs, considering additional vehicle emissions from traffic congestion, and addressing both individual and groups of projects.

Since ICE was released, there have been developments in methods to estimate embodied material energy and emissions, data sources to support these methods, and coordination among various stakeholders. There is increasing interest in measuring upstream energy and emissions of materials, which has led to an increase in availability of data and refinement of infrastructure LCA methodologies and number of detailed LCA studies from which to draw upon, including Environmental Project Declarations (EPDs).

ICE is designed for a pre-engineering analysis of the energy and GHG emissions impacts of constructing and maintaining transportation infrastructure. A planning-level analysis is appropriate to produce "ballpark" estimates of the construction and maintenance impacts of long-range transportation decisions. It should be thought of as a sketch-planning analysis, rather than a detailed analysis of infrastructure design and construction parameters. A planning level analysis uses high-level estimates of construction activity in terms of lane miles or track miles before refined estimates are available. It is appropriate to analyze decisions that are made in the long-range planning or project development processes, before details about specific facility dimensions, materials, and construction practices are known. ICE does not analyze any tradeoffs between pavement types (e.g., asphalt vs. concrete), roadway designs (e.g., specific alignments and associated grading or structural differences), or bridge designs (e.g., steel vs. concrete structure). Rather it supports broad decision-making, such as the decision to build or not build a certain type of infrastructure, such as a freeway, bike path, or subway station, and alternatives analysis.

ICE2.0 was released in November 2019. ICE2.1 was subsequently released in October of 2020. This version of ICE, 2.2, continues the updates of the second version of ICE (ICE2). ICE2 was developed to address these issues and modernize the tool to increase its utility to its primary users:

transportation planners and NEPA analysts. It is intended to remain a pre-engineering tool but provide options for scenarios where users have additional information for their analyses through inclusion of a "project" mode that allows customization in many cases. Energy and emission factors for materials and fuels have been updated to reflect current analysis tools. Additional infrastructure types identified as useful to practitioners have been included, while some existing types have been modernized. The approach to mitigation has been modernized based on practitioner feedback. Functionality has been added to facilitate comparative analyses, such as NEPA-based build vs. no-build and alternatives analyses in a post-modeling approach using ICE outputs. Requested infrastructure categories have been added to ICE2, along with update to numerous inputs and data "under the hood". ICE's functionality has also been completely reworked, following a user-centered design perspective, to:

1. Maximize the utility of the tool to guide users to the content that is most appropriate for them, emphasize the types of projects that users most commonly need to analyze, and limit presentation of information or options that are not relevant.
2. Increase the educational value of the tool for practitioners by answering the questions that users need to answer; providing an understandable conceptual model of facilities for estimation; providing a simple characterization of available mitigations and their potential impacts; presenting an accounting of agency sustainability actions in construction that are both current practice and planned; providing a breakdown of results by material, phase, and individual projects in a plan; and providing summaries of both energy use and GHG emissions on both an annualized or cumulative project lifecycle basis.
3. Provide a platform that both uses the best available science currently and offers simplicity for updating as additional information becomes available.

ICE can be used for analysis to help answer the following types of questions from a full project lifecycle perspective:

1. *Planning and Programming:* What is the total energy and emissions impact of maintaining the current regional transportation system? What is the scale of impact of constructing projects included in a long-range plan, transportation improvement program, or corridor plan? Are there alternative plans or projects considered that would result in fewer construction emissions? What is the relative contribution by different project types in the plan?
2. *Evaluating the net energy and GHG impacts of individual projects:* If a project is intended to reduce operational energy and GHG emissions, how do these savings compare to emissions generated from the construction and maintenance of the facility itself? What is the payback period for the project to generate a net reduction in emissions?
3. *Mitigation Strategies:* What types of strategies are most effective to reduce energy use and GHG emissions from materials, construction, preservation, and both facility maintenance and pavement preservation? How much can mitigation measures reduce emissions relative to the total? What is the impact of planned mitigations beyond standard agency practices?

ICE2.1 also included modification of the functionality of ICE2.0 to be compliant with Section 508 of the Rehabilitation Act (29 U.S.C. Section 794d, as amended). These changes have been preserved in ICE2.2. These versions of the tool include a toggle that activates features making the tool accessible

to people with disabilities through use of assistive technology. This corresponding version of the User's Guide has also been made compliant with Section 508. Throughout this User's Guide we refer to the latest version, ICE2.2, although the general structure and calculations are similar to that of ICE2.0 and ICE2.1.

ICE 2.2 includes the following improvements:

1) The addition of Interchanges as a new infrastructure category.

2) Improved functionalities for estimating vehicle operating emissions. Users now have the option to incorporate the results from MOVES or other emissions models in ICE. For simple estimates of vehicle operating emissions, ICE has been updated with MOVES3 energy consumption rates (coupled with lifecycle energy and emission rates from GREET), allowing the analysis timeframe for on-road emissions to extend to 2060. Users also have the option to enter separate estimates of VMT and travel speeds for light- and heavy-duty vehicles.

3) The incorporation of updated lifecycle energy and GHG emissions factors for transportation fuels from the most recent version of the Greenhouse gases, Regulated Emissions and Energy Use Technologies (GREET 1 2022) model. These factors include alternative fuels that are now represented as mitigation options in ICE.

4) The incorporation of state-specific energy consumption and emissions rates for electricity.

5) A new method for addressing the roadway rehabilitation (one-time events as well as well as the maintenance schedule of resurfacing / reconstruction for longer-term analysis).

6) A new method for evaluating emissions from construction delay.

7) Internal changes to address issues identified in ICE 2.1.

8) Updates to the model interface, including additional graphics and background information, and the reorganization of summary results.

9) The default setting for certain drop-down options.

Appendix A4 lists the changes in the different versions of ICE2.

3.1 Project vs. Planning Modes

ICE2.2 remains a tool focused on analyses before detailed engineering studies are available (in other words, a "pre-engineering" tool). However, in some cases, users may have additional information on their projects to include in the analysis. For these purposes, ICE2.2 is built around two basic operating modes, referred to as *Project* and *Planning* mode. The two modes differ in the formats for data entry, the level of available information and customization, and in some basic functionality of the tool when one or the other is selected. This splitting of modes is fundamental to satisfying the two potential user groups, planners and engineers, within the basic structure of the tool.

ICE2.2's approach to resolving these competing demands and level of specificity with the framework of a screening-level assessment tool required balancing the level of detail required to produce meaningful results with the tool in-line with the user's desire to use the tool for custom analysis. ICE2.2 resolves this by sorting the analysis into two categories:

Planning mode provides access to all infrastructure types in a single simulation. Facilities may be included or excluded from analysis using ICE's control buttons. ICE navigates through the selected individual facilities, mitigations, and other details. No customization is allowed in *Planning* mode. Much of the underlying data is not presented to facilitate analysis.

The *Project* mode operates similarly in ICE to the *Planning* mode. Selecting the Project mode allows the user to view all inputs or have ICE walk the user through each step of the analysis for a single infrastructure type. Some infrastructure types allow additional customization or access to additional details for the infrastructure type in Project mode. Project mode also reveals additional calculation details for the facility, such as material quantities and fuel volumes used in the estimation. Only a single infrastructure type can be modeled in Project mode for a single ICE simulation.

3.2 Infrastructure Types Included in ICE2.2

The following infrastructure categories are included in ICE2.2. Figure 3 shows examples of each.

1. Roadways
2. Bridges and Overpasses
3. Bus Rapid Transit (BRT)
4. Culverts
5. Heavy Rail
6. Interchanges
7. Light Rail
8. Lighting
9. Parking
10. Pathways
11. Signage
12. Vehicle Operations
13. Custom Pavement (Projects implementing roadway lifecycle energy and emissions data imported from external tools)
14. Roadway Rehabilitation (Standalone Maintenance Projects on Existing Roadways)

Figure 3 Examples of ICE2.1 Infrastructure Types

For each infrastructure type, the tool calculates both mitigated results that take into account the effect of various energy/GHG reduction strategies and unmitigated results. In the Planning mode, infrastructure types can be combined to build out the lifecycle analysis for a custom plan. This could include, for example, a culvert paved with a road surface and including vehicle operating emissions following construction of the project. Section 4 includes a detailed description of each of these prototypes and their underlying assumptions.

Please note that infrastructure types 13 and 14 address specific and limited applications. Roadway Rehabilitation is limited to analysis of shorter term and isolated infrastructure maintenance. It only considers standalone resurfacing or reconstruction projects on existing roadways. The lifecycle of such activities is fixed and, as a result, the results of analyses for these projects may not be combined with other project types. Custom pavements analyses are very simple in ICE2.2. These are designed to allow overriding of ICE pavement factors with those from an external model, such as FHWA's Pavement LCA Tool.[2]

ICE2.2 includes updates to ICE in five major categories:

1. Targeted updates to the Tool's User Interface and related modifications.
2. Updated documentation comparing and contrasting ICE with other tools with similar purposes.
3. Updated emission factors and vehicle use-phase emissions approach.
4. Adding a new infrastructure category, interchanges, to the tool.
5. Updating the available mitigation measures.

3.3 Emission Sources Estimated

Construction and maintenance activities covered by the tool are broken into five categories:

1. Materials – This category includes upstream energy and emissions associated with project materials, particularly from four categories:
   - Energy and fuel used in raw material extraction
   - Energy and fuel used in material production
   - Chemical reactions in material production, such as CO_2 emitted from calcination of limestone.

[2] https://www.fhwa.dot.gov/pavement/lcatool/

- Energy and fuel used in raw material transportation

2. Transportation – This category includes upstream energy and emissions associated with fuel used to transport materials to site.
3. Construction – Energy and fuel used in construction equipment
4. Operations and Maintenance (O&M) – This category includes routine maintenance of infrastructure features, including:
   - Fuel used in snow removal equipment
   - Fuel used in vegetation management equipment
   - Fuel used in other routine maintenance, such as sweeping, stripping, bridge deck repair, litter pickup, and maintenance of appurtenances activities
   - Energy and emissions from roadway repair and rehabilitation
   - Net energy and emissions from pavement preservation activities (optional)
5. Usage – This category is for energy and emissions associated with vehicle operations on roadways. It includes both vehicle use on the infrastructure and additional emissions due to traffic delay from construction. Notably, this does not include bus emissions using BRT or emissions from use of light or heavy rail infrastructure. It does include additional vehicle emissions due to construction delay.

Notably, ICE does not include energy or emissions associated with land use change from the project.

3.4 Pavement Material Neutrality

ICE2.2 maintains several of the estimates of the typical volumes of materials and amount of on-site construction activity associated with building various types of facilities, such as an urban freeway, an at-grade rail line, or an off-street bike path from ICE1.0. These assumptions were based on data from a broad sample of projects.

Specifically regarding pavement type, ICE retains its designation to be "pavement material-neutral." That is, assumptions about the proportions of asphalt and concrete used as pavement surfaces are derived from the representative sample of projects from which all data are drawn. Since pavement surfaces are generally not determined at the planning or NEPA level, the tool does not ask the user for inputs related to surfacing material. Rather the tool assumes a typical mix of asphalt and concrete surfaces drawn from project data in several states. This is not alterable.

3.5 Relationship to Other Tools

Users may want to consider the relationship of other GHG emissions analysis tools to ICE. This section briefly summarizes some complementary tools. A complete discussion of tools identified as potentially relevant for similar analyses – namely those that address lifecycle transportation emissions, particularly on the infrastructure side – and how available tools can interact to provide a more complete analysis, in included as Appendix A6. Documentation of Relevant other Tools.

That appendix identified two notable energy/fuels tools (GREET and AFLEET) and three infrastructure/pavement lifecycle tools (LCA Pave, GASCAP, and GreenDOT). It also addressed uses for EPA's MOVES model, the CalEEMod model, and the Congestion Mitigation and Air Quality Improvement (CMAQ) Emissions Calculator Toolkit.

These models all serve different purposes. This section is only a very cursory overview. The user is encouraged to research each further.

3.5.1 Construction Emission Models

1. *Road Construction Model (RCM)* – The Sacramento Metropolitan Air Quality Management District's Road Construction Model was designed for air quality analysis of construction projects. It estimates emissions from construction equipment and vehicles but does not cover emissions embodied in materials. The data used to populate the tool's emission factors are drawn from a small sample of projects.
2. *California Emissions Estimator Model (CalEEMod)* – CalEEMod is an emissions estimator tool intended for analysis of air quality impacts in CEQA documents. It captures both direct (tailpipe) emissions and indirect emissions associated with land use projects, including emissions associated with construction. CalEEMod's focus is on building and site construction, rather than construction of transportation facilities.

3.5.2 Lifecycle Assessment Models

3. *Pavement Life-cycle Tool Assessment Tool for Environmental and Economic Effects (PaLATE)* – PaLATE is a lifecycle emissions assessment tool for roadway construction. It captures energy, GHG emissions, and criteria pollutant emissions associated with construction materials, construction equipment, and transportation of materials to construction sites. PaLATE requires detailed inputs on roadway design and dimensions. Lifecycle emission factors for materials from PaLATE were incorporated in both GreenDOT and the estimator tool created in this project.
4. *GreenDOT* – The Greenhouse Gas Calculator for State DOTs (GreenDOT) was developed for AASHTO to quantify the GHG emissions from roadway construction, including emissions from materials, construction equipment, and transportation of materials to construction sites. GreenDOT is capable of assessing detailed inputs in terms of tons of materials and hours of equipment use of specific equipment types. GreenDOT's input requirements are too detailed for a planning level assessment; however, GreenDOT is recommended for more detailed emissions analysis once engineering documents, materials quantities, and construction plans are established. GreenDOT includesa PaLATE based factors for materials energy and GHG emissions.
5. *The Greenhouse-Gas Assessment Spreadsheet for CAPital Projects (GasCAP)* – GasCAP is a tool developed by Rutgers University which estimates GHG emissions from transportation construction projects and maintenance activities. GasCAP includes components to estimate emissions associated with materials, non-road equipment, recyclables, lifecycle maintenance, project staging, traffic delays, lighting, rail projects, induced travel, and routine maintenance. GasCAP asks the user for detailed information about types and amounts of materials quantities and construction activities. It can be used for a more detailed emissions analysis following a planning-level analysis, once engineering documents, materials quantities, and construction plans are established.
6. *Pavement LCA Tool* – FHWA is developing a comprehensive Pavement Lifecycle Assessment Tool. The Custom Pavements infrastructure type in ICE is designed to receive outputs from and be compatible with this tool, when it becomes available.

3.5.3 Vehicle Use Emission Models

7. *Motor Vehicle Emission Simulator (MOVES)* – MOVES is EPA's standard motor vehicle emission model which is used by transportation agencies outside of California for air

quality analyses in compliance with the Clean Air Act. MOVES estimates tailpipe emissions of GHGs and criteria pollutants. The vehicle use phase analyses in ICE are derived from national-scale MOVES analyses.

8. EPA's NONROAD model estimates tailpipe emissions from nonroad engines, equipment, and vehicles, including construction equipment. NONROAD contains emission factors that are unique to specific equipment types, such as bulldozers and paving equipment, and specific fuel types, such as diesel and CNG. NONROAD has been completely incorporated into the MOVES model.
9. *EMFAC* – EMFAC is California's emission model for on-road vehicles. EMFAC is created by the California Air Resources Board and is used in California instead of MOVES. For projects or plans in California, EMFAC can complement an analysis using the estimator tool created in this project, in order to provide an estimate of the operational emissions impacts of transportation plans or projects
10. *OFFROAD and Inventory Models* – In California, non-road mobile source emissions were previously all modeled with OFFROAD. The OFFROAD model has now been replaced by category specific methods and inventory models by the California Air Resources Board (ARB) for most sectors, although OFFROAD is still the preferred model for some sectors. Most equipment considered here would fall under the *Construction, Mining, Industrial and Oil Drilling Equipment* category. In that category, equipment below 25 hp OFFROAD2007 remains the current tool for estimating emissions. For larger equipment, the 2010 Emissions Inventory Model should be used.
11. Congestion Mitigation and Air Quality Improvement Program Emissions Calculator Toolkit (CMAQ Toolkit) – The purpose of the CMAQ Toolkit is to provide users a standardized approach to estimating emission reductions from the implementation of a CMAQ-funded project. The CMAQ toolkit provides users 16 tools to follow a standardized approach for estimating emission reductions from the implementation of a CMAQ-funded project. These are designed to compute emissions from roadway and other transportation projects but are not lifecycle tools.

4 User's Guide

4.1 How to Use ICE

The Infrastructure Carbon Estimator (ICE) is a spreadsheet tool that estimates the lifecycle energy and greenhouse gas (GHG) emissions from the construction and maintenance of transportation facilities. The ICE tool was created to solve the problem of "planning level" estimation of embodied carbon emissions in transportation infrastructure. Without the need for any engineering studies, ICE helps answer this question: How much carbon will be embodied in the building, modification, and/or maintenance of this transportation project (or group of projects)?

The inputs to ICE are designed to be as simple as possible to source and input while still producing a reasonable analysis. The primary inputs required by the tool should be readily available metrics, such as roadway lane miles, rail track miles, or number of bridges, signs, or lights.

ICE is designed to be self-explanatory. ICE includes detailed instructions and explanations of key input parameters in the tool itself. These are included as text in the tool as well as using Excel's comment windows to populate "pop-up" windows with useful information.

Any use of ICE will follow the same basic steps. Those are:

Step 1: Select the location (state) and lifetime (years) found on the *Project Inputs* tab.
Step 2: Select operating mode ("Project" or "Planning") for your analysis. The tool can analyze different individual projects ("Project Mode"), or a suite of projects in a comprehensive plan ("Planning Mode"). If applicable, turn on 'Display result in 508 compliant format' toggle to make the tool display in a form compatible with assistive reading devices.
Step 3: Select the infrastructure type(s) to analyze. Input all requested data using information from the project or plan you want to analyze. Then navigate to the relevant analysis page(s) for your project or the individual project(s) in your plan and complete the analysis for each infrastructure type by entering information in all cells that are shaded yellow. Blue and gray cells display fixed values and results; do not change the information in these cells.
Step 4: Apply any selected mitigation measures on the *Mitigation Strategies* tab.
Step 5: Review outputs on the *Summary Results* tab.
Step 6: Print analysis results by navigating to the *Print Results* tab.

Factors and assumptions incorporated in the tool are summarized in Section 4. Additional details are provided in the Appendix. For security purposes, the tool itself is locked and assumptions are hidden. Lastly, users may click on the "Clear All User Data" button, found on the 'Project Inputs' worksheet, which will reset the tool and allow a user to start from scratch. Note that selecting this feature will erase all inputted data and results.

When using the tool, keep in mind that:

- To conduct an accurate analysis, entering information on all project activities is more important than ensuring that all activities are sorted into precise categories. That is, it is most important to ensure that all lane miles and track miles of construction and rehabilitation activity are included.
- Users should make reasonable assumptions based on their knowledge of the project area in order to fill any data gaps.

- If desired, a more detailed analysis may be conducted on certain projects individually using the Project mode once additional information is known.

4.2 Tabs and Navigating the Tool

The tool can be navigated in multiple ways. Users will start by describing their project on the *Project Inputs* tab. This includes the infrastructure type(s), analysis lifetime, location, and analysis mode. Hyperlinks carry users through the various tabs. Three comment boxes allow the user to input descriptive text that will be carried through to the output pages. This could include analysis date, analyst's name, project descriptions, or other information the analyst may want to include in their report. (Section 2.4.1 describes the *Project Inputs* tab more fully.)

First, select your level of analysis ("Project" or "Planning") and input the requested information for your project on the *Project Inputs* tab. Input the state for your analysis[3], the project analysis lifetime (in years), and whether the impacts of a custom electricity emission program, such as a Renewable Portfolio Standard (RPS), are to be included. Answering "yes" on the latter will open the *Annual Electricity Emissions* tab for populating.

If using the Planning level of analysis, "turn on" all infrastructure types to be analyzed on the *Project Inputs* tab. If using the Project level of analysis, then select the single infrastructure type to analyze. This "toggle" functionality is new to ICE2.1 and is the key to its utility. The user only sees what is needed for their analysis and what they select.

Hyperlinks from the *Project Inputs* tab will take you to the analysis page for your project type(s). (The project analysis pages are titled according to the infrastructure type and described more fully in Section 2.6.) Here some additional inputs for your project may be requested. At the top of each analysis page is a hyperlink that carries you to the *Mitigation Strategies* tab (Section 2.4.2).

Each analysis page includes the following sections:

1. Specifications – Fixed and input values describing the project
2. Baseline Energy Use and GHG Emissions – Total energy use and GHG emissions over the project's lifetime
3. Mitigated Results – Annualized energy use and GHG emissions for the project without (baseline) and with (both business-as-usual and control scenario) mitigations applied.
4. Results - Charts – Summary charts and tables of the mitigated and unmitigated energy use and emissions by emission category, material, and individualized mitigation effects. Results can be viewed as annualized or cumulative GHG emissions or energy.

On the *Mitigation Strategies* tab, you have the option to input certain strategies that reduce energy and GHG emissions for your project. This tab will only show relevant strategies for the selected infrastructure types. Hyperlinks at the top return you to the analysis page for your project type.

Below the project specifications in each analysis page, the calculated, annualized or cumulative baseline, business-as-usual (BAU), and mitigated levels of energy or GHG emissions for your project type(s) are displayed. This shows results by the five emission categories and by material for both mitigated and unmitigated cases. It also shows emission or energy reductions by mitigation measure.

[3] 50 states plus District of Columbia (DC).

The *Summary Results* tab displays an overview of results for all infrastructure types analyzed. If the analysis is at the Project level, this display is nearly identical to that on the analysis page. However, a comparative summary of results by infrastructure is first displayed in the *Summary Results* tab for quick reference, For Planning level, buttons appear allowing the user to turn on or off the different project types included in the combined results. The "Show" dropdown menu selects the results displayed: Annualized Greenhouse Gas Emissions, Annualized Energy Use, Cumulative Greenhouse Gas Emissions, and Cumulative Energy Use. An additional chart in the *Summary Results* tab (not available in the individual analysis pages) displays values by infrastructure type.

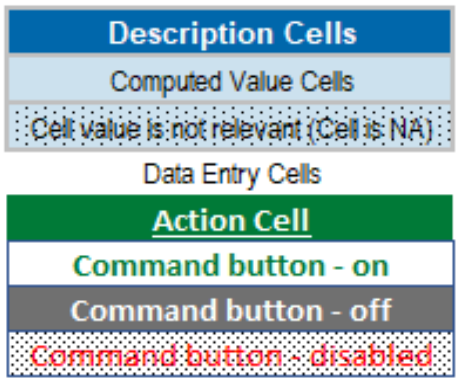
If the use phase of automobiles is to be considered in your project, you must include the Vehicle Operations project type. Resulting energy and emissions from project use will be added to the summary charts on the *Summary Results* tab. Note that vehicle use phase emissions only apply to the on-road vehicles in the Vehicle Operations project type. Use of other vehicle types, such as railroads, are not included in ICE2.2.

At any time, the user can view overall results in the *Summary Results* tab or enter a custom mitigation approach for energy and GHG emissions in the *Mitigation Strategies* tab. The user can switch directly between Excel tabs at any time. The *Print Results* tab collects outputs and formats them for standard printing, either to an electronic or paper copy for archiving the outputs of your simulation. This can be used to compare multiple simulations, such as for a Build vs. No-Build analysis in a post-model application.

4.3 Color Scheme

ICE uses a consistent color scheme to illustrate the function of each cell. This includes descriptive cells, computed value cells, cells whose value is irrelevant for the current calculations (e.g., is not applicable, N/A), as well as action cells and buttons. Figure 4 illustrates the cell-specific color scheme used throughout the tool.

Figure 4. Cell-Specific Color Scheme in ICE



4.4 Tool Controlling Tabs

ICE is Microsoft Excel based. It relies on Excel's worksheet-based approach for functionality. This sorts all tool actions, inputs, outputs, and controls into individual worksheets, or tabs. ICE consists of three primary user-facing sheets:

1. A **Project Inputs** sheet where users enter baseline information on the transportation network and information on their project.
2. A **Mitigation Inputs** sheet where users enter information on the current and planned use of strategies that can reduce energy use and GHG emissions.
3. A **Summary Results** sheet that displays estimates of mitigated and unmitigated energy use and GHG emissions under the project, as well as the total amount of materials and fuel that will be used in the construction and maintenance of the project.

There are also secondary, special purpose sheets:

4. The **Introduction** sheet provides a summary of user instructions and tool functionality.
5. The **Print Results** sheet pulls results from the Summary Results sheet into a formatted output that may be printed to paper or electronic format for archiving and post-model comparison of results, such as in a NEPA-based build vs. no-build analysis.

There is also 14 individual tabs for each of the thirteen infrastructure types included in ICE, as shown below:

These are named for the infrastructure category they represent. Section 2.6 discusses these individually.

If selected, there is a special sheet for including the effects of a renewable portfolio standard (RPS) or other mitigation policy effects on electricity emission factors on the project.

Users can navigate between all these sheets using the buttons that are embedded throughout the tool or the tabs at the bottom of the Excel window. The following subsections describe each of these tabs. There are also numerous hidden sheets that provide the tool's functionality. These are only available after unlocking the tool. See Appendix A4 for more information.

4.4.1 Project Inputs Tab

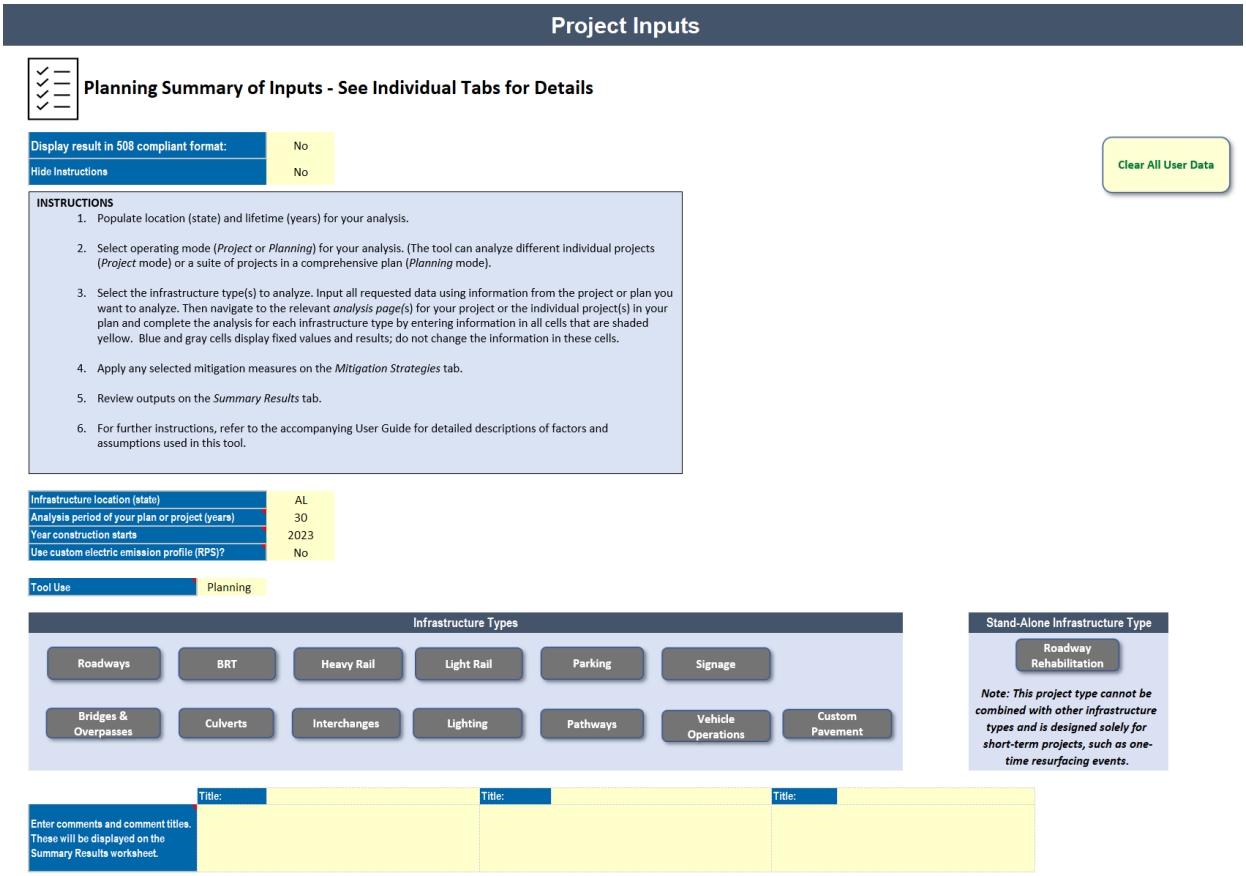
The *Project Inputs* tab allows users to specify the relative quantities associated with each category of infrastructure deployment and other activities included in the tool. For example, users can define the total number of lane miles by classification for a roadway construction project. The numbers provided in this worksheet are used in conjunction with infrastructure prototypes to define total material demand for user-defined infrastructure projects.

The *Project Inputs* tab includes two main sections.

1. A General Information section providing instructions and where the user sets basic parameters for the simulation, such as location and the types of infrastructure included.
2. An input section where the user enters specific parameters for the simulation for each of the selected infrastructure types.

Figure 5 shows a screenshot of the upper portion of this tab. For explanation of the color scheme of each cell and control button, see Section 2.3.

Figure 5. Project Inputs Tab



ICE2.2 interface is similar to ICE2.1 but significantly different from 1.0. ICE2.1 opens to the *Project Inputs* tab. The user will first enter a state and project analysis lifespan in years before the rest of the Tool is displayed. Users are also asked to populate the year construction starts, whether a custom electric emissions profile should be applied, and whether the Section 508-compliant version of the tool will be used.

When those inputs are populated, the rest of the tool is unlocked. The next required entry in the *Project Inputs* tab is whether the analysis will be conducted in the project or planning mode. If the project mode is selected from the dropdown the only available inputs here will be to select the infrastructure type and the three input text boxes. The user should select the desired infrastructure type and populate any (or all) of the input text boxes with a title and corresponding answer. Entered values should describe relevant project details, such as internal project numbers, freeway names, project analyst, etc. For example, title could be "Analyst" and comment could be "Jane".

If the planning mode is selected then the buttons for all the various infrastructure types shown in Figure 5 appear, along with the same three input text boxes described above. The user should "turn on" all infrastructure types in their analysis by clicking on the respective buttons. Note that the order of the Infrastructure Type buttons has been reorganized in ICE2.2 to emphasize the more commonly used items.

The user should then move to the lower portion of this tab. If the project mode has been selected, the required inputs for the one selected infrastructure type are presented. If the planning mode is selected, the required inputs for all selected infrastructure types are presented. The user will populate all necessary inputs. Then proceed to the individual infrastructure type tabs for further analysis inputs and results. This may be done by clicking on the hyperlinks below the inputs, e.g., "Specification", or by clicking directly on the individual tab.

ICE2.2 has been reorganized and updated to provide additional information to the User to make it more intuitive and present the most used information first. Part of this includes adding a brief summary overview text for each infrastructure type. along with other visual elements. Figure 6 shows an example for the Roadways infrastructure type from the Project Inputs tab.

Figure 6. Project Inputs Tab

See Section 4.2 for more information on navigating ICE.

4.4.2 Mitigation Strategies Tab

The *Mitigation Strategies* tab has been slightly redesigned to accommodate changes in ICE2.2 but maintains the same general approach as ICE2.1 and ICE1.0. Users select from a range of potential mitigation strategies appropriate for their selected infrastructure types. ICE2.1 has the following mitigation categories available, although the mitigation measures displayed are determined by the infrastructure categories considered in the analysis.

1. Alternative fuels and vehicle hybridization,
2. Vegetation management,
3. Snow fencing and removal strategies,
4. In place roadway recycling,
5. Warm mix asphalt,
6. Recycled and reclaimed materials, including use of recycled asphalt, use of industrial byproducts as cement substitutes, and recycled concrete, and
7. Pavement Preservation

The primary entry for all but Pavement Preservation is the deployment value as a percentage. This can be thought of as a penetration depth of the strategy, or the extent to which a mitigation strategy is used, as a percentage relative to unmitigated conditions. In ICE2.1 the user now inputs values in the *Mitigation Strategies* tab for both the business as usual (BAU) deployment and the planned deployment.

The BAU deployment is understood to be the extent to which the strategy is deployed through standard agency practices. This allows ICE to compute and track separately the impacts of any sustainability practices already implemented by an agency. It may be compared to a Baseline deployment, which here refers to values without any mitigations applied. The Planned deployment

represents the extent to which any selected strategy(ies) will be deployed in the project that you are examining.

The Deployment Increase column displays the increase in deployment from implementation of the strategy. Some reduction strategies (e.g., Switch from diesel to Soybean-based BD20 and biodiesel/hybrid maintenance vehicles and equipment) may be incompatible. The user should take care that inputs do not describe a total deployment greater than 100% for overlapping strategies. Logic has been included in ICE2.1 that allows the tool to warn the user if "excess" energy savings from mitigation are predicted. ICE will present a popup "nag window" to warn users of potential incompatible strategy deployment or deployments that exceed 100% when combined and targeting the same reduction category.

The last category of strategies is Pavement Preservation. ICE2.1 considers pavement preservation strategies as a broad category of preventative maintenance strategies that reduce the lifecycle emissions and energy associated with roadway infrastructure by extending the life of the pavement and thus the time required between the major maintenance activities, resurfacing and reconstruction.

Pavement Preservation strategies are treated generically in ICE. This is because there is no standard approach and the type and application frequency varies by region, agency, and facility. Instead, in ICE the user enters both the number of years by which the user's generic pavement preservation program extends roadway life and the pavement preservation application frequency. The frequency is entered as the number of years in a cycle for the entire roadway system to be treated.

The user is reminded that ICE is a screening level tool, particularly with respect to mitigation. For a more refined mitigation analysis, the user should refer to other sources, such as FHWA's upcoming Pavement LCA Tool. (Section 1.5.2)

The summary results tab tracks and reports the inputs of each mitigation measure on each infrastructure type. These are reported for the BAU and Planned deployment levels, along with the baseline (unmitigated) case.

Figure 7. Mitigation Strategies Tab

Mitigation Strategies

Return To Project Inputs

Instructions: Follow the steps below to calculate the impact of energy and GHG mitigation strategies:

The user will enter both the business as usual (BAU) deployment (i.e., the extent to which the strategy is deployed through standard agency practices) in Column F and the planned deployment (i.e., the extent to which the strategy will be deployed in the project that you are examining) in Column G. (Baseline refers to values without any mitigations.) For Pavement Preservation strategies, enter both the schedule change and application frequency.

Column H displays the increase in deployment from implementation of the strategy. Some reduction strategies (e.g., Switch from diesel to Soybean-based Biodiesel and biodiesel/hybrid maintenance vehicles and equipment) may be incompatible. The user should take care that inputs do not describe a total deployment greater than 100% for overlapping strategies. The tool will warn if "excess" energy savings from mitigation are predicted or incompatible strategies are selected.

For a more refined mitigation analysis, please refer to FHWA's upcoming Pavement LCA Tool.

							BAU Reductions		Planned Reductions	
Strategy	BAU deployment	Planned deployment	Deployment increase	Energy reduction factor	GHG reduction factor		Energy reductions	GHG reductions	Energy reductions	GHG reductions
Alternative fuels and vehicle hybridization										
Switch from diesel to Soybean-based Biodiesel			0.0%	-26%	14%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to Soybean-based RDII 100			0.0%	-28%	65%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to Forest Residue-based RDII 100			0.0%	-67%	73%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to E-Diesel, Corn			0.0%	-5%	14%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to PHEV: Diesel and Electricity (U.S. Mix)			0.0%	23%	-13%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to Hybrid Diesel			0.0%	11%	11%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to Electricity			0.0%	61%	25%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to CNG, NA NG			0.0%	-9%	11%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to LNG, NA NG			0.0%	-13%	8%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to Conventional Diesel (BD20)			0.0%	-5%	14%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to Hydrogen (from NG)			0.0%	40%	52%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to Biodiesel (from corn)			0.0%	-88%	90%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to RDII (from corn)			0.0%	-81%	87%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to CNG (from Landfill, Off-site Refueling)			0.0%	2%	17%		0.0%	0.0%	0.0%	0.0%
Switch from diesel to Renewable CNG (from Wastewater Treatment, Off-site refueling)			0.0%	62%	136%		0.0%	0.0%	0.0%	0.0%
Hybrid maintenance vehicles and equipment			0.0%	11%	11%		0.0%	0.0%	0.0%	0.0%
Combined hybridization/B20 in maintenance vehicles and equipment			0.0%	1%	27%		0.0%	0.0%	0.0%	0.0%
Hybrid construction vehicles and equipment			0.0%	11%	11%		0.0%	0.0%	0.0%	0.0%
Combined hybridization/B20 in construction vehicles and equipment			0.0%	1%	27%		0.0%	0.0%	0.0%	0.0%
Vegetation management										
Alternative vegetation management strategies (hardscaping, alternative mowing, integrated roadway/vegetation management)			N/A	25%	25%		0.0%	0.0%	0.0%	0.0%
Snow fencing and removal strategies										
Alternative snow removal strategies (snow fencing, wing plows)			N/A	0%	0%		0.0%	0.0%	0.0%	0.0%
In-place roadway recycling										
Cold In-place recycling			0.0%	33%	37%		0.0%	0.0%	0.0%	0.0%
Full depth reclamation			0.0%	68%	68%		0.0%	0.0%	0.0%	0.0%
Warm-mix asphalt										
Warm-mix asphalt			0.0%	37%	37%		0.0%	0.0%	0.0%	0.0%
Recycled and reclaimed materials										
Use recycled asphalt pavement as a substitute for virgin asphalt aggregate			0.0%	12%	12%		0.0%	0.0%	0.0%	0.0%
Use recycled asphalt pavement as a substitute for virgin asphalt bitumen			0.0%	84%	84%		0.0%	0.0%	0.0%	0.0%
Use industrial byproducts as substitutes for Portland cement			0.0%	59%	59%		0.0%	0.0%	0.0%	0.0%
Use recycled concrete aggregate as a substitute for base stone			0.0%	58%	58%		0.0%	0.0%	0.0%	0.0%

4.4.3 Summary Results Tab

The *Summary Results* tab has been redesigned for ICE2.2 to make the output display more refined, easy to use, and useful. ICE's Summary Results tab is organized in three parts.

The topmost part consists of introductory material. In *Project* mode, this allows the user to view the text input in the text boxes in the *Project Inputs* tab and allows the user to select outputs to view and in which units. There are four available options for display from the "Show" dropdown menu:

1. Annualized Energy Use,
2. Annualized Greenhouse Gas Emissions,
3. Total Energy Use, and
4. Cumulative Greenhouse Gas Emissions.

The cumulative impact display is designed to allow better representation of the environmental impacts of a project over the specified lifetime. The annualized values consider the impacts on an annualized basis over the specified project's lifetime. ICE *Summary Results* tab allows display of either emissions or energy use. Finally, there is a dropdown menu to allow selection of reporting

units. This is designed to help facilitate the display for cases with small emissions or energy values. The selection of one of the four reporting values and units filters down to the charts and tables sections below.

In ICE2.2 the reporting units for GHG emissions are:

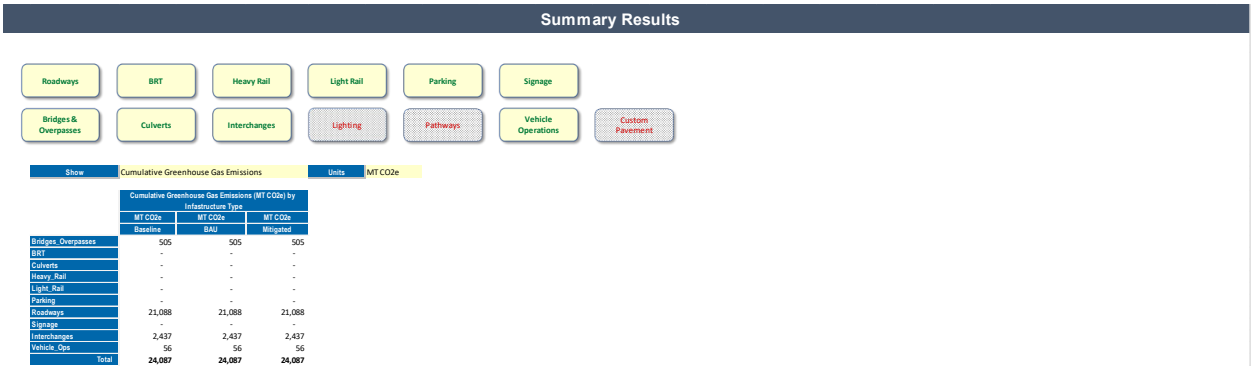
- MT CO2e – metric tonnes[4] of carbon dioxide equivalent. 1 MT = 1,000 kg.
- MMT CO2e – million metric tonnes of CO_2e.
- kg CO2e – kilograms of CO_2e.

For energy use, the reporting units are:

- BTU – British thermal units.
- kBTU – thousands of BTU.
- mmBTU – millions of BTU.

In *Planning* mode, the topmost introductory section is nearly identical to that from the Project mode. However, in Planning mode there are a series of action buttons similar to those shown in the Project Inputs tab. Here the user will select which – any or all – of the infrastructure categories considered in their analysis will be displayed in the charts and tables. Those categories that were not included in the analysis are not available. Those that were included may be turned on or off individually in the display. Figure 8 shows an example of the introductory section of the *Summary Results* tab.

Figure 8. Introduction Section of the Summary Results Tab



The second and third sections in the *Summary Results* tab show *Summary Results – Charts* and *Summary Results – Tables*, respectively for the selected analysis. The layout of these sections is identical between the Planning and Project modes. However, the values displayed depend on those infrastructure types (multiple types available only for Planning mode) selected for display in the introductory section.

The second section, "Summary Results – Charts", consists of three charts.[5]

[4] Sometimes referred to as a "metric ton". Here we use "tonne" to distinguish a metric tonne (1,000 kg) from a short (English) ton (2,000 lbs).

[5] The fourth chart type, results by Material have been removed from IC2.2 at user request. These still appear in the bottom right of the individual infrastructure type tabs but not in the Summary Results tab. There, this chart breaks down results by material used in the project or plan. Note that some materials are actually pseudo-materials used in ICE calculations, such as usage or operations and maintenance (O&M)

1. Phase – The top left chart (and the corresponding table further below in the sheet)) breaks down results (annualized or cumulative energy or emissions, as selected above) by phase. This is designed to enhance the educational value of ICE by illustrating the relative contribution of different phases/materials to the overall lifecycle values. Here the resulting total energy and emissions from all infrastructure type(s) are presented by the distinct contributing phases to facilitate in the analysis of upstream versus direct emissions from the project:
   - Materials,
   - Transportation,
   - Construction processes,
   - Operations and maintenance, and
   - Usage.

   There are three stacked bar charts shown with this breakdown, representing the baseline, BAU, and Planned mitigation deployments. If no or negligible mitigations are applied in any case, the bar charts will be identical.
2. Mitigation Impacts by Phase – The top right chart (and corresponding table further below in the sheet) breaks down the effects of applied mitigations by phase. This shows the energy or emission (as selected) reductions for each of the selected mitigation strategies individually.
3. Infrastructure Category – The bottom left chart (and corresponding table near the top of the sheet) breaks down results by selected infrastructure category. For the Planning mode, when multiple infrastructure categories are included, the bar charts show the contribution to the total plan emissions by each of the infrastructure categories included. As with the first chart, there are three stacked bar charts shown with this breakdown, representing the baseline, BAU, and Planned mitigation deployments.

Figure 8 shows an example of the three charts in the *Summary Results* tab.

The third section is the "Summary Results – Tables" section. This consists of four tables, corresponding to the four charts listed above.

Note that in these charts, *Vehicle Ops* refers to the vehicle operations infrastructure type, while *Usage* refers to use phase emissions from vehicle operations. In most cases these are synonymous, but reported differently in the first (emissions by phase) and third (emissions by infrastructure type) charts to track reporting consistent with the tool's calculations. Vehicle usage is explained on the *Introduction* tab.

pavement preservation. These pseudo materials are used for accounting in ICE but do not correspond to the physical materials in ICE, discussed in Section 4.1.

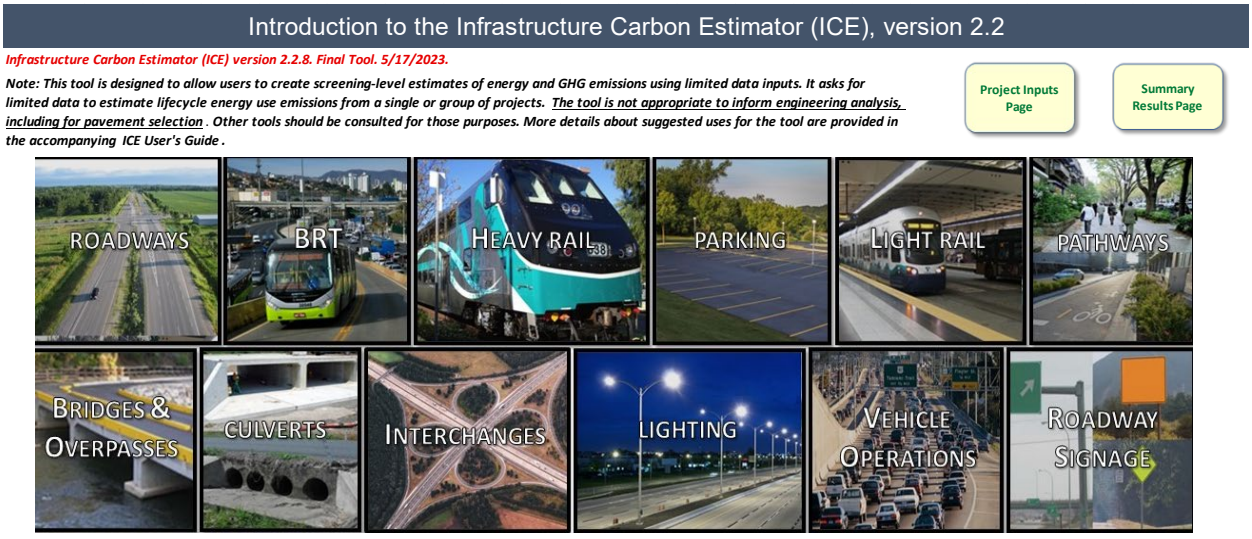
Figure 9. Summary Results Graphs

4.5 Secondary Tabs

4.5.1 Introduction

The Introduction tab provides an overview of the tool and general user instructions. It is referential only, entirely text based, and without any user interaction. Figure 9 provides a partial image of this sheet.

Figure 10. Introduction Tab.



This tab, although not a substitute for the user's guide, is meant to better orient the user. This includes an overview of each infrastructure type, the difference between planning and project mode,

how to navigate the tool, and a brief description of the emissions associated with the five constructure and maintenance categories.

4.5.2 Print Results

The Print Results tab collects the tabular and chart outputs from the Summary Results tab and reformats for printing or archiving. This tab also requires no user interaction unless the user changes the reporting units with the drop-down menu. This tab is designed to provide a simple form for the user to save model results and use after simulations are complete. This could facilitate a comparison of complex simulations involving multiple infrastructure types.

We do not include an image of the Print Results tab here since no new information is included in this tab.

4.6 Infrastructure Type Tabs

Use of the various infrastructure types in ICE2.1 is described here. For more information on the prototypes and calculations for each type, see Section 6.2.

Each of the fourteen infrastructure tabs follow the same organization:

1. The topmost section provides a text overview of information about or needed for calculations.
2. The Specification section typically echoes back key inputs from the Project Inputs tab. It may also request or allow additional inputs depending on the infrastructure type.
3. The Baseline Energy Use and GHG Emissions section summarizes the baseline, or unmitigated, energy and emissions calculation results. In the project mode, it also displays material quantities and related values. All values in this section are cumulative over the specified lifetime.
4. The Mitigated Results section summarizes the annualized energy use and GHG emissions results for three cases: the baseline (unmitigated), the Business-as-Usual (BAU) (agency standard practice mitigations), and Mitigated (planned mitigations applied to the scenario).
5. The Results-Charts section summarizes the results of all calculations in both tables and figures. This includes breakdowns of results by material, phase, and mitigation strategy.

4.6.1 Bridges and Overpasses

4.6.1.1 Overview

ICE estimates the energy and GHG emissions associated with the construction, reconstruction, or lane addition for single span, two-span, and multi-span bridges and overpasses. Bridges and overpasses are treated as being functionally equivalent in ICE.

The Bridges and Overpasses module in ICE applies to the construction of the bridge structure rather than the pavement surface. Bridge paving activities should be entered as part of the Roadway construction activities.

Approximately half of short bridges in the U.S. (less than 1,000 feet long) are single-span or double-span. If information about number of spans is not available, it is reasonable to assume a mix of single-span and two-span bridges. Note that the number of spans is an important factor in energy use and GHG emissions. The bridge module in ICE is only applicable to bridges shorter than 1,000

feet. Longer bridges are major projects that are characterized by different material and energy intensities than those used to develop these prototypes.

Please note that very large bridges that carry traffic very high or span very deep spaces are unique and likely require additional materials and construction processes that cannot be approximated by ICE.

4.6.1.2 Required Inputs to Use in ICE

The configuration of inputs and outputs for bridges and overpasses is significantly updated in ICE2.1. Figure 10 and Figure 11 are screenshots of inputs for planning and project roadway analyses. Please note that for Planning mode, Figure 10 shows the inputs entered on the *Project Inputs* tab. For Project mode, more specific inputs are entered. Accordingly, there are no inputs on the *Project Inputs* tab. The user is instead directed to the *Bridges_Overpasses* tab to populate the inputs shown in Figure 11. The inputs for both are defined below.

The tool model four types of bridge spans:

1. Single-span: A single-span bridge is anchored at each end with no supports in the middle
2. Two-span: A two-span bridge has two sections of bridge structure between supports.
3. Multi-span (over land): This is a bridge crossing over land with more than two sections of structure between supports.
4. Multi-span (over water): This is a bridge crossing over water with more than two sections of structure between supports.

Figure 11. Bridges & Overpasses Inputs for Planning Level Analysis (Project Inputs tab)

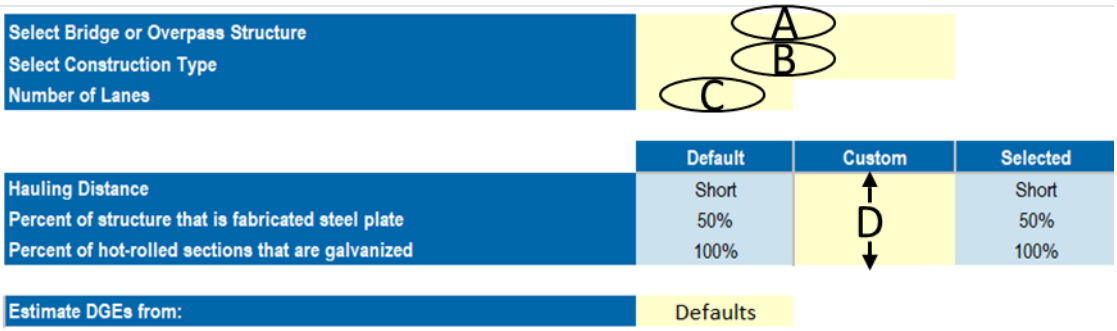
	Construct New Bridge/Overpass				Reconstruct Bridge/Overpass				Add Lane to Bridge/Overpass			
Bridge/Overpass Structure	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes per structure	Total number of lane-spans	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes per structure	Total number of lane-spans	Number of bridges & overpasses	Average number of spans per structure	Average number of lanes per structure	Total number of lane-spans
Single-Span	A	1	C	0	D	1	F	0	G	1	I	0
Two-Span		2		0		2		0		2		0
Multi-Span (over land)		B		0		E		0		H		0
Multi-Span (over water)				0				0				0

The following list explains each input element in Figure 10:

A. Enter the number of newly constructed bridges or overpasses
B. For multi-span (over land or water), enter the average number of spans per newly constructed bridge or overpass.
C. Enter the average number of lanes per newly constructed bridge or overpass.
D. Enter the number of reconstructed bridges or overpasses.
E. For multi-span (over land or water), enter the average number of spans per reconstructed bridge or overpass.
F. Enter the average number of lanes reconstructed per bridge or overpass.
G. Enter the number of bridges or overpasses where a lane addition is occurring.
H. Enter the average number of spans for multi-span bridge per bridge or overpass with a lane addition.

I. Enter the average number of lanes added per bridge or overpass.

Figure 12. Bridges & Overpasses Inputs for Project Level Analysis (Bridges_Overpasses tab)



The following list explains each input element in Figure 11Figure 18:

A. Select the type of bridge or overpass from the dropdown menu.
B. Select the type of construction (i.e., construction, reconstruction, lane addition).
C. Enter the number of lanes for the bridge or overpass.
D. Enter customized values (if available) for the hauling distance, percent fabricated steel, and percent of hot-rolled sections that are galvanized.

4.6.2 Culverts

4.6.2.1 Overview

ICE characterizes single box culverts, double box culverts, and pipe culverts of various sizes and lengths.

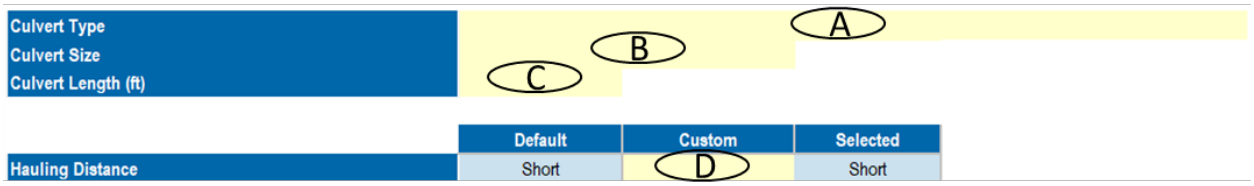
Box culverts are typically constructed with reinforced concrete with thickness and size dependent on application. Box culvert designs are based on a maximum fill height of 10 feet. Pipe culverts are smaller drainage structures with common diameters ranging from one to four feet depending on application. Pipe culvert prototypes include corrugated steel pipe and reinforced concrete headwalls on both ends.

In ICE, culvert size follows a small/medium/large classification. Approximate pipe diameter/cell size is shown to illustrate these sizes. Project mode allows for customization of pipe diameter, length, width, etc. by selecting the "custom" culvert size.

4.6.2.2 Required Inputs to use in ICE

Figure 12 and Figure 13 are screenshots of Planning and Project level inputs for culvert analyses; the inputs are defined below.

Figure 13. Culvert inputs for Project Level Analysis

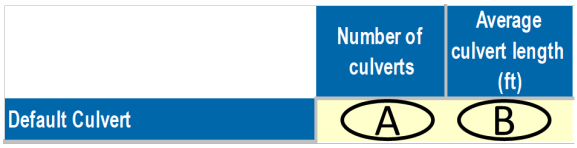


The following list explains each input element in Figure 13 for project level analyses:

A. Select the culvert type (single box, double box, pipe).
B. Select the culvert size (small, medium, large, or custom).
C. Enter the culvert length in feet.
D. Enter a custom value (if available) for the hauling distance.

The Project mode includes several inputs not available with the Planning mode, including hauling distance. It also allows for a "custom" culvert size. If selected, the user can customize the culvert size and materials used. When pipe size is shown in Planning mode, the diameter is intended to guide this selection with minimal user information. If using Planning mode and your project does not match exactly the values shown, user should select the best approximation from these sample values.

Figure 14. Culvert Inputs for Planning Level Analysis



The following list explains each input element in Figure 13 for a planning level analysis:

A. Enter the number of "default"-type culverts.
B. Enter the average length of the culverts.

4.6.3 Custom Pavement

4.6.3.1 Overview

ICE is designed to be "pavement material-neutral" regarding pavement surfaces. That is, mix design and proportions of asphalt and concrete used as pavement surfaces are derived from the representative sample of projects, represent a composite average of asphalt and concrete surfaces, and remain fixed in all ICE calculations. ICE is also prescriptive for most operations and maintenance activities.

The Custom Pavements tab allows users to bypass the default proportions of asphalt and concrete that are typically fixed in ICE calculations, and input energy and emissions factors for specific pavement mixes. These factors can be estimated using outputs from external lifecycle analysis or tools such as FHWA's LCA Pave model, which can be used to analyze the lifecycle impacts of custom mix designs. Any such factors should be comprehensive of the pavement's full lifecycle, inclusive of operations and maintenance, for the same lifetime specified in the Project Inputs tab. This is unchanged in ICE2.2.

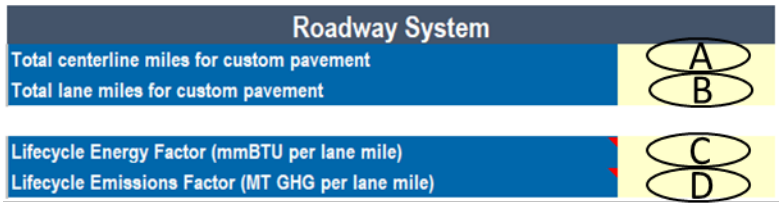
Inputs and outputs for this analysis are limited. Users enter the lane miles of the roadway to receive the custom pavement and the composite lifecycle GHG emission and energy factors from the external data source, per lane mile. ICE uses these values without modification. Most mitigation strategies cannot be applied to custom pavements in ICE. They must be built into the aggregate factors from the external model or data source. However, alternative snow and vegetation management mitigations may be applied here.

To maintain compatibility with ICE, only total energy and emissions are output and display of results is more limited than for other infrastructure types. However, combining custom pavements with other infrastructure is possible. Use this approach to analyze a bridge with a custom asphalt overlay, for example.

4.6.3.2 Required Inputs to Use in ICE

Figure 15 is a screenshot of inputs for a custom pavement analysis; the inputs are defined below. Please note that custom pavement inputs for a Planning and Project level analysis are the same.

Figure 15. Custom Pavement Inputs



The following list explains each input element in Figure 14:

A. Enter the total number of centerline miles where custom pavement will be applied.
B. Enter the total lane miles (2X centerline miles) where custom pavement will be applied.
C. Enter lifecycle energy factor for custom pavement. This should be derived from an external data source or tool, such as FHWA's Pavement LCA Tool.
D. Enter lifecycle GHG emissions factor for custom pavement. This should be derived from an external data source or tool, such as FHWA's Pavement LCA Tool. Note that GHG should be reported in values of CO2e (GWP-weighted) in metric tonnes, consistent with the ICE approach.

4.6.4 Rail, Bus, Bicycle, and Pedestrian Facilities

4.6.4.1 Overview

In ICE1.0, these infrastructure types were collected into a single input group. In ICE2.1, each has been treated as its own separate category.

1. *BRT* analyzes construction or conversion of bus rapid transit facilities. This is characterized in terms of roadway lanes dedicated to bus transit and not shared with general traffic.
2. *Heavy Rail* analyzes projects including four new construction project types for heavy rail lines: underground – hard rock; underground – soft soil; elevated; or at grade. ICE also allows for assessing the impacts of building new underground, elevated, or at grade stations for heavy rail.

3. *Light Rail* projects include five categories of new construction project types for light rail lines: underground – hard rock; underground – soft soil; elevated; at grade; or converted/upgraded existing facilities. ICE also allows for assessing the impacts of building new underground, elevated, or at grade light rail stations.
4. The *Pathways* infrastructure category characterizes the new construction, resurfacing, and restriping of off-street bicycle or pedestrian paths, on-street bicycle lanes, and on-street pedestrian sidewalks.

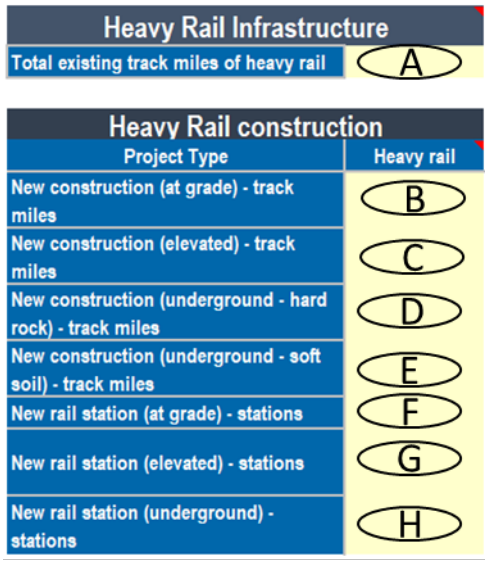
In the *Pathways* category, on-street bicycle lanes apply where new roadway service is constructed for a bicycle lane. Roadway resurfacing of existing surfaces to create a bicycle lane should be included under 'Resurfacing'. Bicycle lanes created by restriping existing roadway space should be entered under 'Restriping'. However, restriping will not affect the energy and GHG estimates of the tool, since energy expended in restriping is negligible compared to energy expended in resurfacing or new construction. Pedestrian facilities include the construction and resurfacing of new off-street paths and the construction of new on-street sidewalk miles. Note that sidewalk construction must be entered in this table, as roadway projects are assumed to include no sidewalks. For example, plans that include sidewalks on all newly constructed roads should multiply centerline miles of roadway by two to calculate construction of new on-street sidewalk miles. Only new construction of sidewalks is included in the tool because property owners are typically responsible for maintenance and repair of sidewalks.

Note that vehicle use phase emissions are currently incompatible with all of these infrastructure types.

4.6.4.2 Required Inputs to use in ICE

Figure 16 is a screenshot of inputs for a heavy rail infrastructure analysis; the inputs are defined below. Please note that heavy rail inputs are the same for a Planning and Project level analysis. However, the *Heavy_Rail* tab in the Project mode allows for customization of many parameters, including materials, fuels, hauling distance, use of steel plates, and use of galvanized materials.

Figure 16. Heavy Rail Inputs

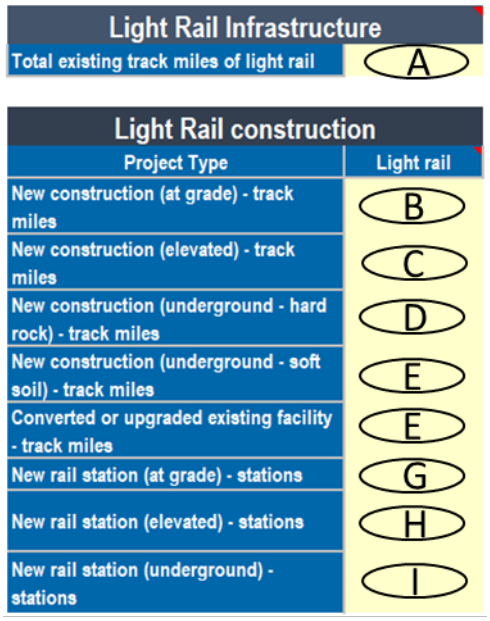


The following list explains each input element in Figure 16:

A. Enter the total existing track miles of the heavy rail system being analyzed.
B. Enter the total number of newly constructed, at grade, heavy rail track miles.
C. Enter the total number of newly constructed, elevated, heavy rail track miles.
D. Enter the total number of newly constructed, underground – hard rock, heavy rail track miles.
E. Enter the total number of newly constructed, underground – soft soil, heavy rail track miles.
F. Enter the total number of, at grade, new heavy rail stations
G. Enter the total number of, elevated, new heavy rail stations
H. Enter the total number of, underground, new heavy rail stations

Figure 17 is a screenshot of inputs for a light rail infrastructure analysis; the inputs are defined below. Please note that light rail inputs are the same for a Planning and Project level analysis. However, the Project mode allows customization of the same parameters listed for Heavy Rail.

Figure 17. Light Rail Inputs

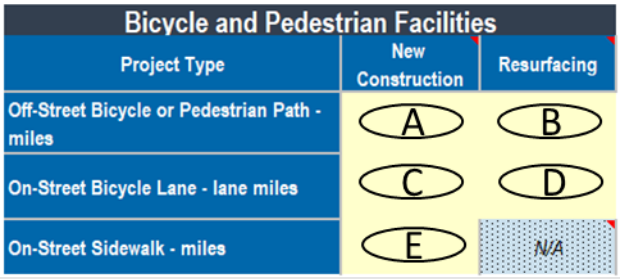


The following list explains each input element in Figure 17:

A. Enter the total existing track miles of the light rail system being analyzed.
B. Enter the total number of newly constructed, at grade, light rail track miles.
C. Enter the total number of newly constructed, elevated, light rail track miles.
D. Enter the total number of newly constructed, underground – hard rock, light rail track miles.
E. Enter the total number of newly constructed, underground – soft soil, light rail track miles.
F. Enter the total number of, at grade, new light rail stations
G. Enter the total number of, elevated, new light rail stations
H. Enter the total number of, underground, new light rail stations

Figure 18 is a screenshot of inputs for a bicycle and pedestrian infrastructure analysis; the inputs are defined below. Please note that bicycle and pedestrian inputs are the same for a Planning and Project level analysis. Like rail facilities, the Project mode allows customization of material amounts, hauling distance, and galvanized materials if known.

Figure 18. Bicycle and Pedestrian Infrastructure Inputs



The following list explains each input element in **Figure 17**:

A. Enter the number of newly constructed off-street bicycle or pedestrian path miles
B. Enter the number of off-street bicycle or pedestrian path miles to be resurfaced
C. Enter the number of newly constructed on-street bicycle lane miles
D. Enter the number of on-street bicycle lane miles to be resurfaced
E. Enter the number of newly constructed miles of sidewalk

4.6.5 Roadways

4.6.5.1 Overview

Roadways may be the most complicated feature included in ICE and also the most common application. Roadways have been updated significantly in ICE2.2 to account for user needs.

ICE accounts for the full roadway lifespan of both new and existing road networks through the *Roadways* tab. This includes construction, rehabilitation, routine maintenance, and preventive maintenance. ICE handles these activities in different ways.

Emissions and energy associated with routine maintenance (sweeping, striping, bridge deck repair, litter pickup, and maintenance of appurtenances) and roadway rehabilitation is automatically estimated per lane mile of both new and existing roadways associated with a project. (Vehicle use-phase emissions are estimated via the Vehicle Operations tab.)

Note that roadway projects do not include sidewalks. If your project or plan includes constructing sidewalks, they should be entered separately in the Rail, Bus, Bicycle, and Pedestrian Facilities section of the tool. Also, ICE2.1 does not calculate energy or GHG emissions savings from pavement smoothness effects related to any resurfacing and reconstruction projects.

ICE also does not intrinsically allow customized pavement configurations. Most analyses should use this Roadway tab and ICE's internal pavement configuration. The Custom Pavement analysis relies on external data rather than ICE's calculations to estimate lifecycle values for different configurations. Please see the Custom Pavement tab for more information. Users should not enter both Roadway and Custom Pavement values for the same project.

Roadway analysis includes the option to analyze roadway rehabilitation projects over the project's lifetime, such as resurfacing and reconstruction activities, on both new and existing roads. This

should not be confused with standalone roadway rehabilitation projects, discussed in Section 4.6.7. Roadway projects analyzed with the Roadways project type can include such activities as maintenance for the roadway's lifetime to create a complete lifecycle assessment of a road network. Standalone rehabilitation projects, such as one-time resurfacing, are analyzed with the Roadway Rehabilitation project type and may not be combined with other project types or represent full roadway lifecycle values.

Pavement preservation strategies, such as crack and chip sealing techniques, may also be associated with both new and existing roadways. These are treated generically as a mitigation measure. See Section 6.3.8 for more information.

In *Project* mode for roadways, ICE2.2 asks for some additional inputs. First, the user has the option to input custom lane widths for each roadway type. The user is also allowed to specify the material hauling distance. Most significantly, the user may specify a custom maintenance schedule for roadway rehabilitation activities. This schedule is used to define when reconstruction and resurfacing activities occur, which is the basic parameter affected by the generic pavement preventive maintenance plan set in the Mitigation Measures tab. When set there, such a plan extends road life, and thus extends the schedule of these activities, reducing their frequency within the analysis lifetime, and thus reducing the emissions associated with these activities over that lifetime. Finally, the user may overwrite the schedule for reconstruction and resurfacing events on the project.

The definition of the seven roadway types modeled in ICE2.1 are as follows:

1. *Rural Interstate*: Interstates are limited-access, high-speed, divided roadways that accommodate long-distance travel.
2. *Rural Principal Arterials*: Principal arterials move high volumes of traffic at high speeds over long distances between major destinations.
3. *Rural Minor Arterials*: Minor arterials move high volumes of traffic at high speeds over shorter distances and connect destinations to each other or connect collectors to larger roads.
4. *Rural Collector*: Collectors are low- to medium-capacity roads that connect local roads to higher-volume arterial roads
5. *Urban Interstates/ Expressways*: Interstates and expressways are limited-access, high-speed, divided roadways that accommodate long-distance travel.
6. *Urban Principal Arterials*: Principal arterials move high volumes of traffic at high speeds over long distances between major destinations.
7. *Urban Minor Arterials/Collectors*: Minor arterials move high volumes of traffic at high speeds over shorter distances and connect destinations to each other or connect collectors to larger roads. Collectors are low- to medium-capacity roads that connect local roads to higher-volume arterial roads.

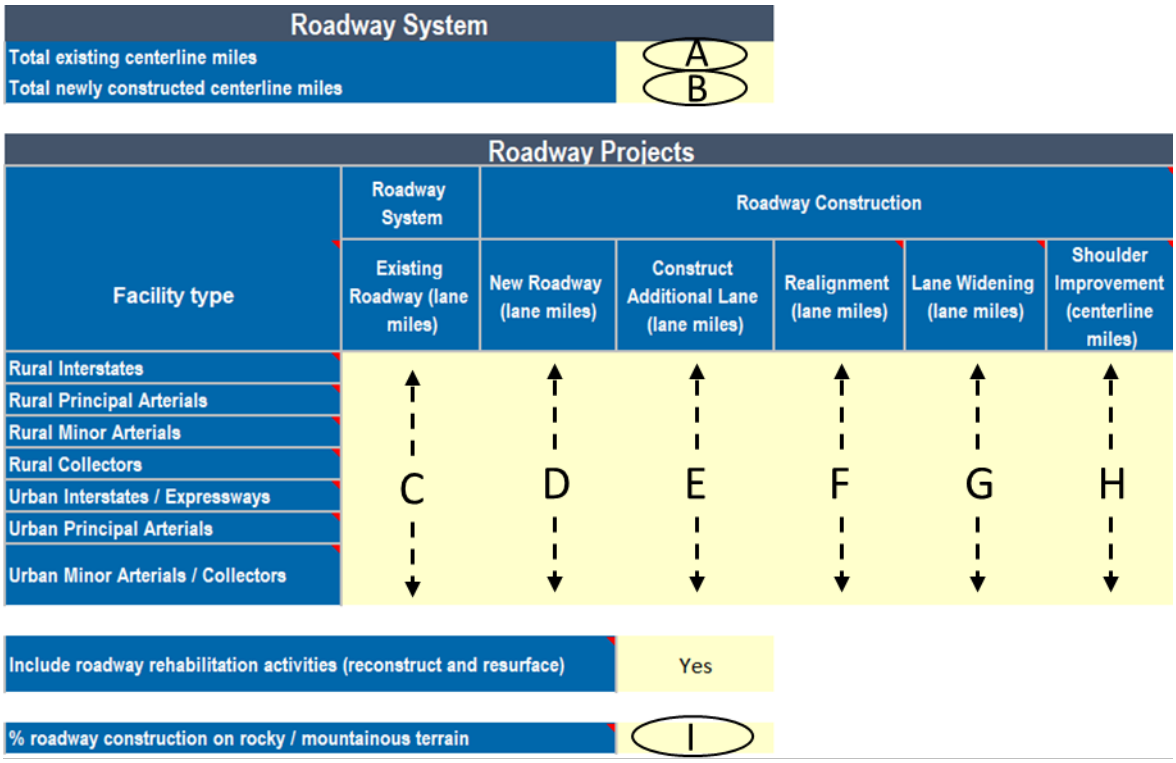
4.6.5.2 Required Inputs to Use in ICE

Figure 19 is a screenshot of inputs for roadway analyses. The inputs are defined below. Please note that Roadway inputs for a Planning and Project level analysis on the *Project Inputs* tab are the same. However, additional specifications are available in the *Roadways* tab as discussed above.

One of these specifications is lane width, which may be set at the Project level of analysis. Note Material quantity estimates are based on a nominal lane width. If the lane width used in the

calculations differs from the nominal width, the "ICE-equivalent lane miles" value shown on the *Roadways* tab will differ from the "lane miles" value entered in the *Project Inputs* tab. Note that the default and nominal values are not necessarily equal.

Figure 19. Roadway System Inputs (Project and Planning Mode)



The following list explains each input element in Figure 18:

A. Enter the total centerline miles for the existing roadway network.
B. Enter the total newly constructed centerline miles for the proposed project analysis.
C. Enter the total lane miles, of each roadway type, for the existing roadway network
   - (Note: A should sum to the same amount of lane miles as C).
D. Enter the total lane miles of new roadway for the project.
E. Enter the number of lane miles when adding additional lanes to an existing roadway.
F. Enter the total lane miles when analyzing roadway realignment.
   - These are projects in which there is a change to the horizontal and/or vertical alignment of a portion of an existing roadway.
G. Enter the total lane miles when analyzing lane widening.
   - These are projects in which there is a reconstruction with lanes wider than the replaced section of roadway.
H. Enter the total centerline miles of a shoulder improvement project.

- These are projects in which there is a widening of shoulders to design standards or the complete reconstruction of shoulders to provide additional strength.

I. Estimate the percentage of the project area that is in hilly or mountainous terrain. The energy and emissions impacts are higher for projects in these terrains because of higher energy intensity of construction activities such as cut and fill in rocky soils and longer hauls of materials and equipment for projects located in mountainous areas.

The last roadway input needed for the *Project Inputs* tab is incorporating roadway rehabilitation activities. This appears above input "I" (Figure 19). Roadway rehabilitation can be added or withdrawn from the analysis by selecting yes or no from the dropdown menu, respectively. The default schedule for Roadway Rehabilitation is to have a resurfacing event at years 15 and 45 and a reconstruction even at years 30 and 60. To change these values, perform the analysis in the Project Mode. The tool now demonstrates this schedule graphically on the Roadways tab in the Project Mode.

Note that, in the mitigation breakdown in the last Results-Charts section of the *Roadways* tab the mitigations for "Cold In-place recycling" and "Full depth reclamation" do not appear as line items in the table or charts. However, if selected, they are included in the calculations through impacts on roadway rehabilitation activities.

4.6.6 Roadway Lighting

4.6.6.1 Overview

Roadway lighting projects can be a significant contributor to the annual energy use and GHG emissions of many transportation agencies.

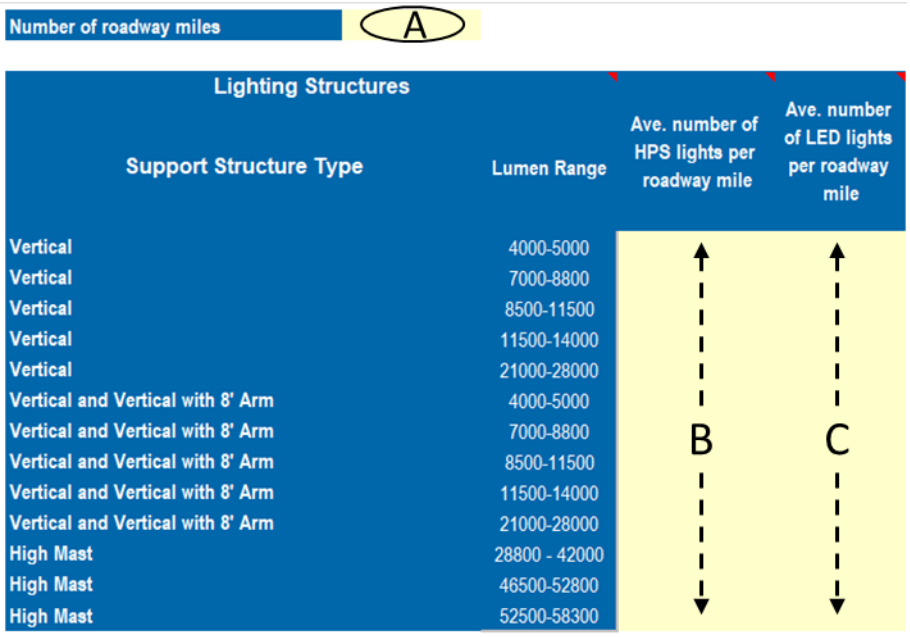
ICE estimates the energy and GHG emissions associated with lighting projects. ICE evaluates the impacts of two of the most common lighting technologies: High Pressure Sodium (HPS) & Light Emitting Diode (LED). It includes lifecycle impacts associated with common support structures: High Mast, Vertical, and Vertical with arm.

To estimate the energy and GHG emissions associated with lighting use projects, ICE pairs annual energy consumption with state-specific energy emission factors to determine GHG emissions.

4.6.6.2 Required Inputs to Use in ICE

Figure 20 is a screenshot of inputs for a roadway lighting analysis; the inputs are defined below. Please note that roadway lighting inputs for a Planning and Project level analysis are the same. However, in the *Lighting* tab in the Project mode, the user can input customize hauling distance and use of galvanized materials.

Figure 20. Roadway Lighting Inputs



The following list explains each input element in Figure 20:

A. Enter the number of roadway miles where roadway lighting is being applied.
B. Enter the average number of high-pressure sodium (HPS) roadway lights (by structure type) being applied to the roadway system (specified in input A).
C. Enter the average number of light-emitting diode (LED) roadway lights (by structure type) being applied to the roadway system (specified in input A).

4.6.7 Roadway Rehabilitation

4.6.7.1 Overview

The existing roadway rehabilitation, stand-alone project type was a new infrastructure feature in ICE2.1, added by request. This infrastructure category is unchanged in ICE2.2. See Section 6.2.2 for description of the methodology.

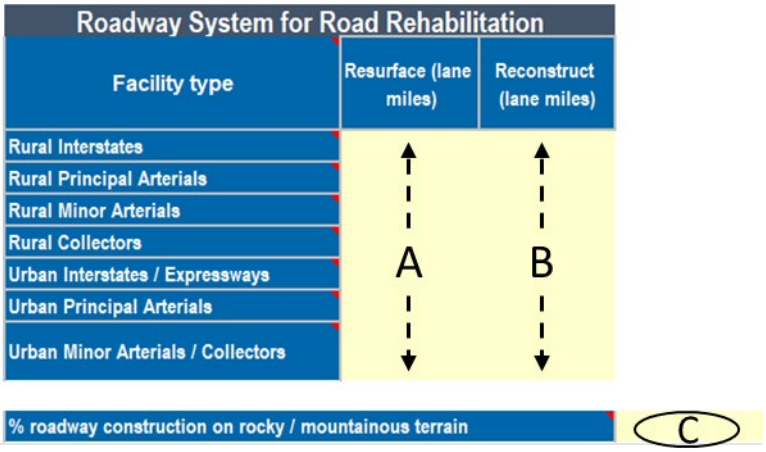
Roadway Rehabilitation analyses are designed solely for short-term projects, such as one-time resurfacing events. ICE accounts for the full roadway lifespan, including construction, rehabilitation, routine maintenance, and preventive maintenance for new and existing roadways in the Roadways infrastructure type (Section 4.6.5). That includes roadway rehabilitation projects applied on a schedule throughout the lifetime. The Roadway Rehabilitation infrastructure type is designed for isolated, standalone projects involving resurfacing and reconstructing pavements on existing facilities.

The lifecycle assessment for Roadway Rehabilitation analyses is more limited than for other infrastructure types. Roadway Rehabilitation applies only to standalone roadway maintenance for existing roadways. It does not cover the full lifetime of other projects (although all factors for fuels and materials used do include cradle to gate lifecycle) and thus may not be combined with other types of analyses in ICE. Combining with other analyses, such as on the Roadways tab could also lead to double counting maintenance activities.

4.6.7.2 Required Inputs to Use in ICE

Figure 21 is a screenshot of inputs for roadway analyses; the inputs are defined below. All inputs for roadway rehabilitation projects are the same in both the Planning and Project modes. However, additional inputs are available in the Roadway_Rehab tab in the Project mode for custom lane width, galvanized material, and hauling distance.

Figure 21. Roadway Rehabilitation Inputs



The following list explains each input element in Figure 21:

A. Enter the total lane miles of roadway resurfacing for each roadway type.
B. Enter the total lane miles of roadway reconstruction for each roadway type.
C. Enter an estimate (percentage) of the project area that is in hilly or mountainous terrain. The energy and emissions impacts are higher for projects in these terrains because of higher energy intensity of construction activities such as cut and fill in rocky soils and longer hauls of materials and equipment for projects located in mountainous areas.

4.6.7.3 Special Note about Printing and Viewing Roadway Rehabilitation Results

Note that the results of a Roadway Rehabilitation analysis may only be viewed in ICE's *Roadway Rehabilitation* tab. As discussed in Section 4.6.7.1, it is inappropriate to combine short-term results from Roadway Rehabilitation project types with full lifecycle values from other ICE project types. For this reason, although the *Summary Results* and *Print Results* tabs will show if Roadway Rehabilitation and another infrastructure type is (incorrectly) selected in the same simulation, no data from the Roadway Rehabilitation analysis is carried into the *Summary Results* and *Print Results* tabs, and no energy use or emission values associated with a Roadway Rehabilitation project are displayed in these two tabs. Also, to avoid confusion in any post-model comparisons and since no Roadway Rehabilitation project data is carried into the *Summary Results* and *Print Results* tabs, these tabs are not available if Roadway Rehabilitation is the only project type selected.

4.6.8 Roadway Signage

4.6.8.1 Overview

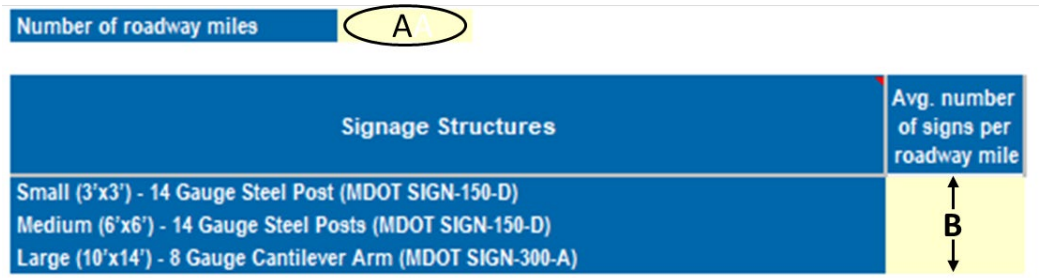
Signage infrastructure is a combination of aluminum sheet metal, and directly embedded or concrete encased steel. The signage category was divided into small, medium, and large structures representing the three most common types of roadway signs.

ICE divides the signage category is divided into small, medium, and large structures representing the three most common types of roadway signs. Small and medium sized signs are typically regulatory and warning signs supported by a single post. Large signs include overhead guidance highway signs, typically supported by two posts or hung overhead on large steel cantilever arms.

4.6.8.2 Required Inputs to Use in ICE

Figure 21 is a screenshot of inputs for a roadway signage analysis; the inputs are defined below. Please note that roadway signage inputs for a Planning and Project level analysis are the same. However, in the *Signage* tab in the Project mode, the user can input customize hauling distance and use of galvanized materials.

Figure 22. Roadway Signage Inputs



The following list explains each input element in Figure 22:

A. Enter the number of roadway miles where roadway signage is being applied.
B. Enter the average number of roadway signs (by size) being applied to the roadway system (specified in input A).

4.6.9 Interchanges

4.6.9.1 Overview

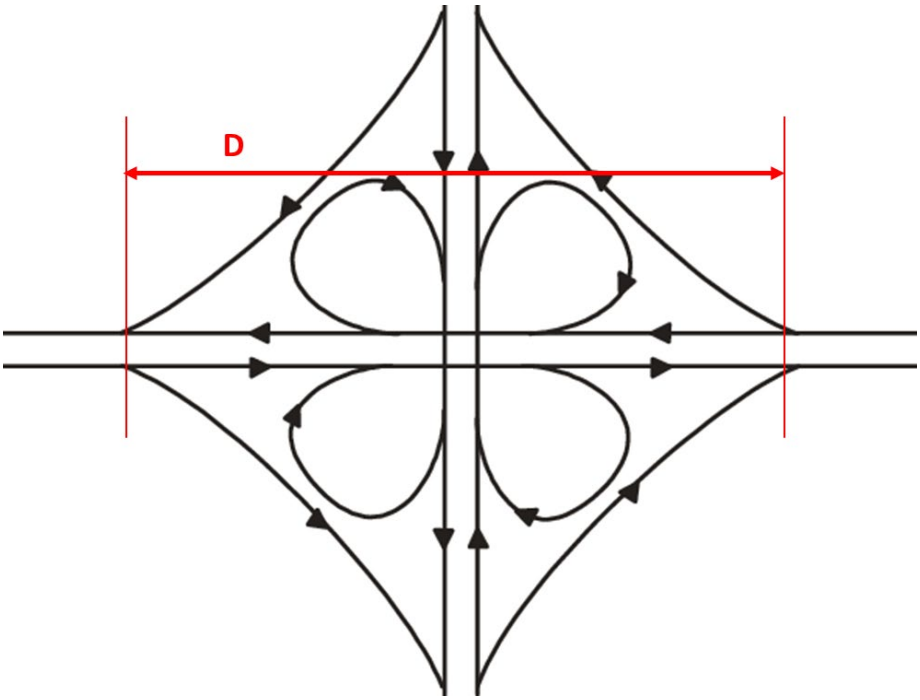
In response to user feedback, ICE2.2 has been updated with the addition of a new Interchange infrastructure category. This enhancement aims to provide a more accurate and user-friendly experience for freeway/highway interchange projects. The Interchange category in ICE2.2 incorporates features from Roadways and Bridges/Overpasses categories. When users select Interchanges, a new tab opens with inputs linked to the Project Inputs tab, and hidden tabs for interchange calculations based on underlying infrastructure types are generated. Inline user instructions are provided for guidance.

The Interchange category is designed for newly constructed interchanges only. For modifications to existing interchanges, users should evaluate them according to individual components, such as bridges or roadways. This category is designed to be high-level, requiring minimal inputs. Interchanges in ICE are limited to a symmetric, 4-sided, cloverleaf geometry with a 2-span bridge overpass. Users only need to input the distance ("D" from the schematic below) from the first exit to the last entrance in one travel direction and the number of lanes on the bridge to represent all elements. ICE also asks for the number of (identical) interchanges in the plan. ICE determines all other roadways Earth moving is excluded from calculations, consistent with other ICE prototypes. Th interchange prototype assumes four lanes for the underpass and one lane for the eight connectors.

In Project Mode only, when there is no existing roadway, users can also add the number of lanes for the new underpass roadway.

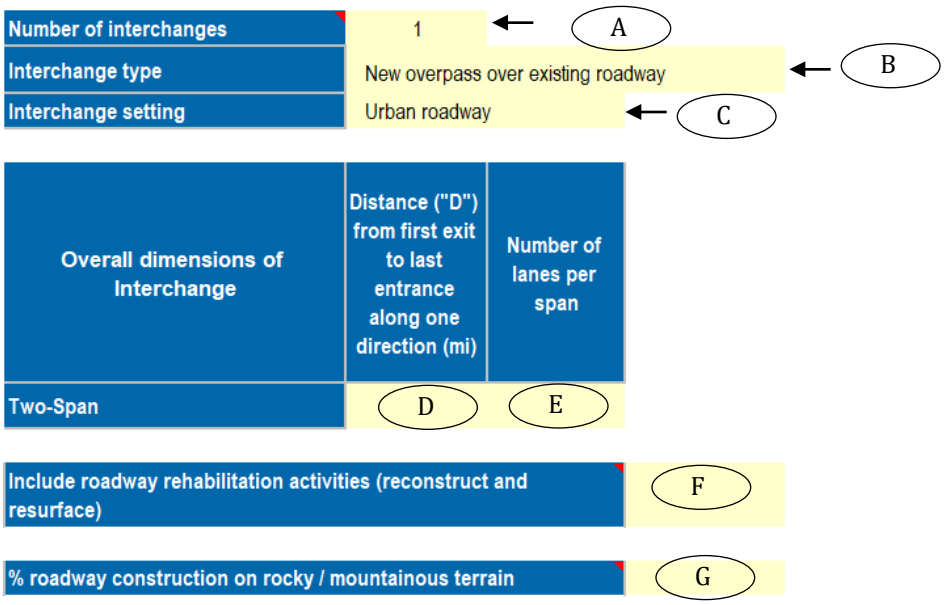
Emissions and energy for routine maintenance are automatically applied consistent with the Roadway infrastructure type. As for all roadways, ICE2.2 does not account for energy or GHG emission savings from pavement smoothness or allow custom pavement configurations. All other emissions and energy calculations are derived from the underlying infrastructure types, including operations and maintenance activities.

Figure 23. ICE2.2 Interchange Geometry Schematic



4.6.9.2 Required Inputs to Use in ICE

Figure 24. Interchange Inputs



The following list explains each input element in **Figure 23**:

A. Enter the number of interchanges.
B. Use the dropdown to select the interchange type, either 'New overpass over existing roadway' or 'New roadways and overpasses'.
C. Use dropdown to select the interchange setting, either urban or rural roadway.
D. Enter the distance in miles from the first exit to the last entrance.
E. Enter the number of lanes per bridge span.
F. Select 'yes' or 'no' from the dropdown if roadway rehabilitation activities should be including in the analysis.
G. Enter the estimated percent of the project area that is in hilly or mountainous terrain.

Note that the changes for Roadway Rehabilitation in the Roadways section (4.6.5) also apply here.

4.6.10 Parking

4.6.10.1 Overview

The approach to calculating energy and emissions associated with parking facilities has been completely updated since ICE1.0. In ICE2.1, parking is now a separate infrastructure type where it was combined with other infrastructure types in the previous version. This was done to allow users to isolate these facilities and determine distinct results.

ICE2.1 estimates energy and emissions associated with two types of parking facilities: surface lots and parking structures. Both are characterized in terms of the number of spaces. Parking structures are treated generically and may also be characterized in terms of their total area.

4.6.10.2 Required Inputs to Use in ICE

Figure 24 is a screenshot of inputs for a parking structure analysis; the inputs are defined below. Please note that parking inputs for a Planning and Project level analysis are the same in the *Project*

Inputs tab. However, in the *Parking* tab, additional inputs are available in the Project mode. These allow customization of hauling distance, galvanized materials, and the share of steel that is structural versus fencing.

Figure 25. Parking Structure Inputs

The following list explains each input element in Figure 24:

A. Enter the number of surface level parking spaces.
B. Enter the number of parking structure parking spaces.

4.6.11 Vehicle Operations

4.6.11.1 Overview

ICE estimates the vehicle operations impact of infrastructure projects based on two distinct effects:

1. Vehicle Operating Emissions: The cumulative operating energy and GHG emissions over the project's lifetime from vehicles operating on the roadway.
2. Construction Delay Emissions: The additional energy and GHG emissions due to vehicle delay during construction.

Introduced in ICE2.1, the Vehicle Operations ("Vehicle_Ops") infrastructure category estimates emissions associated with the road surface of the selected infrastructure type, using a national average vehicle fleet for the specified lifetime (operating emissions) or the additional emissions associated with construction delay. These estimates provided a rough sense of the scale of emissions relative to the construction processes themselves and were not meant to replace estimates derived from traffic modeling software. Similarly, construction delay estimates the additional emissions from the VMT impacted by the construction period.

This approach has been refined in ICE2.2 to make this distinction more clear. Specifically, ICE2.2 provides two approaches for computing these emissions, with the preferred approach of directly inputting emissions computed from more refined software ("off-model" calculation).

Option 1: Emissions Computed with an External Model

The preferred option for users is to input custom emissions calculated outside of ICE. This approach, new in ICE2.2, accepts that significant construction projects impacting high volume roads or multiple roads in an area should be evaluated using traffic and emissions modeling software. Users can calculate emissions off-model, then incorporate these results into ICE. The tool will then combine them with other infrastructure types for reporting. It may also convert between different lifecycle boundaries ("downstream only" or "full lifecycle"). Note that for construction delay, these inputs should reflect only the additional emissions due to construction.

Option 2: ICE-Estimated Emissions based on Traffic and Speed

This option is similar to that from ICE2.1. Users input the traffic, speed, and time metrics needed to compute emissions with the MOVES and GREET factors inherent in ICE2.2. These metrics differ

between the two vehicle operation categories (standard vehicle operations and construction delay) as follows.

1. Vehicle Operating Emissions: Users input two years – the project opening year and the project design or horizon year. For each of these years, users enter the average daily traffic (ADVMT) and average speed on the project. ICE2.2 now allows separate entries for light and heavy vehicles if this is known. Otherwise, ICE assumes a default fleet mix. In either case, ICE computes the cumulative operating emissions over the project's lifetime, interpolating between these starting (opening) and ending (horizon) year.[6]
2. Construction Delay Emissions: Users input the construction start and project opening years. Users then input the amount of daily traffic (ADVMT) that is impacted by construction. Importantly, this input should only reflect the traffic that is experiencing delay. For example, if construction happens at night, only the amount of daily traffic that occurs during construction hours should be input. Users similarly enter the delayed (congested) speed and hypothetical speed that this same amount of traffic would have experienced under conditions without the construction delay. ICE computes the additional energy and GHG emissions due to vehicle delay during construction.

4.6.11.2 Required Inputs to use in ICE

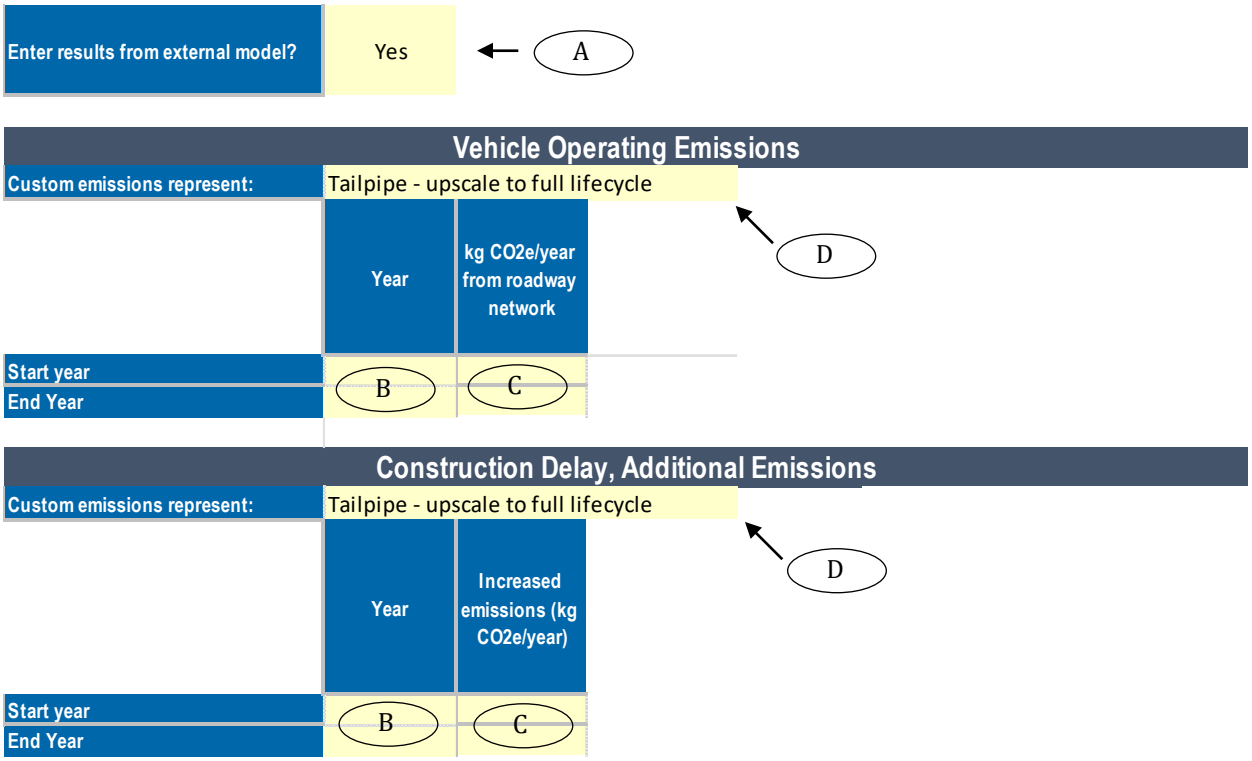
This section outlines these options and provides guidance on their use.

Note that mitigations are not applicable for vehicle operating emissions. The calculations can be customized to reflect a national average, or separate light- and heavy-duty vehicle fleet. They should not be used to estimate bus emissions on BRT or train emissions from Light- or Heavy-Rail.

Figure 24 and Figure 25 are screenshots of inputs for a vehicle operations analysis depending on whether a user uses emission factors from an external model (figure 24) or using ICE default emission factors (figure 25); the inputs are defined below. Please note that vehicle operations inputs are the same for a Planning and Project level analysis.

[6] Note that this is a bilinear interpolation between the starting, ending, and midpoint years. See Section 6.2.9.

Figure 26. Vehicle Operations Inputs (using external model emission factor)



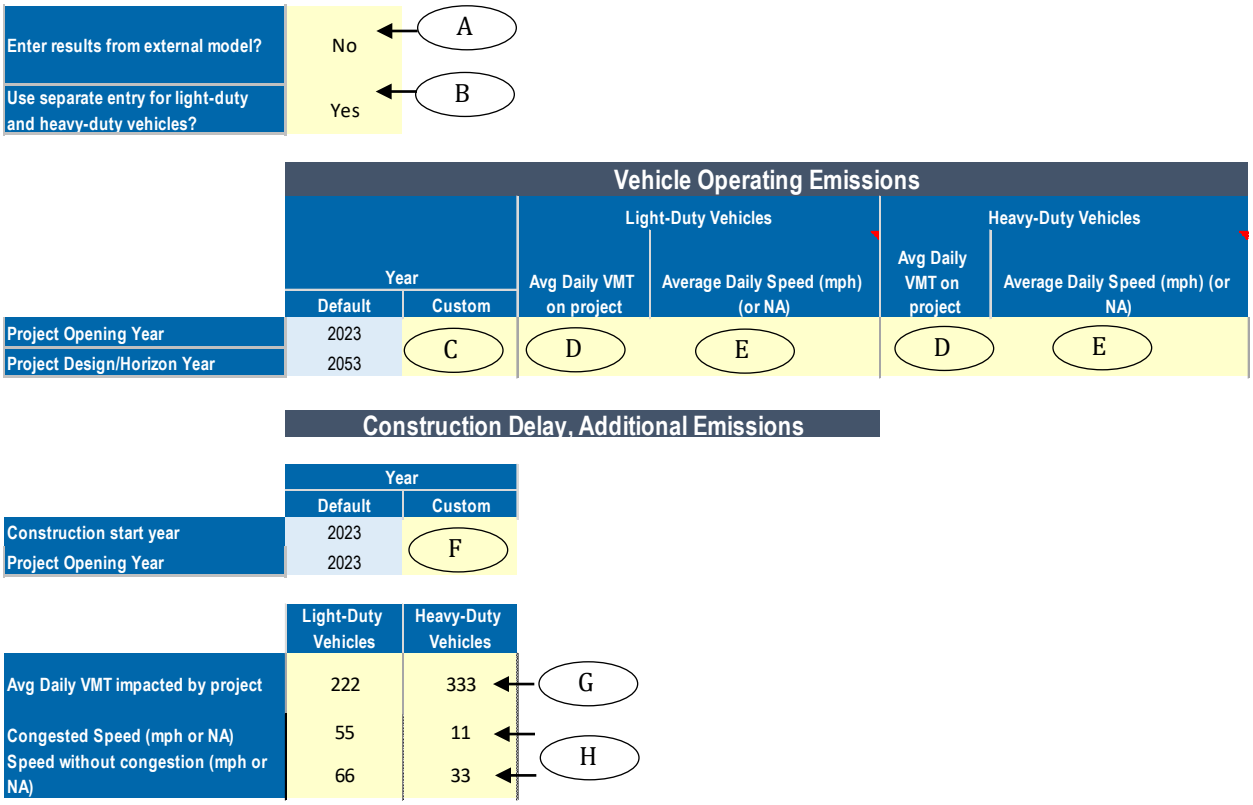
The following list explains each input element in **Figure 25**:

A. Use the dropdown to select "yes" when using emission factors from external model.
B. Enter in a custom start and end year for vehicle emissions and construction delay.
C. Enter the off-model emission estimates for the start and end year for vehicle operations and construction delay.
D. This drop down allows the user to select the boundaries of the emissions estimates. Since most on-road emissions models estimate GHG emissions on a tailpipe or "tank-to-wheels" basis, ICE by default upscales these inputs to compute on-road emissions on a full lifecycle basis that is consistent with the lifecycle scope of other emissions estimates in the model. However, users can use the drop-down menu selections to preserve inputs as tailpipe-only estimates for reporting, or specify that input emissions already represent full-lifecycle values.

A note about Item D: Most calculations in ICE represent full lifecycle values. Most typical emission calcualtions, such as those based on MOVES modeling, represent tailpipe only values. There may be reasons to select either. For this reason, the item D dropdown box allows the user to specify what is being reported as tailpipe only (which remains tailpipe only), full lifecycle (which remains full lifecycle), or tailpipe which will be converted to full lifecycle. If the user selects the first option, no conversion is made and ICE warns the user that the values are inconsistent with other ICE outputs.

Note that either/both Vehicle Operating Emissions and/or Construction Delay Additional Emissions may be entered. Both sets of inputs are optional. If only one is entered, use phase emissions will reflect only those of the entered conditions.

Figure 27. Vehicle Operations Inputs (using default emission factors)



The following list explains each input element in **Figure 26**:

A. Use the dropdown to select "no" when using ICE's own calculation of emissions.
B. Use dropdown to select whether to provide separate inputs for light- and heavy-duty vehicles, or to use ICE's internal, default fleet mix.
C. Enter the project opening year and project design/horizon year in the Vehicle Operating Emissions table.
D. In the Vehicle Operating Emissions table, enter average daily VMT for the project opening year and project design/horizon year.
E. Enter in the Vehicle Operating Emissions table the average daily speed for the project opening and design/horizon years. If unknown enter, "NA" (in capital letters).
F. Enter the construction start and project opening years in the Construction Delay, Additional Emissions table.
G. Input estimates of the amount of VMT impacted by the project. This should only reflect the traffic that is experiencing delay, as discussed above. If modeling light- and heavy-vehicles seperately, enter appropriate values for both.
H. Enter the speeds for the delayed traffic and what those speeds would have been without construction during the period affected by construction.

Note that if the user does not enter a construction-delayed speed it is assumed to be half of the pre-construction speed. If the user does not know the pre-construction speed, they should enter the speed limit.

4.7 Unique Issues in Using ICE

4.7.1 Projects that Require Multiple Types of Analyses

Some analyses may require multiple features to be considered for the complete project. Consider the example of a plan that called for the construction of, and paving over, a culvert structure to make a bridge. In this case the User would follow the general guidance described in the ICE1.0 User Guide for bridges. As noted there, ICE's bridge section focuses on construction of bridge structures rather than the construction and maintenance of the roadway surfaces of the bridges. The user should also include the roadway surface using the Roadway infrastructure inputs to complete the analysis. In this case, the structure would be molded with the Culvert project type and the roadway surface with the Roadway project type. These complimentary project types should give a reasonable approximation for the entire culvert-roadway structure.

Other project types are likely to follow similarly. As discussed in Section 2.1, the user should attempt to enter information on all project activities to obtain the most accurate analysis possible and make reasonable assumptions based on their knowledge of the project in order to fill any data gaps.

4.7.2 Matching Very Specific Projects to ICE Prototypes

Cases have been reported where users have attempted to match very specific roadway rehabilitation projects, such as milling, overlaying, slope stabilization, or bituminous shoulder replacement, to the general categories included in ICE, such as resurfacing and reconstructing pavement.

ICE is built on average material quantity estimates across a representative sample of projects nationwide, making it a "pavement neutral" tool that does not differentiate between asphalt and concrete pavements or address specific pavement mix designs. It is also built on national average estimates of lifecycle GHG emissions for each construction material, average estimates of construction vehicle fuel consumption for roads and bridges, and average estimates of lifecycle GHG emissions for transportation fuels. ICE is intended to provide "ballpark" estimates to support planning, NEPA, and other pre-engineering analysis. It is not likely to provide accurate estimates to inform pavement design or project engineering decisions.

If attempting to use ICE to evaluate specific project types, the user should first see if the Project level of analysis for the infrastructure type provides any customization to better represent the project. Then the user should attempt to match the project to the best available information in ICE. ICE will not accurately represent energy or emissions from projects more finely resolved than the prototypes on which ICE calculations are made. However, "ballpark" estimates can be obtained with ICE by following the same guidance from Section 2.1 discussed above.

4.7.3 Roadway Rehabilitation Projects

The *Roadway Rehabilitation* tab for existing roadway projects was new in ICE2.1. Its current use is discussed in detail in Section 2.6.7. The approach for this infrastructure type is similar to that for the more general Roadways category but is only intended to address new rehabilitation projects for existing roadways. The existing roadway rehabilitation project type cannot be combined with other project types, including other roadway analyses. Doing so would lead to misleading results, both by potentially double counting impacts and by mismatching project lifecycle analysis scales. Existing roadway rehabilitation is designed only for short term projects. Unlike other infrastructure types, it

does not calculate a full lifecycle analysis. It does include cradle-to-gate material and fuel factors in all calculations, but does not include general operations and maintenance, use phase, and other metrics integrated into other project types.

For this reason, existing roadway rehabilitation analysis types in the tool do not activate ICE's Print Results and Summary Results tabs. As standalone analysis, the results must be viewed in the Roadway Rehabilitation tab.

4.7.4 Analysis of Pavement Configurations beyond those Encapsulated in ICE

Section 2.6.3 provided an overview of the Custom Pavement tab. This infrastructure type is designed to allow ICE2 to integrate with the more detailed external LCA analysis of road and pavement infrastructure. This is designed to allow users to override ICE's fixed pavement configuration with a custom mix design output by FHWA's LCA Pave or other lifecycle analysis tools. To do so, a user would input aggregate emission and energy estimates from the external tool on a lane-mile basis representing the custom configuration as modeled in the external LCA tool (such as FHWA's LCA Pave), into ICE. This is accomplished by adding the pseudo-infrastructure type, "Custom Pavement". In this case, inputs are limited. In order to be consistent with other aspects of ICE, and the estimates from the external tool should address the same lifecycle processes as ICE as summarized in Figure ES-1,.

Because of ICE's fixed pavement configuration, ICE cannot disaggregate custom pavements, cannot apply mitigations (other than alternate snow vegetation maintenance), and cannot show resulting emissions broken down by material. Only total energy and emissions will be output. Because the three output charts that provide such a breakdown in the *Summary Results* tab depend on these breakdowns, they are not available if the *Custom Roadways* infrastructure type is activated. However, the "Results by Infrastructure Type" chart does provide results that include this infrastructure type.

This will be useful for a plan that includes custom roadways along with other infrastructure, such as analysis of a bridge with a custom asphalt overlay that includes vehicle traffic.

4.7.5 Custom Electricity Emission Factors

ICE electricity emission factors are prescribed at the state level. Since ICE2.1, the tool allows the use of a custom electricity standard phase-ins, such as from implementation of a renewable portfolio standard (RPS). This is selectable in the *Project Inputs* tab. Doing so activates an additional *Annual Electricity Emissions* tab. In that tab, the user will input a percent reduction value from the baseline factor at the top of the page for each year in which a reduction occurs. These factors are included in the integrated results over the specified project lifetime.

4.7.6 Comparative Analysis

ICE is not currently structured in a way that allows users to create two or more scenarios and then compare outcomes within a single workbook. (such as a build versus no-build analysis in a NEPA context, or the comparison of scenarios associated with a long range transportation plan). This is an important use of ICE. To facilitate such a comparison, ICE2.1 includes user-specified text boxes that may be employed to describe important details about the simulation. These text boxes are provided in the Project Inputs tab. The user enters a title and content for any or all three of the provided boxes. These text box titles and the corresponding text are then repeated to the analysis' outputs in

the Summary Results and Print Results tab. This text is then echoed back to. Examples of these inputs and outputs are provided below.

	Title: Analyst	Title: Date of Analysis	Title: Description
Enter comments and comment titles. These will be displayed on the Summary Results worksheet.	Jane Planner	November 1, 2019	Sample build analysis for construction of new arterials in Anytown, CO.

Analyst	Date of Analysis	Description
Jane Planner	November 1, 2019	Sample build analysis for construction of new arterials in Anytown, CO.

To use this information in a comparative analysis, the user would populate the text boxes and their titles such as in the above examples. The user will then execute their simulation for each of scenarios to be analyzed individually. After completion of the analysis for each individual scenario, the user would print, save, or otherwise archive results for the simulation available in the Print Results or Summary Results tab. The user would then compare the archived results from each simulation after completing all ICE modeling. This post-modeling application can be used to compare aggregate results from the different simulations.

4.7.7 Lifecycle Versus Tailpipe Only Emissions for Use Phase

As discussed in Section 2.6.11, the vehicle operations inputs have been redesigned in ICE2.2 to allow direct input of emissions computed in another model, which bypasses ICE's own internal estimates. As part of this input, the user selects which of three categories the emissions their inputs represent:

- tailpipe which will remain tailpipe,
- tailpipe which ICE will upscale to estimate full lifecycle values, or
- full lifecycle.

This selection is designed to accommodate various user needs. Many analyses only report tailpipe (downstream) emissions, so ICE2.2 allows the first option. Notably, outputs with this option are inconsistent with other, full lifecycle values computed by ICE, and the tool notifies the user of this. For the second option, ICE uses a simple factor based on GREET values and MOVES' fleet projections (Section 4.3.2) to add on the upstream energy and emissions to those the user inputs.

4.7.8 Native Units

ICE calculates lifecycle energy use and greenhouse gas (GHG) emissions. To do this, ICE requests the analysis timeframe (in years) from the user. It produces lifecycle (to end-of-life) estimates of energy use and/or GHG emissions. Both values can be reported on an annualized or total lifespan basis. ICE includes the building, modification, maintenance, and/or use of a transportation project or group of projects in its analysis.

The standard reporting unit for energy is "mmBTU", or millions of British Thermal Units. The standard reporting unit for GHG emissions is "MT CO2e", or metric tonnes of CO2-equivalent gases. 1 metric tonne equals 1,000 kg. CO2 equivalency is defined on a 100-year global-warming potential basis. This is defined in Table 4 of Appendix A. Material factors are defined as cradle-to-gate. Operations

and maintenance activities and operational (use-phase) emissions are determined by integrating over the specified project lifetime.[7]

The final units presented in outputs are user-selectable in the output tabs. This allows reporting in units different from the native units and avoids cases with insufficient resolution in the reported values. Reported values may be reported on an annualized basis, or cumulative values integrated over the project's specified lifespan.

[7] Note that the standalone Roadway Rehabilitation project type is different. As described in Section 2.6.7, these are limited to short duration projects and not combinable with other project types that investigate long project lifetimes.

5 Example Use Cases

To illustrate how the tool works and the results one can expect, we present results for two different types of projects in this section —one at the planning scale and one at the project scale.

5.1 Planning Level Case Study: Culvert with Custom Pavement

For this case study, we model an example of when a user would need to utilize the planning mode functionality of ICE2.1. Specifically, we modeled a hypothetical scenario that includes many culverts that are then scheduled to be covered with a custom pavement configuration. This scenario is modeled in Louisiana with a project lifetime of 20-years and without any custom RPS electricity factors applied.

In order to model a custom pavement configuration in ICE – i.e., one that does not follow ICE's fixed pavement material configuration – we approximated emissions and energy factors that would be produced by a tool such as FHWAs pavement LCA Tool. Such custom factors can be used in ICE currently via the *Custom Pavement* infrastructure type. This example uses ballpark estimates to calculate results for this case study (not determined with LCA Pave). Inputs for the two infrastructure types are found in **Figure 24** and **Figure 25** below:

Figure 28. Planning level case study: Culvert Inputs

	Number of culverts	Average culvert length (ft)
Default Culvert	30	10

Figure 29. Planning level case study: Custom Pavement Inputs

Roadway System	
Total centerline miles for custom pavement	2
Total lane miles for custom pavement	4
Lifecycle Energy Factor (mmBTU per lane mile)	5000
Lifecycle Emissions Factor (MT GHG per lane mile)	500

This example is not meant to be an accurate depiction of a real situation, particularly due to lack of access to detailed custom pavement lifecycle data, but to show the flexibility users have in order to utilize custom pavement energy and emission factors. It is also meant to illustrate the limited display of output information available from custom pavements, given ICE's inability to break these down by material or apply external mitigation measures. Finally, it must be noted again that the custom pavement factors input to ICE must include all maintenance and other lifecycle factors to be included with ICE and properly match analysis boundaries. See Section 2.6.3 for more information.

For this case study, we applied five mitigation measures: switch from diesel to Soy bean-based RD 100, switch from diesel to forest residue-based RD100, alternative vegetation management, alternative snow control, and the use of industrial biproducts as substitutes for Portland cement (Figure 26). Of these, only the snow and vegetation management measures apply to the roadway surface, due to use of the Custom Pavements infrastructure (for which all applicable mitigations should be included in the energy and emission factors output from the external data source or

model. See Section 2.6.3.1 for more information). All other mitigation measures apply to the culverts. Note that there is no effect from including the snow management mitigation in Louisiana.

Figure 30. Mitigation Measures Applied to Planning Level Case Study

						BAU Reductions		Planned Reductions	
Strategy	BAU deployment	Planned deployment	Deployment increase	Energy reduction factor	GHG reduction factor	Energy reductions	GHG reductions	Energy reductions	GHG reductions
Alternative fuels and vehicle hybridization									
Switch from diesel to Soybean-based Biodiesel			0.0%	-26%	14%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Soybean-based RDII 100	0%	50%	50.0%	-28%	65%	0.0%	0.0%	-14.1%	32.6%
Switch from diesel to Forest Residue-based RDII 100	0%	50%	50.0%	-67%	73%	0.0%	0.0%	-33.6%	36.4%
Switch from diesel to E-Diesel, Corn			0.0%	-5%	14%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to PHEV: Diesel and Electricity (U.S. Mix)			0.0%	23%	4%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Hybrid Diesel			0.0%	11%	11%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Electricity			0.0%	61%	42%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to CNG, NA NG			0.0%	-9%	11%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to LNG, NA NG			0.0%	-13%	8%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Conventional Diesel (BD20)			0.0%	-5%	14%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Hydrogen (from NG)			0.0%	40%	52%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Biodiesel (from corn)			0.0%	-88%	90%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to RDII (from corn)			0.0%	-81%	87%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to CNG (from Landfill, Off-site Refueling)			0.0%	2%	17%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Renewable CNG (from Wastewater Treatment, Off-site refueling)			0.0%	62%	136%	0.0%	0.0%	0.0%	0.0%
Hybrid maintenance vehicles and equipment			0.0%	11%	11%	0.0%	0.0%	0.0%	0.0%
Combined hybridization/B20 in maintenance vehicles and equipment			0.0%	1%	27%	0.0%	0.0%	0.0%	0.0%
Hybrid construction vehicles and equipment			0.0%	11%	11%	0.0%	0.0%	0.0%	0.0%
Combined hybridization/B20 in construction vehicles and equipment			0.0%	1%	27%	0.0%	0.0%	0.0%	0.0%
Vegetation management									
Alternative vegetation management strategies (hardscaping, alternative mowing, integrated roadway/vegetation management)	No	Yes	N/A	25%	25%	0.0%	0.0%	25.0%	25.0%
Snow fencing and removal strategies									
Alternative snow removal strategies (snow fencing, wing plows)	No	Yes	N/A	0%	0%	0.0%	0.0%	0.0%	0.0%
In-place roadway recycling									
Cold In-place recycling			0.0%	33%	37%	0.0%	0.0%	0.0%	0.0%
Full depth reclamation			0.0%	68%	68%	0.0%	0.0%	0.0%	0.0%
Warm-mix asphalt									
Warm-mix asphalt			0.0%	37%	37%	0.0%	0.0%	0.0%	0.0%
Recycled and reclaimed materials									
Use recycled asphalt pavement as a substitute for virgin asphalt aggregate			0.0%	12%	12%	0.0%	0.0%	0.0%	0.0%
Use recycled asphalt pavement as a substitute for virgin asphalt bitumen			0.0%	84%	84%	0.0%	0.0%	0.0%	0.0%
Use industrial byproducts as substitutes for Portland cement	0%	50%	50.0%	59%	59%	0.0%	0.0%	29.5%	29.5%
Use recycled concrete aggregate as a substitute for base stone			0.0%	58%	58%	0.0%	0.0%	0.0%	0.0%

When viewing the cumulative energy use of this project by material – which is representative only of the culverts portion – the results show that total energy consumption is primarily due to materials, approximately 70-75% of the energy use of the project, with materials transportation and construction responsible for the remaining portion. The planned mitigations have little impact on energy use (Figure 27). These results can be compared to total GHG emissions. Here, too, a large share of the GHG emissions associated with the culverts (only) stems from the materials category, but the mitigated scenario shows the reduction in lifecycle GHG emissions associated with the selected mitigation measures, and the difference these measures have in energy consumption and GHG emissions. (Figure 28). However, it must be restated that these results are only for the culvert portion of the infrastructure.

To include the effects of the custom pavement, the reported emissions or energy by should be viewed by infrastructure type. As discussed in Section 2.4.3, only this chart includes results from any custom pavement infrastructure type. Figure 29 shows the cumulative GHG emissions over both the 20-year lifetime and both infrastructure types. It also shows the small impact of these mitigations on the overall impact of this hypothetical project.

Figure 31. Total Energy Usage Results from Culverts in the Planning Level Case Study

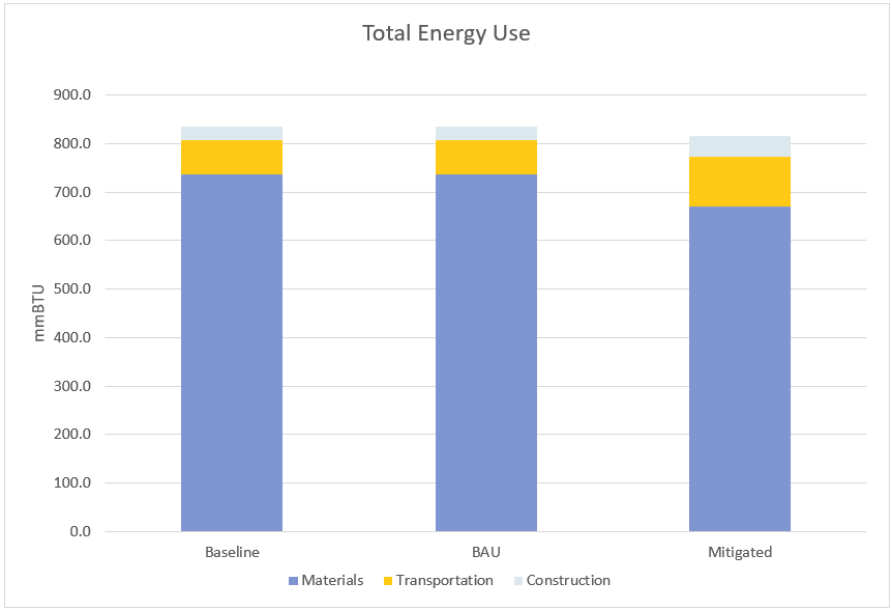


Figure 32. Cumulative GHG Emissions Results from Culverts in the Planning Level Case Study

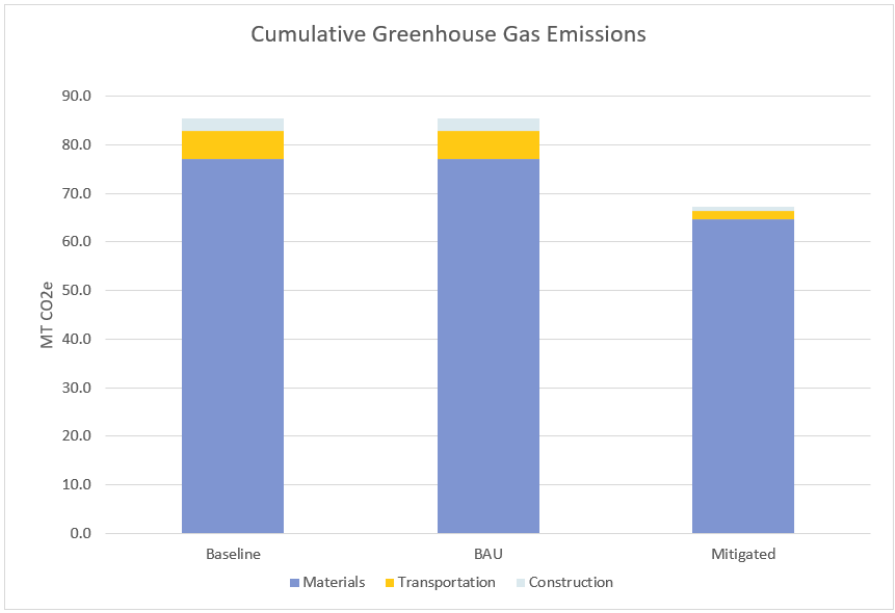
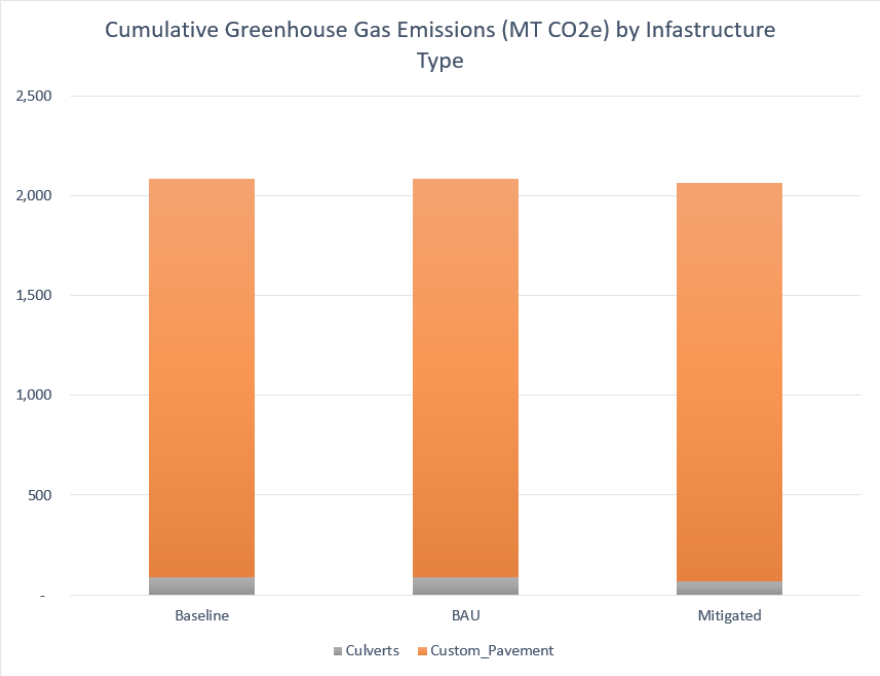


Figure 33. Cumulative GHG Emissions Results from the Planning Level Case Study



5.2 Project Level Case Study: Roadways

For the project level case study, a roadway construction project was modeled. This would be a project adding a relatively significant amount of roadway, including interstate, to a small rural area. All existing and new roads are 2-lane, so the ratio of lane miles to centerline miles is 2 in both the existing and new cases. Only 50 existing centerline miles are considered, which will require maintenance. To this small amount of existing roads, we are adding 30% more roadway miles.

Note that this example may deviate from a traditional "project" by considering both new and existing roadways. This is designed to illustrate the impact of considering impacts beyond the immediate, new construction "project" on results, highlighted below. A more traditional "build" project could be analyzed by removing the existing road network from consideration.

This scenario is modeled in Florida with a project lifetime of 30-years and without any custom RPS electricity factors applied. Figure 33 illustrates the specific inputs used on the *Project Inputs* tab.

Figure 34. Project level case study: Roadway Inputs

Roadway System	
Total existing centerline miles	50
Total newly constructed centerline miles	15

Roadway Projects						
Facility type	Roadway System	Roadway Construction				
	Existing Roadway (lane miles)	New Roadway (lane miles)	Construct Additional Lane (lane miles)	Realignment (lane miles)	Lane Widening (lane miles)	Shoulder Improvement (centerline miles)
Rural Interstates		10				
Rural Principal Arterials	33	10				
Rural Minor Arterials	33	10				
Rural Collectors	33					
Urban Interstates / Expressways						
Urban Principal Arterials						
Urban Minor Arterials / Collectors						

Include roadway rehabilitation activities (reconstruct and resurface)	Yes
% roadway construction on rocky / mountainous terrain	0%

The mitigation measures applied for this case study were: switch from diesel to soy bean-based renewable diesel (RD100), switch from diesel to E-Diesel (Corn), vegetation management, use of industrial byproducts as substitutes for Portland cement, and use of recycled concrete aggregate as substitute for base stone. Also, pavement preservation was included in the planned scenario, with an expected 5-year lifetime extension from the application and a 5-year cycle to treat the entire roadway system. Figure 34 shows these inputs.

In addition to the inputs available in the *Project Inputs* tab, inputs allowing further customization are available in the specific infrastructure type tab, *Roadways*. This allows for customization of road width, material hauling distance, and the portion of roadway guard railing that is galvanized. It also allows entry of a custom schedule for roadway resurfacing and reconstruction activities. ICE then computes the average number of reconstruction and resurfacing events per year over the project's lifetime, which are based on the input schedule and the input pavement preservation parameters (Figure 34). These calculated values may then be overridden if custom values are known. In this example, we have not adjusted any of these parameters. Figure 35 shows the available roadway rehabilitation maintenance schedule inputs. The effect of the pavement preservation strategy selected in the "mitigated" deployment but not in the BAU are shown in the resulting average number of reconstructs and resurfaces per year.

Figure 35. Mitigation Measures Applied to Project Level Case Study

Strategy	BAU deployment	Planned deployment	Deployment increase	Energy reduction factor	GHG reduction factor	BAU Reductions: Energy reductions	BAU Reductions: GHG reductions	Planned Reductions: Energy reductions	Planned Reductions: GHG reductions
Alternative fuels and vehicle hybridization									
Switch from diesel to Soybean-based Biodiesel			0.0%	-26%	14%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Soybean-based RDII 100	0%	25%	25.0%	-28%	65%	0.0%	0.0%	-7.1%	16.3%
Switch from diesel to Forest Residue-based RDII 100			0.0%	-67%	73%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to E-Diesel, Corn	0%	25%	25.0%	-5%	14%	0.0%	0.0%	-1.3%	3.6%
Switch from diesel to PHEV: Diesel and Electricity (U.S. Mix)			0.0%	23%	4%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Hybrid Diesel			0.0%	11%	11%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Electricity			0.0%	61%	42%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to CNG, NA NG			0.0%	-9%	11%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to LNG, NA NG			0.0%	-13%	8%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Conventional Diesel (BD20)			0.0%	-5%	14%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Hydrogen (from NG)			0.0%	40%	52%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Biodiesel (from corn)			0.0%	-88%	90%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to RDII (from corn)			0.0%	-81%	87%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to CNG (from Landfill, Off-site Refueling)			0.0%	2%	17%	0.0%	0.0%	0.0%	0.0%
Switch from diesel to Renewable CNG (from Wastewater Treatment, Off-site refueling)			0.0%	62%	136%	0.0%	0.0%	0.0%	0.0%
Hybrid maintenance vehicles and equipment			0.0%	11%	11%	0.0%	0.0%	0.0%	0.0%
Combined hybridization/B20 in maintenance vehicles and equipment			0.0%	1%	27%	0.0%	0.0%	0.0%	0.0%
Hybrid construction vehicles and equipment			0.0%	11%	11%	0.0%	0.0%	0.0%	0.0%
Combined hybridization/B20 in construction vehicles and equipment			0.0%	1%	27%	0.0%	0.0%	0.0%	0.0%
Vegetation management									
Alternative vegetation management strategies (hardscaping, alternative mowing, integrated roadway/vegetation management)	No	Yes	N/A	25%	25%	0.0%	0.0%	25.0%	25.0%
Snow fencing and removal strategies									
Alternative snow removal strategies (snow fencing, wing plows)			N/A	0%	0%	0.0%	0.0%	0.0%	0.0%
In-place roadway recycling									
Cold In-place recycling			0.0%	33%	37%	0.0%	0.0%	0.0%	0.0%
Full depth reclamation			0.0%	68%	68%	0.0%	0.0%	0.0%	0.0%
Warm-mix asphalt									
Warm-mix asphalt			0.0%	37%	37%	0.0%	0.0%	0.0%	0.0%
Recycled and reclaimed materials									
Use recycled asphalt pavement as a substitute for virgin asphalt aggregate			0.0%	12%	12%	0.0%	0.0%	0.0%	0.0%
Use recycled asphalt pavement as a substitute for virgin asphalt bitumen			0.0%	84%	84%	0.0%	0.0%	0.0%	0.0%
Use industrial byproducts as substitutes for Portland cement	0%	50%	50.0%	59%	59%	0.0%	0.0%	29.5%	29.5%
Use recycled concrete aggregate as a substitute for base stone	0%	50%	50.0%	58%	58%	0.0%	0.0%	29.0%	29.0%
Pavement preservation									
Pavement preservation extends roadway maintenance activities by (%)		5.0%	5.0%	N/A	N/A	N/A	N/A	N/A	N/A
Pavement preservation frequency (every N years, for entire roadway system)		5.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figure 36. Custom Roadway Rehabilitation Maintenance Schedule Parameters available in the Project Level Roadway Case Study

Maintenance Schedule

Default: Activity	Default: Year	Custom: Activity	Custom: Year	Selected Year Per Activity: Activity	Selected Year Per Activity: Baseline	Selected Year Per Activity: BAU (with Pavement Preservation)	Selected Year Per Activity: Mitigated (with Pavement Preservation)
Construction	0			Construction	0	0.0	0
Resurface	15			Resurface	15.0	15.0	17.5
Reconstruct	30			Reconstruct	30.0	30.0	35.0
Resurface	45			Resurface	45.0	45.0	52.5
Reconstruct	60			Reconstruct	60.0	60.0	70.0

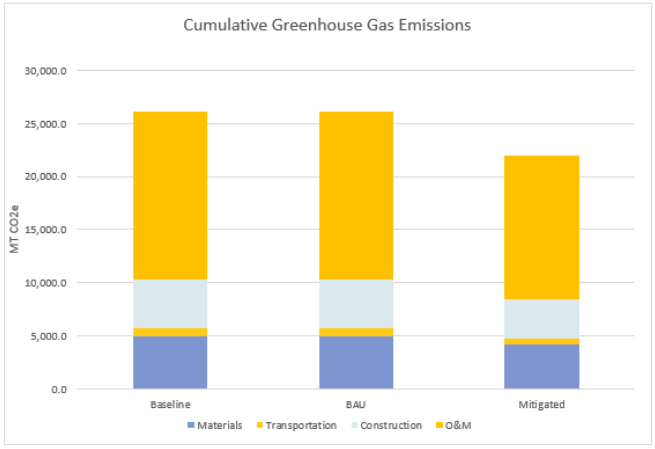
Computed Factors - Based on Selected Schedule

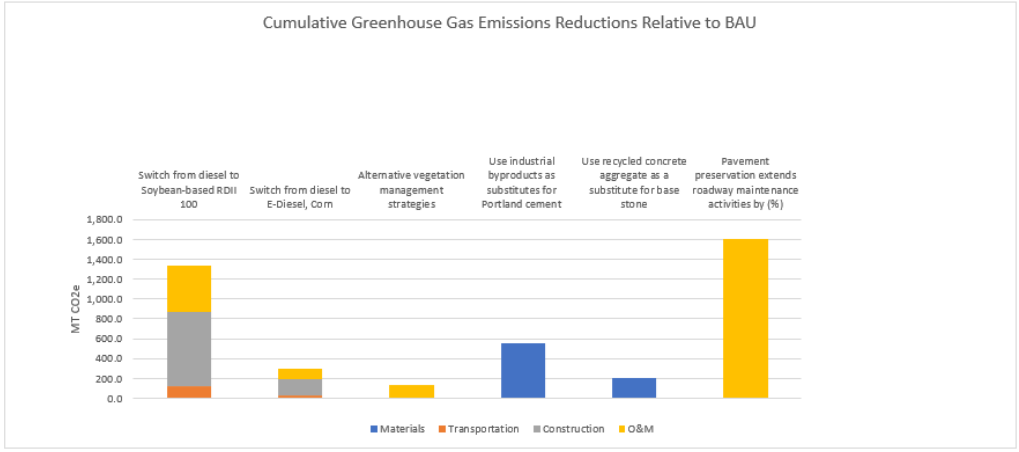
Avg Times Per 30 years	Baseline (without Pavement Preservation)	BAU: With Pavement Preservation	BAU: Custom	BAU: Selected	Mitigated: With Pavement Preservation	Mitigated: Custom	Mitigated: Selected
Avg # Reconstructs	0.67	0.67		0.67	0.57		0.57
Avg # Resurfaces	1.00	1.00		1.00	0.86		0.86

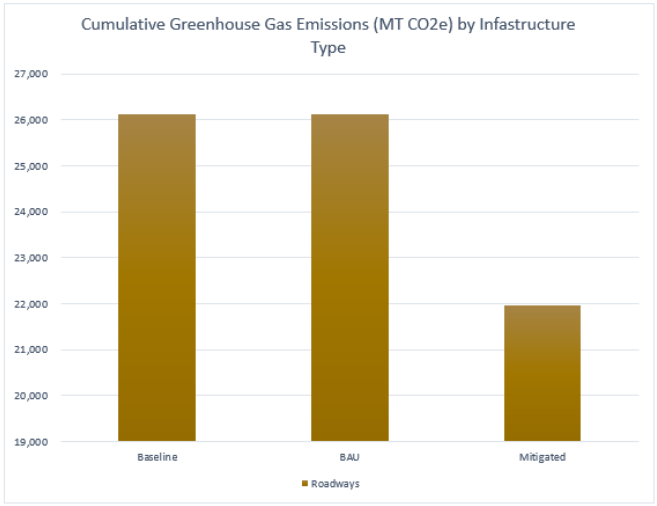
The predicted results from this project, in terms of total GHG emissions over the 30-year lifespan are shown by Figure 36. Moving clockwise around the charts, the upper left chart shows the total emissions by project phase. As expected, operations and maintenance (O&M) dominate emissions

over the lifespan for the baseline, BAU, and planned scenarios, due largely to the roadway rehabilitation, which includes the 100-lane mile existing road network. The top right figure shows the effect of the selected mitigations. Pavement preservation activities are seen to be the largest reduction in emissions over the lifecycle. This is expected given that operations and maintenance are the biggest lifecycle emitter, and this reduces those efforts. The bottom right chart shows the total GHG emissions associated with each material. "Material" here is understood to be those tracked in ICE. For this reason, O&M roadway rehabilitation and O&M pavement preservation show as materials. ICE tracks these internally for accounting reasons. The rightmost bar in this chart shows the emissions "cost" associated with the pavement preservation schedule, which may be compared to its "benefit" in the chart above it. Finally, the bottom left chart shows the total emissions by infrastructure type. Since the project mode only allows a single infrastructure type, this chart is identical to the one above it, but without the breakdown by material.

Figure 37. Total GHG Emissions Results from the Roadway Project Level Case Study







6 Tool Details: Methods, Prototypes, and Mitigations

6.1 Materials, Transportation, and Electricity Factors used in ICE

6.1.1 Primary Material Emission Factors

ICE1.0 relied on a small selection of primary materials to generate the total GHG emissions and energy use associated with modeled transportation infrastructure. The embodied emissions and energy use of aggregate, cement, steel, water, bitumen, timber and soil were the foundation of the model. Emission and energy factors for each material were applied to material ratios for asphalt and concrete mixtures and infrastructure prototypes to estimate final emissions and energy use. These values were taken from PaLATE and GreenDOT and are now outdated.

Higher quality data and modeling efforts now exist. Among the new potential data sources are Environmental Product Declarations. EPDs are independently verified and registered documents that follow ISO standards and provide comparable information about the lifecycle impacts of products. Most available EPDs inventory the emissions and energy use associated raw material extraction, transportation, and processing and represent a cradle-to-gate lifecycle boundary. EPDs present the most up to date data available and are produced using both primary and secondary data. For several primary materials there are a significant number of EPDs available. For others, notably bitumen, EPDs are currently in development but there are no publicly available documents. We took emission and energy factor values from available EPDs and, for bitumen (asphalt binder) and water, from a survey of relevant academic and grey literature. The studies were assessed for boundary and scope continuity.

In addition to updating the energy and emission factors, we also included several additional materials in the prototypes. The rest of this section presents the updated materials and associated factors for ICE2.1.

6.1.1.1 Aggregate

Construction aggregate is a broad category capturing medium grained materials used in construction including sand, gravel, and crushed stone. Aggregates are the most significant component of asphalt and concrete construction by volume. The size and relative quantities of different aggregates largely depend on the application (Asphalt vs Concrete, Mix Design). There is a growing number of EPDs associated with construction aggregates. While ICE1.0 used a single value for all aggregate, ICE2.1 distinguishes between aggregates used as sand, subbase, asphalt, and concrete based on the information from available EPD data. Consistent with ICE's material neutrality, the use is fixed by infrastructure; users may not select individual aggregate types. Table 16 in Appendix A1 details the factors for various aggregates identified in EPDs for the United States and Canada.

6.1.1.2 Cement

Cement is the primary binder used in concrete construction. Two common types of cementitious materials used in construction are Portland Cement and Blended Hydraulic Cement. In 2016, the Portland Cement Association produced EPDs for both materials that describe average U.S. and Canadian values for the materials. Blended Hydraulic Cement contains 1.3% fly ash and is a lower carbon alternative to Portland cement. The default factor for cement in ICE2.1 is Portland Cement.

Table 18 in Appendix A1 shows United States average factors for Cement from EPDs for the United States.

6.1.1.3 Steel

ICE1.0 included only a single value for steel that was used to estimate GHG emissions and energy use associated with steel-reinforced concrete, steel bridge designs, guard rails and other features. A review of EPDs produced by steel producers found differentiations made between steel types. In order to increase the veracity of ICE2.1, additional emission and energy factors were added to address specific steel type use cases, including those for galvanized steel and regular steel used in fencing, guard rails and steel pipe culverts and heavy duty structural steel used in bridges and other structures. ICE2.1 considers the following types of steel:

1. Structural Steel, Galvanized
2. Structural Steel, Ungalvanized
3. Steel Plate, Galvanized
4. Steel Plate, Ungalvanized
5. Hollow Structural Steel, Galvanized
6. Hollow Structural Steel, Ungalvanized
7. Corrugated Steel Conduits
8. Concrete reinforcing steel

Table 20 in Appendix A shows all values of energy and emissions factors for steel from relevant EPDs.

6.1.1.4 Aluminum

Aluminum was not included in ICE1.0 but is added to ICE2.1 as a required material for roadway signage. Table 21 in Appendix A1 shows values of energy and emissions factors for aluminum from relevant EPDs.

6.1.1.5 Water

Water is the primary material that was most difficult to develop a U.S. average estimate. The reason for this is that sources of water and the associated technologies required for extraction, treatment and delivery can vary significantly. Meta-analyses of potable water life-cycle assessment studies have been performed and both have found large variation in the global warming potential of potable tap water. The findings of these meta-analyses suggest that production technology is the most important differentiating factor. In particular, the use of desalinization is responsible for the values found at the upper end of the spectrum. While there is a significant range identified in the literature even modern, low-end values are several orders of magnitude greater than the current value in ICE1.0.

Table 22 in Appendix A1 shows values of energy and emissions factors for water from relevant EPDs.

6.1.1.6 Bitumen (Asphalt Binder)

We were unable to identify a published environmental product declaration for bitumen but we understand one in preparation supported in part by the National Asphalt Pavement Association. Upon its publication it should be compared to the values shown in Table 23 in Appendix A and ICE2.1 may be updated. For ICE2.1, we used factors based on a review of academic and grey literature of

pavement life-cycle assessment literature, selecting the study completed by Yang[8] as the most comprehensive attempt in the U.S. to estimate the impacts associated with bitumen.

Table 23 in Appendix A shows literature values for bitumen factors.

6.1.1.7 Diesel Fuel

ICE2.2 assumes all equipment is diesel fueled for baseline calculations. (This can be changed by applying mitigations.) To determine appropriate energy and emission factors for baseline diesel fuel we used the latest version of Argonne National Lab's Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET). Table 13 in Section 4.3.2 lists the resulting energy and emissions values of baseline diesel and diesel alternatives. To convert this lifecycle emissions value to diesel gallon equivalent (DGE) emission factors, we applied factors representing the lower heating value of diesel fuel determined by API.[9] The DGE factor for energy is the (downstream only) lower heating value from API. This converts diesel fuel consumption volume to work.

6.1.1.8 Summary

Table 2 summarizes the default material energy and emission factors used in ICE2.1.

[8] Yang R. Development of a Pavement Lifecycle Assessment Tool Utilizing Regional Data and Introducing an Asphalt Binder Model. University of Illinois at Urbana-Champaign; 2014.
[9] Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry, American Petroleum Institute, August 2009.

Table 2: Summary of Material Fuel Usage Factors used in ICE

Quantity	Energy Factor		Emissions Factor	
	Unit	Default Value	Unit	Default Value
Aggregate Sand	Million BTU per metric tonne	0.060	metric tonnes CO2eq per metric tonne	0.003
Aggregate Subbase	Million BTU per metric tonne	0.090	metric tonnes CO2eq per metric tonne	0.005
Aggregate Asphalt	Million BTU per metric tonne	0.097	metric tonnes CO2eq per metric tonne	0.006
Aggregate Concrete	Million BTU per metric tonne	0.079	metric tonnes CO2eq per metric tonne	0.004
Aluminum	Million BTU per metric tonne	80.280	metric tonnes CO2eq per metric tonne	5.330
Bitumen	Million BTU per metric tonne	5.170	metric tonnes CO2eq per metric tonne	0.400
Cement	Million BTU per metric tonne	5.580	metric tonnes CO2eq per metric tonne	1.040
DGE	Million BTU per gallon[1]	0.132	Metric tonnes CO2eq per gallon[2]	0.013
Electricity	Million BTU per kWh	0.0034	Metric tonnes CO2eq per kWh	0.0002
Structural Steel - Galvanized	Million BTU per metric tonne	18.470	metric tonnes CO2eq per metric tonne	1.460
Structural Steel - Ungalvanized	Million BTU per metric tonne	17.810	metric tonnes CO2eq per metric tonne	1.160
Steel Plate - Galvanized	Million BTU per metric tonne	21.920	metric tonnes CO2eq per metric tonne	1.770
Steel Plate - Ungalvanized	Million BTU per metric tonne	17.810	metric tonnes CO2eq per metric tonne	1.470
Hollow Structural Steel - Galvanized	Million BTU per metric tonne	30.680	metric tonnes CO2eq per metric tonne	2.660
Hollow Structural Steel - Ungalvanized	Million BTU per metric tonne	26.750	metric tonnes CO2eq per metric tonne	2.390
Corrugated Steel Conduits	Million BTU per metric tonne	28.280	metric tonnes CO2eq per metric tonne	2.260
Concrete reinforcing steel	Million BTU per metric tonne	10.625	metric tonnes CO2eq per metric tonne	0.728
Water	Million BTU per metric tonne	0.0044	metric tonnes CO2eq per metric tonne	0.0006

[1] Downstream only

[2] Up and downstream

6.1.2 Transportation and Construction Process Emission Factors

In ICE1.0, emissions associated with transportation and construction processes were pre-estimated using NHCRP's Fuel Usage Factors in Highway and Bridge Construction and stored as constants within the tool. In order to improve the functionality of ICE while remaining consistent with the original scope the revised ICE transportation and process emissions will be calculated within the tool by directly referencing NHCRP Fuel Usage Factors. This allows the emissions and energy calculations associated with infrastructure features to focus specifically on material quantities.

Table 25 in Appendix A2 shows the fuel usage factors by process category underlying ICE.

Table 3: Summary of Fuel Usage Factors used in ICE

Quantity	Fuel Usage Factor	
	Unit	Default Value
Asphalt - Short Haul - Fuel Use Factor	Gallons/Ton	0.293
Asphalt - Long Haul - Fuel Use Factor	Gallons/Ton	0.514
Base Stone- Short Haul - Fuel Use Factor	Gallons/Ton	0.406
Base Stone - Long Haul - Fuel Use Factor	Gallons/Ton	0.558
Concrete - Short Haul - Fuel Use Factor	Gallons/C.Y.	0.6
Concrete - Long Haul - Fuel Use Factor	Gallons/C.Y.	1.1
Steel- Short Haul - Fuel Use Factor	Gallons/Ton	0.406
Steel - Long Haul - Fuel Use Factor	Gallons/Ton	0.558
Structures - Reinforcing Steel	Gallons/Lbs.	0.004
Structures - Superstructure Concrete	Gallons/C.Y.	4.15
Asphalt Production (Diesel)	Gallons/Ton	2.04
Asphalt Placement	Gallons/Ton	0.273
Concrete Production (Support Equipment)	Gallons/C.Y.	0.09
Concrete Placement	Gallons/C.Y.	0.267
Small Pipe Crew - Fuel Use Factor	Gallons/L.F.	0.871
Medium Pipe Crew - Fuel Use Factor	Gallons/L.F.	1.481
Large Pipe Crew - Fuel Use Factor	Gallons/L.F.	4.338
Drainage Structures - Fuel Use Factor	Gallons/Each	26.175
Bridges - Gallons fuel per sq. ft	Gallons/S.F.	0.616

6.1.3 Electricity Emissions Factors

ICE2.2 estimates the lifecycle emissions associated with direct electricity use at the state level (District of Columbia included). These factors have all been updated to represent the current slate of electricity generation portfolios, many of which have changed.

Lifecycle Emission Factors and Energy consumption were developed for electricity on a state-by-state basis consistent with the tool's formulation. Multiple assumptions were made to build state-specific values, presented in Table 2 below.

The factors used in ICE2.1 are based on the most recent Emissions & Generation Resource Integrated Database (eGRID) developed by the U.S. EPA[10] and the GREET 2022 model.[11] The database considers the quantity of electricity generated by various generation technologies and provides weighted average emissions for many regional boundaries for greenhouse gasses (CO_2, CH_4 and N_20) and other pollutants. Carbon dioxide equivalent (CO_2e) values are based on IPCC factors shown in Table 4.

[10] U.S. EPA. Emissions & Generation Resource Integrated Database (eGRID2016) [Internet]. 2018. Available from: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

[11] https://greet.es.anl.gov/

GREET 2022 uses the North American Electric Reliability Corporation (NERC) regional classification, as illustrated in Figure 37 below, to quantify the energy use and greenhouse gas emissions from electricity generation. Several NERC regions have intersecting states. For ICE2.2, states were allocated to each region.

Figure 38: Electricity Regions in the GREET 2022 Model

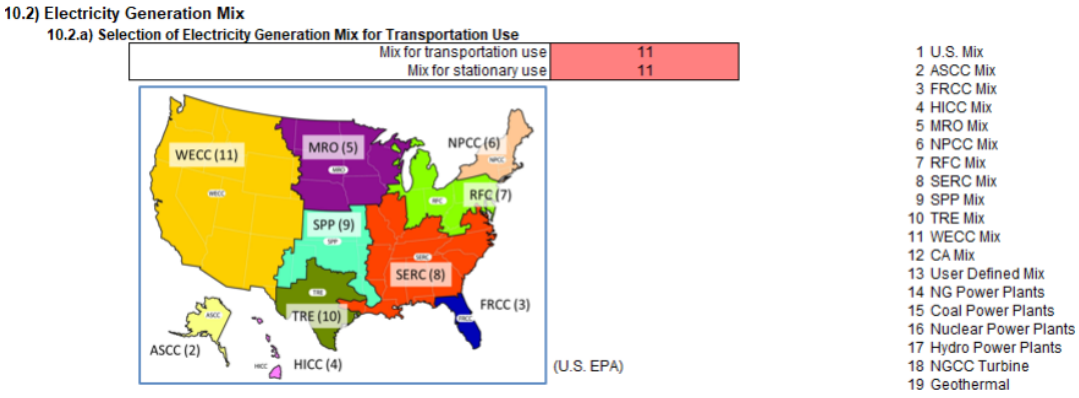


Table 4: Sources and Assumptions used for Lifecycle Electricity Emission Factors and Energy Consumption

Data Point	Assumption Description	Source
ASCC (2)	State - Alaska	GREET 2022
FRCC (3)	State - Florida	GREET 2022
HICC (4)	State - Hawaii	GREET 2022
MRO (5)	States - Minnesota, North Dakota, South Dakota, Nebraska, Iowa, Wisconsin	GREET 2022 MRO Google Maps
NPCC (6)	States - Maine, Vermont, New Hampshire, Massachusetts, New York, Connecticut, Rhode Island	GREET 2022 NPCC Google Maps
RFC (7)	States - New Jersey, Pennsylvania, Delaware, Maryland, West Virginia, Ohio, Michigan, Indiana, and the District of Columbia	GREET 2022 Reliability First Google Maps
SERC (8)	States - Missouri, Illinois, Kentucky, Virginia, Arkansas, Tennessee, Louisiana, Mississippi, Alabama, Georgia, North Carolina, South Carolina	GREET 2022 SERC Google Maps
SPP (9)	States - Kansas, Oklahoma	GREET 2022 SPP Google Maps
TRE (10)	State - Texas	GREET 2022
WECC (11)	States - Montana, New Mexico, Wyoming, Arizona, California, Colorado, Idaho, Nevada, Oregon, Utah, Washington	GREET 2022 WECC Google Maps
CA (12)	State – California	GREET 2022

Data Point	Assumption Description	Source
2060 Values Interpolation for Emissions, Energy, and Fuels	Linear Interpolation was used between 2020-2050 values to create new data points for 2060 as GREET 2022 does not simulate values for 2060.	Calculated
Upstream Emission Factors	Upstream EFs for emissions, energy, and fuels were derived from GREET. Upstream EFs include the entire life cycle except for the generation-related emissions, and downstream (of power plant) operations, such as transmission and distribution.	GREET 2022
Energy Consumption	Energy consumed from upstream activities for the generation of a unit of electricity including feedstock and fuel production.	GREET 2022
Combustion Emissions	Direct emissions from the electricity generation were provided on a state-specific basis, using eGRID 2022 values.	eGRID 2022
Transmission and Distribution Losses	Latest available data on U.S. Transmission and Distribution losses of 5.911% (2018 data) were applied to all Transmission and Distribution assumptions from 2020 through 2060, representing a conservative assumption as T&D losses are expected to decrease over time, in practice	The World Bank 2018

Table 5 shows the resulting default ICE2.1 electricity emission factors. Note that, unlike ICE2.1 and ICE1.0, these factors now vary by calendar year.

Table 5: 100-Year Global Warming Potential of Greenhouse Gasses

Gas	100-Year GWP
CO_2	1
CH_4	25
N_2O	298

Source: IPCC AR4

Table 6: Statewide Average Electricity Emission (kg CO2eq per kWh)[12,13] and Energy (BTU per BTU) Factors

	2020		2030		2040		2050		2060	
State	**Emissions**	**Energy**	**Emissions**	**Energy**	**Emissions**	**Energy**	**Emissions**	**Energy**	**Emissions**	**Energy**
AK	0.733	2.59	0.616	2.58	0.465	2.59	0.444	2.59	0.431	2.58
FL	0.545	2.20	0.445	1.99	0.327	1.86	0.315	1.88	0.294	1.71

[12] Note that electricity emission factors are used for both construction and operation calculations. They cannot be built in as variability for the primary materials due to ICE's reliance on whole values from EPDs.
[13] Note that ICE2.1 included similar results but were labeled as lbs/kWh and were treated as such. This has been corrected in ICE2.2 and all references to the older version have been removed.

	2020		2030		2040		2050		2060	
State	Emissions	Energy	Emissions	Energy	Emissions	Energy	Emissions	Energy	Emissions	Energy
HI	0.974	3.34	0.819	3.25	0.625	3.26	0.598	3.26	0.579	3.22
IA	0.880	2.39	0.734	2.30	0.541	2.24	0.514	2.20	0.497	2.12
MN	0.824	2.39	0.688	2.30	0.508	2.24	0.483	2.20	0.467	2.12
ND	1.138	2.39	0.946	2.30	0.693	2.24	0.658	2.20	0.636	2.12
NE	1.119	2.39	0.931	2.30	0.682	2.24	0.648	2.20	0.626	2.12
SD	0.896	2.39	0.747	2.30	0.551	2.24	0.523	2.20	0.506	2.12
WI	0.808	2.39	0.675	2.30	0.499	2.24	0.474	2.20	0.458	2.12
CT	0.465	1.76	0.374	1.52	0.268	1.39	0.256	1.41	0.235	1.23
MA	0.522	1.76	0.420	1.52	0.301	1.39	0.288	1.41	0.265	1.23
ME	0.293	1.76	0.232	1.52	0.166	1.39	0.160	1.41	0.142	1.23
NH	0.456	1.76	0.366	1.52	0.262	1.39	0.251	1.41	0.230	1.23
NY	0.504	1.76	0.406	1.52	0.290	1.39	0.278	1.41	0.256	1.23
RI	0.462	1.76	0.371	1.52	0.265	1.39	0.254	1.41	0.233	1.23
VT	0.113	1.76	0.084	1.52	0.060	1.39	0.059	1.41	0.046	1.23
DC	0.469	2.04	0.389	1.91	0.295	1.91	0.283	1.92	0.273	1.85
DE	0.421	2.04	0.349	1.91	0.266	1.91	0.256	1.92	0.247	1.85
IN	0.861	2.04	0.711	1.91	0.526	1.91	0.502	1.92	0.484	1.85
MD	0.669	2.04	0.553	1.91	0.412	1.91	0.395	1.92	0.380	1.85
MI	0.755	2.04	0.624	1.91	0.463	1.91	0.443	1.92	0.427	1.85
NJ	0.490	2.04	0.406	1.91	0.307	1.91	0.295	1.92	0.284	1.85
OH	0.783	2.04	0.647	1.91	0.479	1.91	0.458	1.92	0.442	1.85
PA	0.576	2.04	0.477	1.91	0.358	1.91	0.343	1.92	0.331	1.85
WV	1.039	2.04	0.857	1.91	0.630	1.91	0.601	1.92	0.579	1.85
AL	0.648	2.00	0.532	1.88	0.388	1.74	0.368	1.69	0.348	1.56
AR	0.772	2.00	0.634	1.88	0.461	1.74	0.437	1.69	0.415	1.56
GA	0.580	2.00	0.477	1.88	0.348	1.74	0.330	1.69	0.312	1.56
IL	0.870	2.00	0.715	1.88	0.519	1.74	0.492	1.69	0.467	1.56
KY	0.931	2.00	0.765	1.88	0.555	1.74	0.526	1.69	0.500	1.56
LA	0.499	2.00	0.410	1.88	0.300	1.74	0.285	1.69	0.268	1.56
MO	1.002	2.00	0.823	1.88	0.596	1.74	0.565	1.69	0.538	1.56
MS	0.531	2.00	0.437	1.88	0.319	1.74	0.303	1.69	0.286	1.56
NC	0.646	2.00	0.530	1.88	0.387	1.74	0.367	1.69	0.347	1.56
SC	0.678	2.00	0.557	1.88	0.405	1.74	0.385	1.69	0.364	1.56
TN	0.771	2.00	0.633	1.88	0.460	1.74	0.436	1.69	0.414	1.56
VA	0.505	2.00	0.415	1.88	0.304	1.74	0.288	1.69	0.271	1.56
KS	1.106	2.11	0.900	1.77	0.650	1.66	0.618	1.64	0.586	1.41
OK	0.607	2.11	0.490	1.77	0.356	1.66	0.340	1.64	0.318	1.41
TX	0.648	2.03	0.526	1.80	0.383	1.67	0.367	1.68	0.344	1.50
CA	0.461	1.75	0.374	1.54	0.262	1.33	0.248	1.31	0.227	1.10

	2020		2030		2040		2050		2060	
State	Emissions	Energy	Emissions	Energy	Emissions	Energy	Emissions	Energy	Emissions	Energy
AZ	0.639	1.85	0.522	1.64	0.379	1.55	0.357	1.49	0.338	1.33
CO	0.884	1.85	0.723	1.64	0.524	1.55	0.494	1.49	0.470	1.33
ID	0.423	1.85	0.344	1.64	0.252	1.55	0.237	1.49	0.222	1.33
MT	1.117	1.85	0.915	1.64	0.661	1.55	0.624	1.49	0.595	1.33
NM	0.872	1.85	0.713	1.64	0.516	1.55	0.487	1.49	0.463	1.33
NV	0.524	1.85	0.427	1.64	0.311	1.55	0.293	1.49	0.276	1.33
OR	0.523	1.85	0.427	1.64	0.311	1.55	0.293	1.49	0.276	1.33
UT	0.899	1.85	0.736	1.64	0.532	1.55	0.502	1.49	0.478	1.33
WA	0.609	1.85	0.497	1.64	0.362	1.55	0.341	1.49	0.322	1.33
WY	1.181	1.85	0.967	1.64	0.698	1.55	0.660	1.49	0.629	1.33
PR	0.843	2.04	0.693	1.86	0.506	1.78	0.481	1.75	0.458	1.63

Source: eGRID and GREET

These factors may be modified by introducing a custom electricity emission reduction profile. Such a profile may be the result of a state implementing a Renewable Portfolio Standard (RPS). As these could take any form, ICE treats these generically. The user inputs only the percent reduction by projection year. See Section 2.7.5.

6.2 Prototypes

The ICE tool uses a prototyping approach to estimate the carbon intensity of various infrastructure elements. These prototypes are used to determine how much of a primary material is used per unit of infrastructure. For example, how many tons of aggregate are required for an arterial road per mile. Additionally, the prototypes are used to determine the impacts associated with construction processes. ICE2.1 continues to rely on several of the prototypes previously developed for ICE1.0 and adds new infrastructure categories.

This section describes each prototype and provides a summary of the underlying details.

6.2.1 Roadways

Although the approach for roadway calculations was updated in ICE2.1, the underlying prototype and material quantities are largely unchanged from ICE1 and are carried forward into ICE2.2.

6.2.1.1 Material

6.2.1.1.1 Data Sources

We used three primary data sources to estimate roadway materials factors:

- Battelle, Inc. Reports in Support of FHWA's Highway Economic Requirements System ("HERS") Model. Battelle produced several reports documenting in detail the specific construction requirements associated with the project and infrastructure types used in the ICE.[14]

[14] These reports, produced between 2002 and 2006 and identified by the team only in paper form, were entitled "Updating the Highway Improvement Cost Model."

- Oman Systems, Inc.'s BidTabs Database. Oman Systems collects data on all bids for virtually every highway construction project in the country. The BidTabs database contains the most comprehensive information on quantities of materials required for the construction processes associated with each activity type.[15]
- Mikhail Chester's research on the lifecycle environmental impacts of parking infrastructure.[16]

These sources describe the materials used for roadway projects but cover different construction activities. We used key elements of each source in combination in order to estimate materials use.

6.2.1.1.2 Calculation Methods and Assumptions

We utilized the data sources above to establish a representative profile of the inputs required for each combination of project and activity type used in the roadway input table. Since materials and cost factors vary from state to state, we focused our analysis on five geographically diverse states with large transportation budgets that provided us with a large sample of projects to analyze: California, Texas, Indiana, Ohio, and Georgia. Our key assumption in creating these factors was that collectively these five states are representative of transportation construction across the U.S. We filtered the combined project database from these states to focus on projects that neatly conformed to the activity and project combinations used in the tool, and then calculated the average per-unit usage of each of the four materials under consideration. These estimates are "pavement material-neutral;" they represent a weighted average of the concrete and asphalt requirements from a wide range of projects that use both surfacing materials.

Note that if a user does not enter centerline lane miles, ICE2.2 now defaults this value to entered lane miles divided by two for computation of vegetation maintenance emissions.

6.2.1.2 Construction Fuel

6.2.1.2.1 Data Sources

In order to develop construction fuel use estimates, we drew upon fuel factors data from the National Cooperative Highway Research Program (NCHRP), which contains estimates of the fuel required by construction equipment to carry out specific construction activities.[17]

6.2.1.2.2 Calculation Methods and Assumptions

In most cases, the NCHRP data presents fuel usage factors in terms of the gallons of fuel required per physical unit of material used. We applied these factors to the materials factors for each project and activity combination used in the tool and then summed the results across all materials to develop a fuel factor for each combination. For activities where fuel use is not correlated with quantities of the major material types (for example, lane striping), we applied fuel factors based on the amount of a construction activity per lane or centerline mile of construction. All fuel is assumed to be diesel fuel, since the majority of equipment types considered in the development of the NCHRP report use

[15] This database is proprietary, and held by Oman Systems, Inc. in Nashville, Tennessee.
[16] Chester, Mikhail. "Parking Infrastructure: Energy, Emissions, and Automobile Life-Cycle Environmental Accounting." Available at http://iopscience.iop.org/1748-9326/5/3/034001/ (behind paywall).
[17] National Cooperative Highway Research Program (NCHRP) Report 744: Fuel Usage Factors in Highway and Bridge Construction. Available at http://www.trb.org/Main/Blurbs/168693.aspx.

diesel. In cases where the user does not enter centerline miles, ICE2.2 assumes the value to be the entered number of lane miles divided by 2.

6.2.1.3 Routine Maintenance Fuel

6.2.1.3.1 Data Sources

We used three data sources to estimate factors for roadway maintenance fuel use:

- Fuel use records collected from state DOTs in Washington, Utah, New York, and Pennsylvania, which provided information on the total amount of fuel used for maintenance and/or the fuel used for specific activities such as vegetation management and snow removal.
- Data on the length of the roadway system maintained by DOTs in these states from FHWA's Highway Statistics.[18]
- Data on state snowfall and rainfall from the National Oceanic and Atmospheric Administration's National Climatic Data Monitoring Center.[19]

6.2.1.3.2 Calculation Methods and Assumptions

We broke maintenance fuel use into three categories: vegetation management, snow management, and other. Three states, Utah, Washington, and New York, provided us with information at a sufficient level of detail to calculate fuel use for vegetation management and snow removal. For each of these states, we assumed that all fuel used was diesel, and divided the total amount of fuel used by the total number of centerline miles to derive a vegetation management fuel use factor. We used centerline miles because vegetation maintained by DOTs is mainly on the roadside, so the level of effort for maintenance is proportional to the length of the road. We divided states into two level of effort (LOE) categories for vegetation management based on annual rainfall and assigned fuel use factors accordingly:

- Low LOE (under 25 inches average rainfall per year): we assigned these states a value of 5.9 diesel gallon equivalents (DGEs) per centerline mile based on the average of the values for Utah and New York.
- High LOE (over 25 inches average rainfall per year): we assigned these states a value of 33.4 DGEs per centerline mile based on the value for Washington.

Our process for calculating snow removal factors was similar, except that we normalized factors by lane mile rather than centerline mile because fuel use for snow removal is proportional to the width of the roadway. We divided states into three level of effort (LOE) categories for snow removal based on annual snowfall and assigned fuel use factors accordingly:

- Low LOE (states that receive no snow): we assumed that these states do not use fuel for snow removal.
- Medium LOE (between 0- and 13-inches average snowfall per year): we assigned these states a value of 47.2 DGEs per lane mile based on the average of the values for Utah and Washington.

[18] FHWA Highway Statistics 2008, Table HM-81: State highway Agency-Owned Public Roads - 2008 Rural and Urban Miles; Estimated Lane miles and Daily Travel. 2009. Available at: http://www.fhwa.dot.gov/policyinformation/statistics/2008/hm81.cfm

[19] http://www.ncdc.noaa.gov/climate-monitoring/.

- High LOE (over 13 inches average snowfall per year): we assigned these states a value of 83.7 DGEs per lane mile based on the value for New York.

Only two states, Washington and Utah, provided us with sufficient data to calculate fuel use factors for maintenance not related to snow and vegetation (such as sweeping, striping, and crack sealing), which we estimated in terms of DGEs per lane mile. We used the average of the values for these two states, 78.5 DGEs per lane mile, as the value for all states in the tool.

6.2.1.4 Roadway Rehabilitation

For both new build and existing roadways, the approach to calculating energy and emissions associated with regular roadway rehabilitation project – resurfacing and reconstruction – has been updated in ICE2.2.[20] However, the material and fuel factors remain unchanged. ICE relies on a prescribed maintenance schedule to determine the amount of resurfacing or reconstruction over the lifetime. Note that this is applied to the full, specified road network – new and existing roadways combined. This schedule is alterable through the Project mode, or by including pavement preservation activities as a mitigation measure, which "pushes out" the required schedule.

ICE2.2 now asks for a more uniform schedule. In particular, for resurfacing and reconstruction events, the user specifies the year that the activity first starts, and how frequently the activities occur. For instance, resurfacing could be specified to start in year 15 and then occur every 10th year after that. Then ICE uses an accrual accounting method for the GHG emissions that will eventually occur as a result of the roadway being constructed. This is because building a road implies it will need maintenance, and cutting the window short to skip that misrepresents the annualized emissions associated with that maintenance. This was further confused by using pavement preservation, which extends the maintenance period and could shift activities from within to outside of the analysis window. To use the accrual accounting method, ICE includes scheduled activities over a 100-year period. This period is independent of the analysis period the user selects so the results reflect the total lifetime effects of the Pavement Preservation mitigation strategy specified by the user. ICE also staggers resurfacing and reconstruction so there can't be double counting of those emissions at the same time.

This approach gives a smoother average and avoids issues around windowing and a fixed schedule. However, we note that this could be confusing because it includes emissions that technically occur past a user's analysis period. ICE2.2 includes text to the interface explaining the tools' approach to these calculations.

6.2.2 Roadway Rehabilitation

Standalone roadway rehabilitation projects on existing roads are a special case analysis. This was new in ICE2.1 and remains unchanged in ICE2.2. These are designed to treat maintenance projects on existing roads only. Because these are short term projects, the changes identified for roadway

[20] One of the drivers for updates to version 2.2 was user-identified inconsistencies in the way automated estimates of roadway rehabilitation emissions due to the maintenance schedule for short term projects. Specifically, if periods of time were selected where the maintenance schedule did not fit the analysis period (activated by the Tool's "Include Roadway Rehabilitation Activities"), ICE2.1 produced erratic results. For ICE2.2, we identified and corrected an error in the approach to annualizing impacts. The previous version had issues because of the "windowing" approach. It also omitted implied maintenance from the total impact, such as if a reconstruct was scheduled in year 16 and the analysis time period was set to 15 years. We determined this was not the optimal approach.

rehabilitation in Section 4.2.1.4 do not apply. The only updates included in ICE2.2 relate to universal changes to mitigations and underlying factors, discussed elsewhere.

6.2.3 Custom Pavement

6.2.3.1 Materials and Input

Custom pavement configurations were new in ICE2.1 and are carried unchanged to ICE2.2. As described in Section 2.6.3, the user must obtain energy and emission factors from their external source that matches the full lifecycle analysis boundaries in ICE, in order that these values be compatible with other infrastructure features used here.

There are no specific inputs for this category in ICE2.2, as values are completely determined by independent, exogenous models. No materials are tracked in ICE2.2 with this category to be compatible with ICE's pavement material neutrality requirement.

6.2.3.2 Mitigation

Only two types of mitigation are allowed within ICE to the custom pavement factors imported from a separate tool or research. Those are for alternative snow and vegetation management. In these cases, the energy associated with baseline snow and vegetation management for an equivalent, standard roadway is determined, the amount of energy saved from the mitigation is computed, and this amount is subtracted from the custom roadway lifecycle values.

6.2.4 Roadway Signage

Roadway signage was a new infrastructure type in ICE2.1 and is unchanged in ICE2.2.

6.2.4.1 Materials, Inputs, and Data Sources

Standard drawings and signage details developed by Michigan Department of Transportation were used to develop material estimates for the three sign types along with their support structures.[21] Regulatory and warning signs exhibit similar dimensions and were grouped together and categorized as small (3 ft. x 3 ft.) and medium (6 ft. x 6 ft.). Typical supports for the small sign are a single post while the larger size is supported by two posts of similar dimensions made of steel. Much larger guidance signs are hung overhead or posted on large steel cantilever arms. The large sign size modeled for ICE represents a 10 ft. x 14 ft. sign requiring a cantilever support.

Table 7. Material Estimates for Roadway Signage

Signage Structure	Material Estimates		
	Aluminum (lbs)	Concrete (tons)	Steel (lbs)
Small (3'x3') - 14 Gauge Steel Post (MDOT SIGN-150-D)	8.2	-	31.5
Medium (6'x6') - 14 Gauge Steel Post (MDOT SIGN-150-D)	32.6	0.37	63
Large (10'x14') - 8 Gauge Cantilever Arm (MDOT SIGN-300-A)	253.8	2.46	4,360

[21] Steudle KT. Sign-100-F Thru Sign-890-B English Version Engineer of Traffic and Safety. Michigan Department of Transportation. 2015 [cited 2018 Sep 7]. Available at: https://mdotcf.state.mi.us/public/tands/Details_Web/mdot_sign-support_std.pdf

Aluminum has also been added as a material in ICE2.1 for roadway signage. Aluminum is included in the primary materials list (Section 4.1.1). Energy and emission factors are in Appendix A1.

6.2.5 Roadway Lighting

Roadway lighting was a new infrastructure type in ICE2.1 and is unchanged in ICE2.2.

6.2.5.1 Materials, Inputs, and Data Sources

Roadway lighting is a significant contributor to the annual energy use and greenhouse gas emissions of many transportation agencies. Ożadowicz estimated that streetlights may be responsible for 40% of the electrical energy consumption in cities.[22] The addition of roadway lighting as a category in ICE is intended to help users estimate the energy and GHG emissions associated with lighting use on new projects and provide system wide estimates and evaluate the impacts of two of the most common lighting technologies: High Pressure Sodium (HPS) & Light Emitting Diode (LED). Lifecycle impacts include those associated with various support structures: High Mast, Horizontal (Cobra head), and Vertical.

The baseline of the analysis follows guidelines stipulated in Federal Highway Administration's INVEST tool.[23] This guideline states that baseline analyses of lighting systems should assume system operation 12 hours/day and 7 days/week (4380 hours/year) and use luminaire input wattage to estimate energy consumption. Annual energy consumption is paired with energy emission factors for individual states to determine GHG emissions.

Luminance requirements for roadway lights vary by application and impact the lamp and support structure selected. This addition requires users have some basic information on the types of roadway lighting to be used on their project and/or across their system. To assess the direct energy use and GHG emissions associated with roadway lighting, a survey of several lamp producers was conducted.[24, 25, 26, 27] The survey focused on identifying common luminaries by support type and common lumen output ranges. Table 7 details the power demand for HPS and LED luminaries in ICE2.1.

Table 8. Power demand for typical roadway lights based on luminance requirements and application

Support Structure Type	Lumen Range	Input Wattage

[22] Ożadowicz A, Grela J. Energy Saving in the Street Lighting Control System—A New Approach Based on the EN-15232 Standard. Energy Effic. 2017;10(3):563–76. Available at: https://doi.org/10.1007/s12053-016-9476-1

[23] Federal Highway Adminstration. PD-17 Energy Efficiency [Internet]. INVEST. 2018. Available from: https://www.sustainablehighways.org/files/163.pdf

[24] General Electric. EvolveTM LED Roadway Lighting LED Roadway Luminaire (ERL1-ERLH-ERS1-ERS2) [Internet]. 2016. Available from: https://products.currentbyge.com/sites/products.currentbyge.com/files/documents/document_file/OLP3105-GE-LED-Evolve-Roadway-ERL1-ERLH-ERS1-ERS2-Data-Sheet.pdf

[25] General Electric. GE EvolveTM LED Roadway Lighting High Mast Luminaire (ERHM) [Internet]. 2016. Available from: https://products.currentbyge.com/sites/products.currentbyge.com/files/documents/document_file/OLP3099-GE-LED-Evolve-High-Mast-Light-Data-Sheet.pdf

[26] Phillips. Lumec RoadFocus LED Cobra Head Luminaries [Internet]. 2018. Available from: http://www.usa.lighting.philips.com/products/product-highlights/roadfocus

[27] Phillips. HighFocus LED High Mast [Internet]. 2018. Available from: http://www.usa.lighting.philips.com/products/product-highlights/highfocus-led

		HPS	LED
Vertical and Vertical with Arm	4000-5000	100	40
	7000-8800	150	82
	8500-11500	200	100
	11500-14000	240	125
	21000-28000	400	242
High Mast	28800 - 42000	400	308
	46500-52800	750	402
	52500-58300	1000	474

To model support structures for roadway lights, standard specification and design guidelines were surveyed.[28, 29, 30, 31, 32] Additionally, specification sheets from light support structure manufactures were also consulted.[33, 34, 35] In general, the support structure consists of a steel pole and concrete foundation. Table 8 shows the prototypical structure and materials.

Table 9. Support Structures for Roadway Lighting Applications

	Above Ground Height (ft)	Steel (lbs)	Concrete (lbs)
Vertical	30	380	1600
Vertical with 8-foot Arm	40 ft.	445	2000
High Mast	70 ft.	1270	7000

Note that ICE only includes roadway lighting energy and GHG emissions from the use phase and lighting support structures, as manufacturing energy and emissions for HPS and LED luminaries and replacement parts is currently poorly characterized.

A recent LCA study comparing HPS and LED roadway lighting systems found that the vast majority of the impacts are associated with direct energy consumption of the fixtures over the course of their lifetime.[36] Over a 30-year time frame, the use phase accounted for 96% of the environmental impact

[28] Fouad FH. Structural supports for highway signs, luminaires, and traffic signals. Vol. 494. Transportation Research Board; 2003.
[29] Arizona Department of Transportation. Signals and Lighting Standard Drawings [Internet]. 2018. Available from: https://www.azdot.gov/business/engineering-and-construction/traffic/signals-and-lighting-standard-drawings/current
[30] Iowa Department of Transportation. Lighting. 2014; Available from: https://iowadot.gov/design/SRP/CurrentBook/Sections/eli_section.pdf
[31] Florida Department of Transportation. Roadway Lighiting Details [Internet]. 2006. Available from: http://www.fdot.gov/roadway/DS/06/IDx/17503.pdf
[32] California Department of Transportation. Standard Plans [Internet]. 2010. Available from: http://www.dot.ca.gov/hq/esc/oe/project_plans/HTM/stdplns-US-customary-units-new10.htm#overhead
[33] Light Poles Plus. Steel Light Poles [Internet]. Available from: https://lightpolesplus.com/light-poles/steel-light-poles/
[34] Millerbernd. High Mast Lighting Poles [Internet]. Available from: http://www.millerberndmfg.com/lighting-poles/products/high-mast/
[35] Pemco Lighting Products. Steel Poles [Internet]. 2018. Available from: https://www.pemcolighting.com/steel-poles
[36] Tähkämö L, Halonen L. Life cycle assessment of road lighting luminaires – Comparison of light-emitting diode and high-pressure sodium technologies. J Clean Prod [Internet]. 2015;93:234–42. Available from: http://www.sciencedirect.com/science/article/pii/S0959652615000293

of an HPS light and 87% of the LED light. Less than 1% resulted from end of life for both technologies with the remainder associated with equipment manufacturing. Furthermore, a recent meta-analysis of comparative life-cycle assessments between LEDs and other lighting technologies (not limited to roadway lighting) found discordant impact results associated with luminary component manufacturing and life-cycle maintenance. The authors conclude that these differences arise due to assumptions made about manufacturing materials, processes, and limitations of life-cycle inventory databases in modeling complex electrical components.[37] At this time, the data required to estimate manufacturing impacts of HPS and LED luminaries and replacement parts within ICE in a general way is unreliable. Accordingly, ICE2.1 only considers energy use and GHG emissions associated with roadway lighting from the use phase and light support structures. This may be revisited in subsequent versions if better date becomes available.

6.2.6 Bridges and Overpasses

Bridges are complex structures. The design of superstructure and substructure elements are impacted by countless factors. The prototyping approach in ICE1.0 for calculating emissions associated with bridge construction is based on the national bridge inventory and data from Oman Systems' BidTabs database to define concrete and steel quantities for single span, double span, and multi-span bridges on a per lane basis. When developing ICE2.1, we conducted research to update the existing bridge models from ICE1.0 and include overpasses as a unique infrastructure type. After analyzing national and state level standards, grey literature, and academic literature on bridge construction and design, we found that the prototypes in ICE1.0 are the best available approach. Thus, the prototypes in ICE2.1 for generic bridges and functionally equivalent overpass are identical to those in ICE1.0.

Also as currently noted in ICE1.0, "very large bridges that carry traffic very high or span very deep spaces" are unique and likely require additional materials and construction processes that cannot be approximated by ICE. This remains true in ICE2.2.

6.2.6.1 Materials and Inputs

6.2.6.1.1 Data Sources

We used two primary data sources to produce estimates of the materials required for bridge construction:

1. Oman Systems, Inc.'s BidTabs Database. The database was used to develop profiles for the materials requirements of several distinct components of bridge superstructure and substructure, including deck, beams, footings, piers, caps, barriers, and incidental concrete.
2. FHWA's National Bridge Inventory. This database provides counts of bridges of different wearing surfaces which the team used to develop its basis for weighted average materials requirements.[38]

[37] Franz M, Wenzl FP. Critical review on life cycle inventories and environmental assessments of LED-lamps. Crit Rev Environ Sci Technol. 2017;47(21):2017–78.
[38] The National Bridge Inventory data most used by this effort is available at http://www.fhwa.dot.gov/bridge/nbi/no10/mat13.cfm. The homepage of the inventory is available at http://www.fhwa.dot.gov/bridge/nbi.cfm.

6.2.6.1.2 Calculation methods and assumptions

The consulting team took an approach that estimated materials and fuel required based on the number of spans of each bridge and a default average length of bridge per span. The categories identified were single-span, two-span, and multi-span bridges. Bridge megaprojects (structures similar in scale to the Golden Gate Bridge or Brooklyn Bridge) which span very long distances, and either rise very high or suspend over very deep areas, were explicitly not considered for inclusion in this tool due to their unique characteristics and the rarity of their construction.

With these categories identified, the team utilized the Oman Systems, Inc. database to develop profiles of bridges on a per-lane and per-span basis for each of the three length categories. These were developed for both steel bridge construction and concrete bridge construction. The National Bridge Inventory database was utilized to develop a factor for weighting the bridge materials requirements into a single weighted average for quantities of materials. This would allow planners to proceed with emissions estimation work in the absence of certain knowledge about the details of bridge construction (such as the choice between steel or concrete structures) that may be far into the future.

6.2.6.1.3 Construction Fuel

Data Sources

In order to develop construction fuel use estimates, we again drew upon fuel factors data from the National Cooperative Highway Research Program (NCHRP), which contains estimates of the fuel required by construction equipment to carry out specific construction activities.[39] This research project contains per-unit fuel use requirements by construction equipment for very detailed and specific activities. For bridge work, activities with specific fuel factors included substructure concrete placement, superstructure concrete placement, steel beam placement, concrete barrier placement, concrete pavement placement, pavement removal, and structure demolition.

We relied on Oman Systems' expertise as well in determining the fuel demands for construction, widening, and reconstruction of bridges. While all three require similar materials per lane-span of bridge, activity intensities and categories vary based on the combination.

Calculation methods and assumptions

Using the total quantities of materials above, we identified the quantity of each fuel-using activity to be carried out. Using the appropriate fuel use factor, we identified the amount of fuel for each activity. Emissions and energy use factors were then used to identify the total emissions and energy use required by that activity. The totals of fuel use, emissions and energy use for all activities within a combination were then totaled to produce overall estimates of each impact.

Routine Maintenance Fuel

Maintenance of bridges was considered to be included within the maintenance estimates developed for roadways as described above. This was done because data provided to support the maintenance analysis did not exclude maintenance on bridges, and per-mile data was not adjusted to represent any share of the centerline mileage being represented by bridges. Therefore, out of concern for

[39] National Cooperative Highway Research Program (NCHRP) Report 744: Fuel Usage Factors in Highway and Bridge Construction. Available at http://www.trb.org/Main/Blurbs/168693.aspx.

probable double-counting, we felt it was prudent to treat the energy and emissions associated with bridge maintenance as already estimated within the roadway maintenance analysis.

That said, we note that major maintenance in the form of reconstruction was separately calculated as a form of bridge project, and thus was not included within the estimates of materials, fuels, emissions, and energy use associated with roadway reconstruction.

6.2.7 Culverts

Culverts were a new infrastructure type in ICE2.1 and are unchanged in ICE2.2.

6.2.7.1 Materials, Inputs, and Data Sources

6.2.7.1.1 Box Culverts

Box culverts are typically constructed with reinforced concrete with thickness and size dependent on application. As with signage (Section 4.2.4), the box culvert category was divided into six classifications representing small, medium and large for single and double box structures. Standard specification and design sheets from several state department of transportation were used to develop an average generalized model for each.[40, 41, 42] The material quantities listed in (Table 9) were used to develop the average models. The designs are based on a maximum fill height of 10 feet.

Table 10. Material Quantities - Box Culvers

Culvert Size	Specification Source	Material Estimates (Per Liner Foot)	
		Concrete (tons)	Reinforcing Steel (lbs)
Small-Single (6'x6')	NDOT (6'x6') (10' Fill Height) B-20.1.2.1	1.47	119
	ODOT (6'x6') (10' Fill Height) BR820	1.60	139
	TDOT (6'x6') (10' Fill Height) STD-17-51	1.43	158
	Average	1.50	139
Medium-Single (8x8)	NDOT (8'x8') (10' Fill Height) B-20.1.2.1	2.03	220
	ODOT (8'x8') (10' Fill Height) BR825	2.59	174
	TDOT (8'x8') (10' Fill Height) STD-17-53	1.70	233
	Average	2.10	209
Large-Single (12'x12')	NDOT (12'x12') (10' Fill Height) B-20.1.2.1	3.47	365
	ODOT (12'x12') (10' Fill Height) BR835	4.84	359
	TDOT (12'x12') (10' Fill Height) STD-17-58	3.54	449
	Average	3.95	391
Small-Double (6'x6')	NDOT (6'x6'x9") (10' Fill Height) B-20.1.3.1	2.61	217
	ODOT (6'x6'x9") (10' Fill Height) BR840	3.14	265
	TDOT (6'x6'x9") (10' Fill Height) STD-17-71	2.53	273
	Average	2.76	252
Medium-Double (8x8)	NDOT (8'x8'x9") (10' Fill Height) B-20.1.3.1	3.56	342
	ODOT (8'x8'x9") (10' Fill Height) BR840	4.72	285

[40] Nevada Department of Transportation. 2017 ENGLISH STANDARD PLANS FOREWORD [Internet]. 2017 [cited 2018 Sep 7]. Available from: http://www.nevadadot.com
[41] Oregon Department of Transportation. Oregon Standard Drawings Box Culvert [Internet]. 2018 [cited 2018 Sep 7]. Available from: https://www.oregon.gov/ODOT/Engineering/201801/BR840.pdf
[42] Tennessee Department of Transportation. TDOT LRFD Box Culverts [Internet]. 2018 [cited 2018 Sep 7]. Available from: https://www.tn.gov/content/tn/tdot/structures-/standard-structures-drawings/lrfd-box-culverts.html

	TDOT (8'x8'x9") (10' Fill Height) STD-17-73	3.75	404
	Average	4.01	344
Large-Double (12'x12')	NDOT (12'x12'x9") (10' Fill Height) B-20.1.3.1	6.30	721
	ODOT (12'x12'x9") (10' Fill Height) BR841	9.36	946
	TDOT (12'x12'x9") (10' Fill Height) STD-17-78	7.47	748
	Average	7.71	805

6.2.7.1.2 Pipe Culverts

Pipe Culverts are smaller drainage structures with common diameters ranging from one to four feet depending on application. As with box culverts, several prototypes were developed representing small, medium, and large structures. Standard drawings and details were used to estimate the material quantities associated with the structures.[43, 44] The prototypes include corrugated steel pipe and reinforced concrete headwalls on both ends.

Table 11. Material Estimates for Pipe Culverts

Pipe Culvert Size	Corrugated Metal Pipe (Galvanized Steel) (lbs/foot)	Reinforcing Steel (lbs)	Concrete (tons)
Small (1 Foot Diameter Pipe Culvert)	2.6	46	1.5
Medium (2 Foot Diameter Pipe Culvert)	10.3	50	1.7
Large (4 Foot Diameter Pipe Culvert)	41.2	60	1.8

Note that in the planning mode, only a single, default, culvert option is available. This is equivalent to a medium sized, double box culvert. A default 30' length is also assumed but overridable. This is to simplify the level of input data in ICE consistent with that identified by practitioners as reasonable for a planning level application.

6.2.8 Parking

Parking structure prototypes were completely updated for ICE2.1 but are unchanged in ICE2.2. Two prototypical infrastructure types are included in ICE2.1: surface lots and parking structures. Both are characterized in terms of the number of spaces. They may also be characterized in terms of their total area.

6.2.8.1 Materials, Inputs, and Data Sources

The prototypes for parking lots are derived from the Asphalt Paving Assoc. of Iowa. Pavement thickness by parking lot size is from APAI Design Guide.[45] The prototype for parking garage structures are from an academic study by Griffin et al..[46] here the concrete and steel are set for the

[43] Arkansas Department of Transportation. Arkansas DOT Metal Pipe Culvert Fill Height and Bedding. 2014 [cited 2018 Sep 7]; Available from: https://www.arkansashighways.com/roadway_design_division/usunits/36-pcm-1.pdf

[44] California Department of Transportation. California Pipe Culvert Standard Drawing [Internet]. 2015. Available from: http://www.dot.ca.gov/hq/esc/oe/project_plans/HTM/stdplns-US-customary-units-new15.htm

[45] http://www.apai.net/Files/content/DesignGuide/Chapter_5B.pdf

[46] Comparing the embodied energy of structural systems in parking garages, C.T. Griffin, L. Bynum, A. Green, S. Marandyuk, J. Namgung, Portland State University, and A. Burkhardt, M. Hoffman, KPFF Consulting Engineers. Available at: http://www.personal.psu.edu/czg443/research/cgriffin_parking.pdf

prototype, but the amount of asphalt and construction fuel vary by the parking garage size. Table 11 lists the derived material quantities for each infrastructure type.

Table 12. Material Estimates for Parking Facilities

Infrastructure Type	Subtype	Material Estimates				
		Total Steel (lbs)	Total Concrete (lbs)	Total Asphalt Concrete (lbs)	Total Subbase Aggregate (lbs)	Construction Fuel Use (DGEs)
Parking Structure	Prototype	2189	44990			57.48
	< 50 Spaces			17952	0	20.76
	50-500 Spaces			19932	0	23.05
	> 500 spaces			23925	0	27.67
Parking Lot	< 50 Spaces untreated base			11979	16500	13.85
	50-500 Spaces untreated base			13959	24750	16.14
	> 500 spaces untreated base			13959	33000	16.14

As noted in section 2.6.9.2, additional inputs are available in the Project mode for the *Parking* tab to allow increased customizations, including for the share of steel that is structural versus fencing. Parking structures can have guardrails and fencing. This input allows the user to overwrite the default portion of steel from the prototype that is used for fencing and guardrails. Although small, this value is included for completeness since structural and cellular steel have different emission and energy factors.

Note that there is no Operations and Maintenance included for parking structures.

6.2.9 Vehicle Operations

Although vehicle operations for construction delay were also incorporated in ICE1.0, the format, approach, and underlying data for other vehicle operating emissions was new for ICE2.1. This approach has also been updated for ICE2.2 to allow the preferred approach of inputting custom emissions calculated with a separate model, such as MOVES. ICE2.2 continues to include the option to calculate emissions with basic Inputs of VMT and speed, with an approach similar to that In ICE2.1.

6.2.9.1 Materials, Inputs, and Data Sources

In ICE2.2, full lifecycle vehicle emission and energy factors were derived from EPA's MOVES3 model along with the GREET 2022 model. Energy consumption rates were determined from MOVES3 national scale analysis of energy consumption for all on-road vehicles, all fuels, and all road types by calendar year, both speed-resolved and for overall average values for all speeds.

ICE 2.1 used vehicle energy and emissions factors from MOVES2014b and the 2018 version of the GREET model. Both are outdated. We updated the in-use emission factors in ICE2.2 with factors based on MOVES3.0.4 (with database movesdb20220802) for downstream energy consumption rate and GREET_1_2022 for lifecycle fuel energy and emissions rates and electricity generation energy and emission rates. New factors from MOVES3 extend the calculation period for use-phase through 2060 and fix an issue identified in ICE2.1 for use phase emissions calculations past the end of the available data period.

It is important to note that ICE uses MOVES for projections of the vehicle fleet mix and downstream (tank to wheels; TTW) energy consumption rate (e.g., mmBTU/mile) and fuel-vehicle full lifecycle

energy and emission factors from GREET to get full lifecycle (well to wheels; WTW) rates (g CO2e/mile and mmBTU/mile). ICE2.2 uses rates from MOVES3, which is the current version of the tool as of the time of ICE2.2 release. It is important to note that MOVES3 includes the SAFE rule which has been repealed resulting in more stringent GHG reductions for future vehicle model years than reflected in MOVES, does not account for expected future Heavy-Duty Vehicle rulemakings, and assumes negligible electric vehicle penetration in the fleet, among other limitations. ICE may be updated at a future date when improved vehicle energy rate projections are available. However, MOVS3 is EPA's current version as of release of ICE2.2.

These factors may be updated in ICE via the Advanced Customization tab without changes to the underlying code or operations of the Tool. Thus, updating ICE to other, full lifecycle emission rates can easily be done when new data, such as MOVES4 energy factors, are available.

The current version of MOVES is MOVES3.1 with database movesdb20221007. MOVES3.1 is a minor revision to MOVES3 that adds some inspection and maintenance (I/M) programs for gasoline trucks.[47] Due to the timing of this release, vehicle energy consumption was determined with MOVES3.0.4. To capture full lifecycle emissions in ICE, the approach is to use MOVES to forecast vehicle downstream energy consumption per mile and couple that with lifecycle energy and emissions factors by fuel from GREET. For this reason, the minor update to MOVES3.1 is likely to have negligible impacts on ICE's predictions of vehicle energy and emission rates. When released, MOVES4 is expected to have important differences in the future fleet, including better projections of electric and other alternative vehicles and fuels which may lead to significant differences in ICE's predictions. However, this model is not available in the timeline of this project. We also explored use of EIA's Annual Energy Outlook (AEO) database to forecast fleet energy consumption rates. We were able to determine energy factors comparable to those from MOVES, but the overall fleet comparison fell within +/-10% throughout the modeled period (with MOVES3 generally predicting lower fleet wide energy consumption rates) and required a set of assumptions and extrapolations that we thought were not an improvement to relying on the existing MOVES model. So, we have kept MOVES3 as the underlying fleet forecast in ICE2.2.[48]

As part of this update, we updated ICE's vehicle use-phase emissions to extend to year 2060. We also identified and corrected an issue identified in ICE2.1 for use phase emissions calculations past the end of the available data period.[49] Also part of the updates to ICE2.2 include providing the user with a preferred option of entering emissions directly or having ICE calcualte emissions based on a speed-VMT-emission factor calculation. If the user employs the preferred option of inputting custom values calculated in another model, ICE2.2 asks if the user's inputs represent tailpipe only or full-lifecycle values and whether they would like to have them converted. Conversions are based on the ratio of tailpipe to full lifecycle factors as discussed above.

[47] https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves
[48] Email from Seth Hartley to John Davies, David Kall, Ramon Molina Garcia, and Peter Wasko, February 16, 2023.
[49] ICE2.1 allows years past 2050 when calculated from default inputs. When years past 2050 were input in non-default approaches ICE notes these are erroneous and blocks input. The default values then incorrectly calculated periods after 2050. Both the calculation approach and the underlying emission factor table were updated to fix this issue.

For vehicle operating emissions not using the preferred external emissions calculation, two years are input: project opening year and project design/horizon year, each with a corresponding level of traffic and average speed. From these values, ICE computes the total lifecycle energy and GHG emissions for each year. It then integrates over the specified lifetime, assuming linear trends between the initial, midpoint, and ending years. This bilinear interpolation is used, rather than simple linear interpolation, to better capture variations in the emission factors over time.

For construction delay, ICE requests the construction start year and project opening year, along with the amount of traffic impacted by construction. In this case, the average daily VMT impacted by construction is the speed and VMT in the analysis area. ICE pairs the speed and traffic values with energy consumption rates. ICE calculates the construction duration and takes the affected ADVMT from the input value. The wasted energy and associated emissions are computed as the difference between the emissions during the construction period what those emissions would have been during the construction period had the construction not occurred (no-build).

In both cases, if the user does not enter a specified speed, the overall average emission and energy rates are used. For construction delay, if the user does not enter a construction-delayed speed it is assumed to be half of the pre-construction speed. If the user does not know the pre-construction speed, they should enter the speed limit.

6.2.10 Rail, Bus, Bicycle, and Pedestrian Facilities

Rail, bus, bicycle, and pedestrian infrastructure prototypes remain unchanged from ICE1.0.

6.2.10.1 Materials

6.2.10.1.1 Data Sources

We used three main sources of data and expertise to inform our analysis of the materials required for transportation by non-road modes.

1. The first resource we used in this area is the research of Mikhail Chester, whose work entitled Life-Cycle Environmental Inventory of Passenger Transportation in the United States, contains estimates of the inputs required to construct various types of transit infrastructure. In some cases, Chester's work provides estimates of sources required for specific project types. For light rail and heavy rail, Chester's work develops estimates of the quantities of concrete required for various forms of transit station infrastructure and differentiates between stations at ground level and stations which are either elevated or underground. Also, Chester's work develops GHG emissions estimates for track construction. These estimates are developed for several different transit systems and thus provide more than one estimate each for light and heavy rail.
2. The second was the expertise of team member Hatch Mott MacDonald. Hatch Mott MacDonald completed its own dedicated analysis of the materials requirements associated with digging underground transit tunnels and building above-ground rail transitways. In particular, this analysis estimated the energy requirements associated with boring tunnels for underground transit.
3. The third was the roadway analysis, which we found applicable to certain elements of alternative mode transportation such as bicycle lanes and transit improvements that share road space with general traffic (e.g., streetcars and other light rail). The materials

requirements and fuel use estimates developed for roadway projects were applicable, sometimes with slight modifications, to all or part of the construction of these facilities.

6.2.10.1.2 Calculation Methods and Assumptions

The analysis of infrastructure for alternative modes of transportation was limited to new construction projects and did not include widening, reconstruction, or resurfacing. The methodology, as with roadway and bridge projects, involved identifying the quantities of materials on a per-unit-length basis. Lane mile bases were discarded because few of these modes operate in multiple lanes on a given route.

We relied on Mikhail Chester's analysis for materials required for infrastructure components unique to transit. These included at-grade rail lines on entirely new rights of way and all railway station construction requirements. We relied on Hatch Mott MacDonald to develop estimates of materials requirements for elevated and underground rail lines. Finally, we applied the roadway materials requirements, where appropriate, to project types that included similar materials, or which were done on existing roadways. These included light rail on existing rights of way, bicycle lanes, and bus rapid transit, for which we applied Chester's station estimates along with roadway-based estimates for constructing rights of way.

6.2.10.2 Construction Fuel

6.2.10.2.1 Data Sources

We relied on two main sources to identify the intensity of fuel use associated with the activities required to build these alternative-mode transportation infrastructure projects. The first was the NCHRP Fuel Factors research. While this research focused on roadway construction, many of its estimates covered activities involved here, such as the placement of substructure and superstructure concrete, pavement, earthwork, and retaining-wall construction. For some transit-related activities, such as the placement of rails and ties, no exact fuel factor was produced. In response, we identified the most similar activity for which there was a fuel factor (e.g., the placement of steel structural beams and placement of concrete barriers) and applied adjustments if necessary, to correct for notable differences in weight or required machinery.

The second source was the analysis of transit engineering experts Hatch Mott Macdonald. HMM produced planning-level estimates of the fuel needed to carry out the construction requirements of establishing underground or elevated rights of way (i.e., building elevated platforms or boring transit tunnels).

6.2.10.2.2 Calculation Methods and Assumptions

As with roadway and bridges, we identified for each material involved the activity or activities associated with the placement of that material. Using the fuel factors identified for each activity, we developed fuel-use estimates on a per-mile basis for rights of way and a per-unit basis for stations. Based on those estimates, we developed energy and emissions estimates in the same manner as we did for roadway and bridge projects.

6.2.10.3 Routine Maintenance Fuel

6.2.10.3.1 Data Sources

We based our estimation of transit on two main sources. The first was the roadway maintenance requirements analysis described above, which we considered applicable to infrastructure such as bus rapid transit and bicycle lanes. The second was data produced by the Los Angeles County Metropolitan Transportation Authority and the National Transit Database. These data included maintenance fuel required by the agency on an annual basis and the directional and revenue mileage covered by the agency's different modes of transit service on an annual basis.

6.2.10.3.2 Calculation Methods and Assumptions

For bus rapid transit and bicycle lanes, we drew on the analysis of roadway maintenance costs to estimate the energy use associated with BRT and bicycle lanes, which share the same basic characteristics as vehicular travel lanes and are maintained using similar equipment and approaches. We assumed that the fuel use associated with maintenance, which depends largely upon the surface area of the facility being maintained, varies in proportion to the width of a facility. Though the width of individual BRT lanes and bicycle lanes varies, we made a general assumption that a travel lane dedicated to BRT is roughly the same width as a vehicle travel lane and that the average bike lane is half as wide as the typical vehicle lane. Off-street bicycle lanes were assumed to receive maintenance with half the frequency of on-road facilities.

For rail-based projects, we used data from Los Angeles County Metropolitan Transportation Authority and the National Transit Database to estimate total fuel use for rail. Based on data received from LA Metro, we estimated the amount of fuel used for rail maintenance based on the percentage of the agency's vehicle revenue miles traveled by rail (13%). We then divided this total by LA Metro's 153 directional miles of rail to obtain a value of 686 diesel gallons per directional mile per year for rail maintenance fuel use.

6.2.11 Interchanges

One of the major changes in ICE2.2 is the introduction of the interchange infrastructure category. While this can be manually "pieced together" from other types, this is cumbersome and less accurate than having a matching prototype built into the Tool. Per Panel direction, ICE2.2 includes freeway/highway interchanges as the highest priority feature for state DOT application.

The interchange category operates by duplicating other features in ICE, specifically Roadways and Bridges/Overpasses. When users select Interchanges, ICE2.2 opens a new Interchanges tab, with its inputs tied to the infrastructure inputs on the Project Inputs tab. This also creates duplicate but hidden tabs to do work for interchange calculations based on underlying infrastructure types (Interchanges_Roadways and Interchanges_Bridges_Overpasses). ICE also provides user instructions inline to guide inputs.

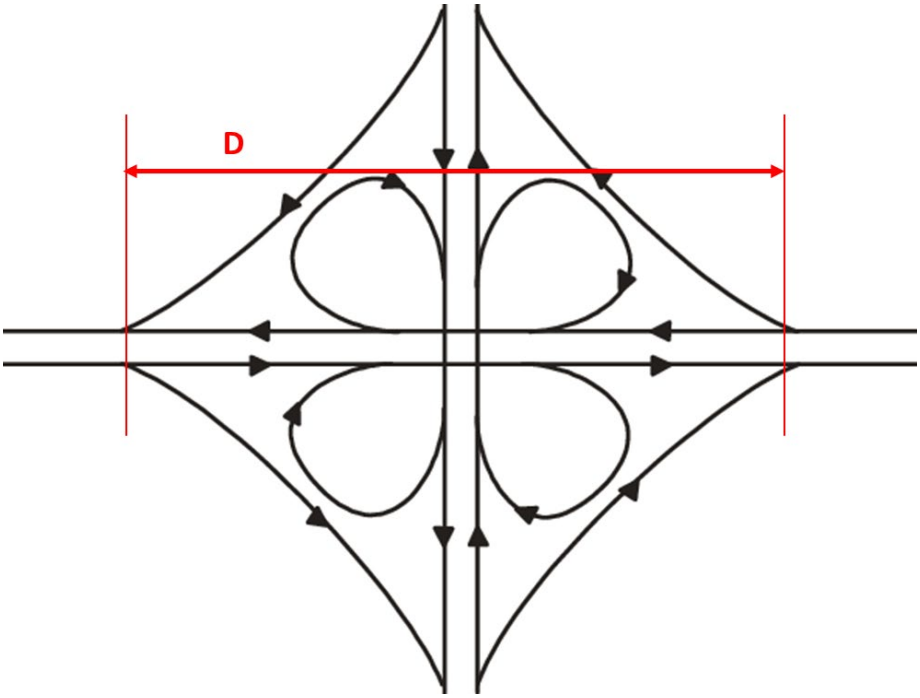
The Interchange project type in ICE is designed for newly built interchanges only. For projects that modify existing interchanges, the user should treat them according to their Individual components being updated, such as bridges or roadways.

The interchange category is designed to be high-level and to require very few inputs. Interchanges are limited to a symmetric, 4-sided, cloverleaf geometry with a 2-span bridge overpass. The schematic below illustrates this geometry. With this shape, the user only needs to enter the distance

from the first exit to the last entrance along a single travel direction to represent all elements. This parameter is shown in the schematic as "D". All other roadway geometry is based on this schematic, scaled to the designed interchange size. Note that, consistent with other ICE infrastructure prototypes, no earth moving is excluded in the calculations.

All other associated emissions and energy are computed from the underlying infrastructure types. This includes operations and maintenance activities. Emissions and energy associated with routine maintenance (sweeping, striping, bridge deck repair, litter pickup, and maintenance of appurtenances) are automatically applied consistent with roadway and bridge component infrastructure.

Figure 39: ICE2.2 Interchange Geometry Schematic



6.3 Mitigation Strategies

The mitigation strategies from ICE1.0 were retained for ICE2.1 and remain mostly unchanged in ICE2.2. Most remain based on the same research and approach from the previous version of the tool. Additional alternate fuels were added for ICE2.2. Pavement preservation, new in ICE2.1, remains, along with the additional logic for implementation of mitigation strategies included throughout.

In order to quantify the energy and GHG emissions reductions due to the mitigation strategies considered in the tool, we drew upon existing research and data from transportation agencies to collect three key pieces of information:

1. The percentage reduction in energy and GHG emissions factors for each strategy.
2. The activities, facilities, and emissions sources that the above reduction factor should be applied to.

3. The maximum potential deployment of each strategy.

The following subsection details the data sources, calculation methods, and assumptions that we used to collect this information.

6.3.1 Overall Logic, Applicability, and Caveats for Mitigation Measures in ICE2.1

Table 13 summarizes the available strategies in ICE2.2 and the cases for which they apply.

Table 13. Mitigation Strategies and Applicability in ICE

Category	Strategy	Use Cases in ICE
Alternative fuels and vehicle hybridization	Switch from diesel to Soybean-based BD20	The fuel mitigation strategies are universal and apply to all transportation, construction, and maintenance DGEs for every infrastructure type.
	Switch from diesel to Soybean-based RDII 100	
	Switch from diesel to Forest Residue-based RDII 100	
	Switch from diesel to E-Diesel, Corn	
	Switch from diesel to PHEV: Diesel and Electricity (State Mix)	
	Switch from diesel to Hybrid Diesel	
	Switch from diesel to Electricity	
	Switch from diesel to CNG, NA NG	
	Switch from diesel to LNG, NA NG	
	Switch from diesel to Conventional Diesel (BD20)	
	Switch from diesel to Hydrogen (from NG)	
	Switch from diesel to Biodiesel (from corn)	
	Switch from diesel to RDII (from corn)	
	Switch from diesel to CNG (from Landfill, Off-site Refueling)	
	Switch from diesel to Renewable CNG (from Wastewater Treatment, Off-site refueling)	
	Hybrid maintenance vehicles and equipment	The factors apply to all construction and maintenance DGEs, including reconstruction and resurfacing.
	Combined hybridization/B20 in maintenance vehicles and equipment	
	Hybrid construction vehicles and equipment	
	Combined hybridization/B20 in construction vehicles and equipment	
Vegetation Management	Alternative vegetation management strategies (hardscaping, alternative mowing, integrated roadway/vegetation management)	Applies to vegetation management DGE for roadway infrastructure only (including custom pavements)
Snow fencing and removal strategies	Alternative snow removal strategies (snow fencing, wing plows)	Applies to snow removal DGE for roadway infrastructure only (including custom pavements)
In-place roadway recycling	Cold In-place recycling	Applies to energy and GHG emissions associated with Asphalt and DGE used in Roadway resurfacing and converted BRT facilities.
	Full depth reclamation	Applies to energy and GHG emissions associated with base stone and construction DGE for roadway reconstruction and BRT construction.
Warm-mix asphalt	Warm-mix asphalt (WMA)	Modifies the emission and energy factor for asphalt batch plant processes. Applies universally for all infrastructure types that include asphalt. WMA and RAP are incompatible.

Recycled and reclaimed materials	Use recycled asphalt pavement (RAP) as a substitute for virgin asphalt aggregate	Reduces energy and GHG emissions associated with all asphalt use. WMA and RAP are incompatible.
	Use recycled asphalt pavement (RAP) as a substitute for virgin asphalt bitumen	
	Use industrial byproducts as substitutes for Portland cement	Reduces the energy and GHG emissions associated with all concrete use.
	Use recycled concrete aggregate as a substitute for base stone	Reduces the energy and GHG emissions associated with all base stone use.
Pavement preservation	Pavement preservation extends roadway life by (years)	These change the frequency of roadway rehabilitation projects (benefit) and set the number of applications of preservation over the project's life (cost). They apply to pavement only.
	Pavement preservation frequency (every N-years, for entire roadway system)	

During development of ICE2.1, a reviewer noted that end-of-life (EOL) phase is not within the life cycle analysis boundary of ICE, but cold-in-place recycling (CIR) and full depth reclamation (FDR), which are EOL strategies, are applied to new pavement construction, which the reviewer found to be inappropriate. The lifecycle boundary for materials in ICE is cradle-to-gate. CIR and FDR do deal with materials at the end of their lifecycle. However, the use of CIR and FDR also offsets some new materials. When considered as a replacement of new materials these do not violate EOL boundaries and fit in the analysis framework. Comparing commensurate boundaries across different materials quickly becomes a "chicken and egg" problem that is difficult to resolve and beyond the scope of ICE. However, while the factors are uncertain, the use of these strategies is common. Thus, ICE maintains the use of these mitigation measures.

It has been noted that ICE may allow mix designs that are unrealistic, beyond an agency's control over mixture design (typically determined by contractors) and can lead to "greenwashing" by applying strategies unrealistically. ICE1.0 avoided this by including an upper limit on allowable values. As there was little information on the source for those values, they were repeatedly questioned during review and user testing, and we believed they would differ by state, those limits were removed in ICE2.1 and remain so in ICE2.2. Please note that ICE may allow users to potentially include strategies in their analysis that they may not have jurisdiction over. This could be considered "greenwashing" of a project. Although we anticipate that the flexibility in ICE2.1 will serve the user community by enhancing the educational value by illustrating potential impacts of mitigation strategies, we note that users are responsible for the scenarios analyzed in ICE. Please note, also, that FHWA's LCA Pave Tool[2] may provide additional, and potentially more accurate analysis of these and other strategies than available in ICE. Users should consult that tool for further information when it becomes available.

A reviewer commented that the tool does not allow partial credit. That is, when a pavement mitigation strategy (WMA, RCA, SCM, FDR, etc.) is selected it is automatically applied to all asphalt in the project or plan. This may not always be true; portions of the asphalt projects can have different techniques. For example, some parts may be made with WMA and some with HMA, or RAP may be used in the first pavement lift and not in the surface course. We agree mitigations may be applied unevenly across a plan or project. However, ICE is designed for screening evaluations and pavement configurations in ICE are limited by design. As a pre-engineering tool, ICE users are unlikely to know which pavement layers would receive which strategies and this is likely beyond their control. Instead, ICE treats this and other mitigations generically. ICE requests the penetration depth of a strategy as a fraction of the project or plan slated to receive the selected strategies. This allows such an

estimation within the tool's scope. E.g., a user is only required to estimate that 50% of a project's pavement will receive WMA. This allows strategies that may be incompatible to both be applied to a project, so long as the total is not greater than 100%. For example, if half the pavement of a road project were to utilize WMA and half RAP, the user would enter 50% for each. This is not necessarily incompatible, as they could occur in different locations or different layers. ICE will prompt if an entered case exceeds 100% penetration for combined, incompatible mitigations, but the user is responsible for ensuring entered strategies are realistic. The user should consult the upcoming FHWA Pavement LCA Tool[2] for such measures in more detail.

The approach for overlapping mitigations in ICE2.2 is similar to that in ICE1.0 and simple. ICE2.2 caps the sum of reductions to be no less than zero. As a bounding approach, this may allow an unreasonable, "greenwashing", deployment scenarios but cannot produce an overall project or plan where the total reductions are negative. As discussed above, logic has also been added to ICE2.1 limiting the deployment of competing strategies for pavement and fuels. User's should ensure the applied mitigations are realistic for both the Planned and BAU scenarios and should consult the upcoming FHWA Pavement LCA Tool[2] for additional details.

6.3.2 Alternative Fuels and Vehicle Hybridization

6.3.2.1 Data Sources

ICE2.2 includes the same approach for alternative fuels and engine technologies as ICE1.0 and ICE2.1 but updates the effects of these fuel alternatives using values from the latest version of Argonne National Lab's Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET)50 and adds new fuels and technology. The top portion of Table 13 summarized the available fuels for mitigation strategies in ICE2.2. Table 14 lists the different fuels and their resulting energy and emissions savings diesel alternatives; These tables show the full lifecycle (well to wheel) emissions associated with each fuel including the upstream (well-to-tank) emissions and tailpipe (tank-to-wheel) emissions. In addition to Biodiesel 20, Biodiesel 100, and hybridization, we also include several other fuel alternatives including renewable diesel (RD) from forest residue and from corn, E-diesel from corn, biodiesel from corn, hybrid diesel, CNG, LNG, biomethane from landfill with off-site refueling, renewable CNG from wastewater treatment with off-site refueling, electricity, conventional and plug-in hybrids (PHEV), and hydrogen from NG.

To quantify the energy and emissions benefits of alternative fuels it is important to take into account the relative efficiency of the alternative compared to the baseline fuel. Table 14 includes the energy efficiencies relative to the baseline where greater than 100% means the fuel is more efficient than the baseline and below 100% means the fuels is less efficient than the baseline. The GREET model includes indirect land use change emissions in the emissions calculation for corn-based ethanol and soy-based biodiesel. We quantified and included indirect land use change GHG impacts for feedstock-based biofuels using the default assumptions in GREET from their Carbon Calculator for Land Use Change from Biofuels (CCLUB) plugin. It is important to note that electricity follows the state specific mix over the project's period. This also applies to PHEV which is a mix of electric and diesel equipment based on GREET.

[50] Argonne National Laboratory. Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET 2022). Available from: https://greet.es.anl.gov

Table 14. Baseline Diesel and Alternative Diesel Comparisons. Positive numbers reflect energy and emission savings; negative numbers reflect energy and emission increases.

	Conventional Diesel (B0)	Conventional Diesel (BD20) - Calculated	CNG, from NG	LNG, from NG	Hydrogen (from Natural Gas)	Soybean-based Biodiesel	Soybean-based RDII 100	Corn to Biodiesel
Total Energy (BTU/ mmBTU)	1,182,701	1,244,180	1,162,783	1,198,498	1,489,924	1,490,097	1,517,148	2,220,769
GHGs (g/ mmBTU)	99,007	84,807	79,481	81,911	98,243	84,807	34,483	10,247
Efficiency Relative to Diesel	100.0%	100.0%	90.0%	90.0%	208.7%	100.0%	100.0%	100.0%
Electric Efficiency Relative Diesel								
Energy Savings (%)	-	-5.2%	-9.2%	-12.6%	39.6%	-26.0%	-28.3%	-87.8%
Emissions Savings (%)	-	14.3%	10.8%	8.1%	52.5%	14.3%	65.2%	89.7%
	Corn to RDII	**Landfill to CNG (Off-site Refueling)**	**Wastewater Treatment to Renewable CNG (Off-site refueling)**	**Forest Residue-based RDII 100**	**E-Diesel, Corn**	**Electricity**	**Hybrid Diesel**	**PHEV: Diesel and Electricity (U.S. Mix)**
Total Energy (BTU/ mmBTU)	2,145,186	1,042,977	403,570	1,976,919	1,244,180	1,865,689		1,437,549
GHGs (g/ mmBTU)	12,850	74,268	-31,697	26,962	84,807	188,693		132,472
Efficiency Relative to Diesel	100.0%	90.0%	90.0%	100.0%	100.0%	436.3%		162.8%
Electric Efficiency Relative Diesel								
Energy Savings (%)	-81.4%	2.0%	62.1%	-67.2%	-5.2%	63.8%	11.0%	25.3%
Emissions Savings (%)	87.0%	16.7%	135.6%	72.8%	14.3%	56.3%	11.0%	17.8%

Source: GREET

The following acronyms are used in Table 13 and Table 14:

1. BD20 - mixture of 20% biodiesel and 80% diesel by volume
2. CNG – Compressed Natural Gas
3. E-Diesel – Ethanol-Diesel Blend
4. LNG – Liquefied Natural Gas
5. PHEV – Plug-in Hybrid Electric Vehicle
6. RDII 100 – 100% Renewable Diesel
7. PHEV – Plug-in Hybrid

6.3.2.2 Calculation Methods, Limitations, and Assumptions

Lifecycle emission factors and energy consumption were developed for different transportation fuels, for usage in the tool as both default fleet fuels and for mitigation strategies. ICE2.2 adds several new alternative fuels for mitigation.

Table 17 below summarizes the approach used in GREET for each one of the assumptions taken to develop these fuel emission factors and energy consumption values. In ICE, the upstream and vehicle combustion values for energy and GHGs are added to derive full lifecycle energy and emissions factors for light-duty, heavy-duty, and construction/off-road heavy-duty vehicles.

Table 15: Sources and Assumptions used for Lifecycle Fuels Emission Factors and Energy Consumption

Data Point	Assumption Description	Source
Diesel (BO)	Upstream Values - Values added from the "Crude for use in U.S. refineries" pathway with the "Conventional Diesel" fuel pathway, under the "Petroleum" tab of the GREET1 2022. Vehicle Combustion - Values taken from the "vehicles" and "HD_WTW" tabs, per the "Diesel" fuel, in the GREET1 2022 spreadsheet.	GREET 2022
Gasoline (E0)	Upstream Values - Values added from the "Crude for use in U.S. refineries" pathway with the "Gasoline" fuel pathway, under the "Petroleum" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "vehicles" and "HD_WTW" tabs, per the "Diesel" fuel, in the GREET1 2022 spreadsheet. There were no values available for heavy-duty vehicles combustion for this fuel, both in the "HD_WTW" tab in the GREET1 2022 spreadsheet, nor in the GREET.net	GREET 2022
Conventional Biodiesel (BD20)	Upstream Values – Calculated by assigning 20% from Soybean-based	GREET 2022

	BD100 upstream values, and 80% from the Conventional Diesel (BD0) values. Vehicle Combustion - Calculated by assigning 20% from Soybean-based BD100 vehicle-specific values, and 80% from the Conventional Diesel (BD0) vehicle-specific values.	
Gasoline (E10)	Upstream Values - Calculated by assigning 10% from Corn Ethanol upstream values, and 90% from the Gasoline (E0) values. Vehicle Combustion - Calculated by assigning 10% from Corn ethanol vehicle-specific values, and 90% from the Gasoline (E0) vehicle-specific values.	GREET 2022
Compressed Natural Gas from Conventional Natural Gas	Upstream Values – Adding "Feedstock" and "Fuel" Values from the "NG or FG to Compressed Natural Gas" fuel pathway, under the "NG" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "vehicles" tab, per the "CNG" fuel, in the GREET1 2022 spreadsheet and the "WTW and C2G Results" tab, per the "Compressed Natural Gas" fuel, in the GREET.net 2022 software.	GREET 2022
Ethanol from Corn Stover	Upstream Values - Adding "Corn Stover" and "Ethanol" Values from the "Corn Stover Ethanol: Combined" fuel pathway, under the "EtOH" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "vehicles" tab, per the "Dedicated EtOH" fuel, in the GREET1 2022 spreadsheet. There were no values available for heavy-duty vehicles combustion for this fuel, both in the "HD_WTW" tab in the GREET1 2022 spreadsheet, nor in the GREET.net	GREET 2022
Gaseous Hydrogen from Natural Gas	Upstream Values - Adding "Feedstock" and "Fuel" Values from the "Central Plants: NG or FG to Gaseous Hydrogen" fuel pathway, under the "Hydrogen" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "vehicles" and "HD_WTW" tabs, per the "G.H2 ICE Vehicle" fuel and "Fuel-Cell Vehicle: G. H2" fuel respectively, in the GREET1 2022.	GREET 2022
Soybean to Biodiesel	Upstream Values - Adding "Feedstock" and "Fuel" Values from the "Soy Oil-	GREET 2022

	based Biodiesel" fuel pathway, under the "BioOil" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "HD_WTW" tab, per the "Biodiesel" fuel, in the GREET1 2022 spreadsheet. There were no values available for passenger vehicles combustion for this fuel, both in the "vehicles" tab in the GREET1 2022 spreadsheet, nor in the GREET.net 2022 software.	
Soybean to Renewable Diesel II	Upstream Values - Adding "Feedstock" and "Fuel" Values from the "Soy Oil-based Renewable Diesel II" fuel pathway, under the "BioOil" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "WTW and C2G Results" tab, per the "Renewable Diesel II" fuel, in the GREET.net 2022 software. Values for Renewable Diesel II from Greet.net 2022 software include considerations for Biogenic CO2 emissions	GREET 2022
Corn to Biodiesel	Upstream Values – Adding "Feedstock" and "Fuel" Values from the "Corn Oil-based Biodiesel" fuel pathway, under the "BioOil" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "HD_WTW" tab, per the "Biodiesel" fuel, in the GREET1 2022 spreadsheet. There were no values available for passenger vehicles combustion for this fuel, both in the "vehicles" tab in the GREET1 2022 spreadsheet, nor in the GREET.net 2022.	GREET 2022
Corn to Renewable Diesel II	Upstream Values – Adding "Feedstock" and "Fuel" Values from the "Corn Oil-based Renewable Diesel II" fuel pathway, under the "BioOil" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "WTW and C2G Results" tab, per the "Renewable Diesel II" fuel, in the GREET.net 2022 software. Values for Renewable Diesel II from Greet.net 2022 software includes considerations for Biogenic CO2 emissions.	GREET 2022
Landfill to CNG	Assumes the "Off-Site Refueling" pathway in GREET. Upstream Values - Values from the "Landfill Gas to CNG " fuel pathway, under the "RNG" tab of the GREET1 2022 model.	GREET 2022

	Vehicle Combustion - Values taken from the "vehicles" tab, per the "Dedicated CNGV" fuel, in the GREET1 2022 spreadsheet and the "WTW and C2G Results" tab, per the "Compressed.	
Wastewater Treatment to CNG	Assumes the "Off-Site Refueling" pathway in GREET Upstream Values – Values from the "Wastewater Sludge to CNG" fuel pathway, under the "RNG" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "vehicles" tab, per the "Dedicated CNGV" fuel, in the GREET1 2022 spreadsheet and the "WTW and C2G Results" tab, per the "Compressed. Note in Table 14 that GREET predicts the GHG reduction for this measure as more than 100% due to the additional upstream GHG sink.	GREET 2022
Conventional Natural Gas to Liquefied Natural Gas	Upstream Values - Adding "Feedstock" and "Fuel" Values from the "Natural Gas to Liquefied Natural Gas" fuel pathway, under the "NG" tab of the GREET1 2022 model. Vehicle Combustion - Values taken from the "vehicles" tab, per the "Dedicated LNGV" fuel, in the GREET1 2022 spreadsheet and the "WTW and C2G Results" tab, per the "Liquefied Natural Gas" fuel, in the GREET.net 2022 software.	GREET 2022
Forest Residue to Renewable Diesel II	Upstream Values – Adding "Feedstock" and "Fuel" Values from the "Distributed System" option of the "Forest Residue to Pyrolysis Diesel" fuel pathway, under the "Pyrolysis_IDL" tab. Vehicle Combustion - Values taken from the "WTW and C2G Results" tab, per the "Renewable Diesel II" fuel, in the GREET.net 2022 software. Values for Renewable Diesel II from Greet.net 2022 software includes considerations for Biogenic CO2 emissions.	GREET 2022
2060 Values Interpolation for Fuels-Specific Emissions and Energy Values	Linear extrapolation was used between 2020-2050 values to create new data points for 2060 as GREET 2022 does not simulate values for 2060.	Calculated

The emission reduction from hybridization is a direct result of the reduced fuel consumption by hybrid vehicles. ICE2.2 allows a combination of fuels and hybrid technology, so long as the total

alternative fuel use is not greater than 100%. ICE provides a pop-up "nag" window to flag such occurrences.

6.3.3 Vegetation Management

Alternative vegetation management in ICE2.2 is based on that in ICE1.0 and unchanged from ICE2.1.

6.3.3.1 Data Sources

Assumptions for fuel used in alternative vegetation management strategies came from state DOTs in Washington and Utah.

Assumptions were based on e-mail survey responses from Washington and Utah DOTs characterizing the current deployment of alternative vegetation management strategies, estimated fuel savings from the use of alternative strategies, and maximum potential deployment of alternative strategies.

6.3.3.2 Calculation Methods, Limitations, and Assumptions

The climate differences between Washington and Utah allow for applying differentiated impacts to states with varying climates.

1. We assumed that Washington, which is a temperate state with a variety of vegetation zones, represents the upper end of energy use and GHG emissions associated with vegetation management and of the possible reductions in energy use and GHG emissions due to alternative vegetation management strategies.
2. We assumed that Utah, which is primarily a desert climate, represents the lower end of energy use and GHG emissions associated with vegetation management and of the possible reductions in energy use and GHG emissions due to alternative vegetation management strategies.

Alternative vegetation management strategies conserve energy by reducing the amount of fuel consumed for maintenance; furthermore, GHG reductions are proportional to fuel reductions. Total energy and emission reductions were calculated as follows:

1. We divided the estimated potential deployment of alternative vegetation management strategies by the current deployment of alternative strategies to calculate the potential increase in deployment of alternative strategies.
2. We multiplied the current reductions in fuel use due to alternative vegetation management strategies by the potential increase in deployment of alternative strategies in order to calculate the total reduction in energy use and GHG emissions due to these strategies.

ICE1.0 placed limits on the maximum deployment increase of a strategy between the baseline and planned scenarios. Those limitations are removed in ICE2.1. In addition, the mitigations are calculated separately for both the BAU and Planned deployment scenario.

6.3.4 Snow Fencing and Removal Strategies

Alternative snow removal strategies in ICE2.2 are identical to ICE2.1 and are taken from that in ICE1.0.

6.3.4.1 Data Sources

Assumptions for fuel used in alternative snow removal strategies (snow fencing, wing plows) came from activities of Washington and Utah state DOTs.

Assumptions were based on e-mail survey responses from Washington and Utah DOTs characterizing the current deployment of alternative snow fencing and removal strategies, estimated fuel savings from the use of alternative strategies, and maximum potential deployment of alternative strategies.

6.3.4.2 Calculation Methods, Limitations, and Assumptions

The climate differences between Washington and Utah allow for applying differentiated impacts to states with varying climates.

1. We assumed that Washington, which typically experiences heavy snowfall in some areas and lighter snowfall in others and which practices snow removal on all state-maintained roads, represents the upper end of the possible reductions in energy use and GHG emissions due to alternative strategies.
2. We assumed that Utah, which experiences heavy snowfall in some areas and lighter snowfall in others, but which only practices snow removal on one percent of state-maintained roads, represents the moderate range of possible reductions in energy use and GHG emissions due to alternative strategies.
3. We assumed that states that do not experience any snowfall do not devote any energy to snow removal, and therefore do not have any potential to reduce the associated energy use and GHG emissions.

Alternative snow management strategies conserve energy by reducing the amount of fuel consumed for maintenance; furthermore, GHG reductions are proportional to fuel reductions.

State DOT estimates of the maximum possible percentage reductions in energy use due to alternative snow management strategies were used for the percentage reductions from these strategies. Where DOT managers supplied reductions estimates in terms of the total fuel used for maintenance, we converted values in order to express these estimates as a percentage reduction of the energy use associated with snow removal.

ICE1.0 placed limits on the maximum deployment increase of a strategy between the baseline and planned scenarios. Those limitations are removed in ICE2.1. In addition, the mitigations are calculated separately for both the BAU and Planned deployment scenario.

6.3.5 In-place Roadway Recycling

6.3.5.1 Data Sources

Data for cold in-place recycling (CIR) and full depth reclamation (FDR) strategies was obtained from a New York State DOT (NYSDOT) report on the energy and GHG reductions associated with different cold in-place recycling methods and mill-and-fill repaving.

Data was also obtained from NCHRP Synthesis 421 on the GHG reductions associated with a variety of in-place recycling techniques, including both cold in place recycling and full depth reclamation.[51]

6.3.5.2 Calculation Methods, Limitations, and Assumptions

Based on the results of the NYSDOT report, which quantified both energy use and GHG reductions, we assumed that the reductions in energy use from in-place recycling were proportional to the reductions in GHG emissions.

To calculate the reductions:

1. We took the average GHG emissions and energy use per lane mile from the various cold in place approaches quantified by the NYSDOT report and compared them to the emissions and energy usage rates from the various mill-and-fill approaches contained in the report in order to calculate percentage reductions due to cold in place recycling.
2. We took the midpoint of the range of GHG reductions identified for various in place recycling techniques surveyed in NCHRP 421.
3. We took the average of the average reduction values from the NYSDOT report and from NCHRP 421.

ICE1.0 placed limits on the maximum deployment increase of a strategy between the baseline and planned scenarios. Those limitations were removed in ICE2.1. In addition, the mitigations are calculated separately for both the BAU and Planned deployment scenario. ICE2.2 continues the approach of ICE2.1 where these effects are included in the operations and maintenance (O&M) energy and emissions values. Thus, they are not broken out in the summary tables or charts displaying results of individual mitigation measures.

6.3.6 Warm-mix Asphalt

6.3.6.1 Data Sources

Data on the mixing temperatures and energy consumption from warm mix asphalt technologies were pulled from Kristjansdottir et al.[52]

6.3.6.2 Calculation Methods, Limitations, and Assumptions

Reductions in fuel and energy use from warm mix asphalt production result in a proportional reduction in GHG emissions.

Kristjansdottir et al reported percentage reductions in energy consumption for four different WMA processes. The midpoint value was used for those processes with a range of reductions reported. From these four processes, the average energy reduction was calculated.

Limitations on the maximum deployment increase of the strategy from ICE1.0 have been removed in ICE2.1. Also, since warm mix asphalt (WMA) and reclaimed asphalt pavement (RAP) cannot be used simultaneously – the use of RAP necessitates high mixing temperatures and thus eliminates the

[51] National Cooperative Highway Research Program (2011). *NCHRP Synthesis 421: Recycling and Reclamation of Asphalt Pavements Using In-Place Methods*. Transportation Research Board of the National Academies.
[52] Kristjansdottir, O., Muench, S., Michael, L., & Burke, G. (2007). "Assessing Potential for Warm Mix Asphalt Technology Adoption." *Transportation Research Record* 2040, 91-99.

benefits of WMA – ICE2.1 includes logic in the mitigation selection that eliminated the possibility of combining these. The tool notifies the user and limits the ability to use both in the same project area.

6.3.7 Recycled and Reclaimed Materials

6.3.7.1 Data Sources

We calculated the percentage reduction in energy use and GHG emissions by adjusting the makeup of asphalt, concrete, and base stone in GreenDOT to include the maximum feasible amount of recycled materials and then comparing them to results for conventional mixes of these materials. We derived information on the applicability and maximum deployment potential for each recycled and reclaimed material as follows:

1. Recycled asphalt pavement (RAP): recycled (or reclaimed) asphalt pavement can substitute for either virgin aggregate or binder in asphalt mixes. According to conversations with paving experts at Caltrans, RAP can act as a substitute for up to 25 percent of virgin aggregates and up to 40 percent of virgin binder. (The average percentage substitution is closer to 20 percent, per surveys by the AASHTO Subcommittee on Materials and the National Asphalt Pavement Association (NAPA)). Use of CIR and FDR may further limit the potential deployment of RAP since these techniques already involve using recycled materials in the roadway surface.
2. Industrial byproducts: certain industrial byproducts (coal fly ash, ground granulated blast furnace slag, and other industrial waste products) can be used as substitutes for GHG- and energy-intensive portland cement in concrete mixes. According to data collected by ICF for Caltrans, which has been a leader in amending specifications to allow for greater use of industrial byproducts in concrete mixes, these byproducts account for 33 percent of cement in the average statewide mix.
3. Recycled concrete aggregate (RCA): recycled concrete aggregate replaces virgin aggregate in intermediate courses or aggregate base courses. Since base courses are typically not subject to detailed technical specifications, we assume that there is no limit on the applicability or potential deployment of this strategy.

The resulting reductions were determined for ICE1.0 and are applied consistently here.

6.3.7.2 Calculation Methods, Limitations, and Assumptions

Limitations on the maximum deployment increase of the strategy from ICE1.0 are removed. Also, since warm mix asphalt (WMA) and reclaimed asphalt pavement (RAP) cannot be used simultaneously – the use of RAP necessitates high mixing temperatures and thus eliminates the benefits of WMA – ICE2.1 includes logic in the mitigation selection that eliminated the possibility of combining these. The tool notifies the user and limits the ability to use both in the same project area.

6.3.8 Pavement Preservation

ICE1.0 considered preventative maintenance/pavement preservation as a mitigation strategy, and simplistically modeled the use of preventative maintenance by reducing the lifecycle emissions and energy associated with roadway infrastructure by 29% and 33% respectively. ICE2.1 maintained the simplicity of ICE1.0 but have updated the approach for pavement preservation. This approach is unchanged in ICE2.2.

Like ICE1.0, pavement preservation is included as a mitigation measure. However, the form has changed, and unlike other Mitigation Strategies tab inputs, two input values are required. These represent the number of years by which Pavement Preventive Maintenance extends road life for the BAU and Planned Deployment cases and the frequency of application of the generic pavement preservation strategy. They are not yes/no questions or percent penetration depth as for the other mitigation strategies.

6.3.8.1 Data Sources

Pavement preservation is a broad category of activities and treatments that can extend the life of pavement. These include crack filling, slurry seals, and chip seals. In ICE2.2 the benefits of pavement preservation strategies are parameterized as increased infrastructure longevity – longer periods between reconstruction and resurfacing maintenance activities, and thus fewer occurrences within the specified lifetime. The user does not need to know the details of a preventative maintenance regime to apply the mitigation and ICE does not estimate the impacts from any specific category of preventative maintenance. Our research found that no national approach for preventative maintenance exists or should be assumed, and that this information would not typically be available for pre-engineering assessments. Instead, the user only enters the number of years by which the preventative maintenance program extends the time for reconstruction.

We conducted a survey of academic and grey literature to estimate the impacts associated with these activities. Our review identified several papers quantifying the impacts of various pavement preservation processes. Table 26 in Appendix A3 details the results of these studies.

Since ICE treats the benefits generically and does not address any specific preservation program, a similar approach was taken to characterize energy and GHG emission cost from a generic pavement preservation application. We will obtain the default factor by averaging the energy and GHG emission factors presented in Table 26 in Appendix A3, omitting the outlying Torres-Machi data.[53] These factors are considered representative for a generic, average pavement preservation application. Table 18 shows the ICE2.2 emissions and energy factors associated with pavement preservation application.

Table 16. Pavement Preservation Factors

Category	Factor	Value	Units
Pavement Preservation	Emissions Factor	0.000028	million BTUs per S.F.
	Energy Factor	0.000507	metric tonnes per S.F.

Given the challenges and uncertainties associated with characterizing and implementing pavement preservation strategies, future revisions to ICE could benefit by additional research on custom lifecycle values and detailed plans for pavement preservation across the country. The user should also refer to the FHWA LCA Pave Tool.[2]

[53] See "Improvements to the Infrastructure Carbon Estimator (ICE): Task 3: Final Literature Review, New Infrastructure Features, and Mitigation Memo" to ICE Tool Update Oversight Group Panel from Andrew Fraser, Mikhail Chester, ASU, Seth Hartley, Jeff Ang-Olson, Jeffrey Rosenfeld, and Tommy Hendrickson, ICF, January 28, 2019. That memo includes the data and reference cited here.

Appendices

A1. Updated Materials Energy and Emissions Factors

A1.1. Aggregate

Table 19 details the impacts of various aggregates identified in EPDs for the United States and Canada.

Table 17: Aggregate Cradle-to-Gate Emission and Energy Use

Material	Specific Type	Use	kg CO_2eq per metric tonne	Thousand BTUs per metric tonne	Location	Source	Year
Aggregate	5/8 Crushed (CSTC)	Subbase	3.61	81.3	Seattle, WA	Kangley Rock & Recycling (2)	2018
	1 1/4 CSBC	Subbase	4.59	99.0			
	ASTM 467 (1 1/2" Recycled	Not Specified	6.32	129.1			
	2" x 4"	Concrete Aggregate	6.46	132.5			
	2" X 3/4 RC Ballast	Not Specified	4.49	96.8			
	2" Minus Recycled Gravel Barrow	Concrete Aggregate	6.87	138.8			
	4"x 8"	Concrete Aggregate	3.12	72.2			
	#57 Gravel	Concrete Aggregate	1.55	32.4	Vancouver, BC	Polaris Materials (3)	2017
	#7 Gravel	Concrete Aggregate	1.55	32.2			
	Rock Dust	Asphalt Aggregate	5.72	97.5	Pleasanton, CA	Vulcan Materials (4)	2017
	1/2" Crushed	Asphalt Aggregate	5.65	96.3			
	3/4" Crushed	Asphalt Aggregate	5.63	96.0			
	3/8" Crushed	Asphalt Aggregate	5.75	98.0			
	Class II Base	Subbase	5.31	90.0			
	Crushed Class II Perm	Permeable Drainage	5.26	89.3			
	Class II Perm	Permeable Drainage	4.5	75.7			
	1" x #4	Concrete Aggregate	4.43	74.4			
	3/4" x #4	Concrete Aggregate	4.48	75.4			
	3/8" Pea Gravel	Concrete Aggregate	4.61	77.7			

Sand	WCS	Concrete Sand	1.65	37.5	Vancouver, BC	Polaris Materials (3)	2017
	Manufactured (MFG) Sand	Asphalt Aggregate	7.49	128.8	Pleasanton, CA	Vulcan Materials (4)	2017
	Top Sand	Ready Mix	4.87	82.1			

To differentiate between concrete, reinforced concrete, and cement, ICE2.1 uses mix ratios to represent these three concrete types. Table 20 shows these mix ratios.

Table 18: Mix ratios for different types of concrete

	Concrete	**Reinforced Concrete**	**Cement Treated Aggregate**[54]
Asphalt Aggregate	0	0	0
Concrete Aggregate	0.405	0.395	0.853
Subbase Aggregate	0	0	0
Sand	0.37	0.358	0
Cement	0.155	0.15	0.074
Steel	0	0.025	0
Water	0.07	0.072	0.074
Bitumen	0	0	0

A1.2. Cement

Table 21 shows average factors for Cement from EPDs for the United States.

Table 19: Cement Cradle-to-Gate Emission and Energy Use

Material	**Type**	**kg CO_2eq per metric tonne**	**Thousand BTUs per metric tonne**	**Location**	**Source**	**Year**
Cement	Blended Hydraulic Cement[55]	892	4969.8	US Average	Portland Cement Association(5)	2016
Cement	Portland Cement	1040	5579.8	US Average	Portland Cement Association(6)	2016

A1.3. Precast Concrete

While not included in ICE1.0 the review of EPDs for cement also returned EPDs for precast concrete structures including concrete pipes, box culverts, manholes, and catch basins. ICE2 also does not include these factors, although they are useful to validate prototypes and for future updates to infrastructure elements such as box culverts.

Table 20: Precast Concrete Cradle-to-Gate Emission and Energy Use

[54] Cement Treated Aggregate is also known as Cement Treated Base. It is an alternative material sometimes used as a subbase for roadways.

[55] Blended Hydraulic Cement contains 1.3% fly ash. It is intended as a lower impact PC alternative that could be included in the analysis. ICF has also identified resources for fly ash and could possibly be included in ICE, although it would require further adjustments to the material volumes defining concrete, and thus additional parameters and calculations in the tool.

Material	Type	kg CO_2eq per metric tonne	Thousand BTUs per metric tonne	Source	Year
Precast Concrete	Structural	299.7	2483.5	Canadian Precast/Prestressed Concrete Institute, National Precast Concrete Association & Precast/Prestressed Concrete Institute members (7)	2015
	Box	181	2145.9	Canadian Precast Pipe and Precast Association (8)	2018
	Pipe	221	2761.9		2017
	Manhole & Catch Basin	185	1960.1		2017
	Box, Pipe, Manhole, Catch Basin	259.6	2249.5	Canadian Precast/Prestressed Concrete Institute, National Precast Concrete Association & Precast/Prestressed Concrete Institute members (9)	2015

A1.4. Steel

Table 23 shows values of energy and emissions factors for steel from relevant EPDs.

Table 21 :Steel Cradle-to-Gate Emission and Energy Use[56]

Material	Type	kg CO_2e per metric tonne	Thousand BTUs per metric tonne	Location	Source	Year
Steel	Hot-Dip Galvanized Hot Rolled Structural Steel [previously 'Structural Steel – Galvanized in ICE1.0]	1460	18470	North America	American Galvanizers Association[57]	2016
Steel	Hot-Dip Galvanized Steel Plate [previously 'Steel play – Galvanized' in ICE1.0]	1770	21920			
Steel	Hot-Dip Galvanized Hollow Structural Sections [Previously 'Hollow Structural Steel – Galvanized' in ICE1.0]	2660	30680			
Steel	Fabricated Steel Plate [Previously 'Steel Plate – Ungalvanized' in ICE1.0]	1470	17810	United States	American Institute of Steel Construction[58]	2016
Steel	Fabricated Hot-Rolled Structural Sections [Previously 'Structural Steel - Ungalvanized' in ICE1.0]	1160	17810	United States	American Institute of Steel Construction[59]	2016
Steel	Fabricated Hollow Structural Sections [Previously 'Hollow Structural Steel - Ungalvanized' in ICE1.0]	2390	26750	United States	American Institute of Steel Construction[60]	2016
Steel	Corrugated Steel Conduits	2260	28280	Canada	Corrugated Steel Pipe Institute	2018

A1.5. Aluminum

Table 21 shows values of energy and emissions factors for aluminum from relevant EPDs.

Table 22. Aluminum Cradle-to-Gate Emission and Energy Use

Material	Type	kg CO_2eq per metric tonne	Thousand BTUs per metric tonne	Source	Year
Aluminum	Cold-rolled Aluminum	5330	80280	The Aluminum Association (46)	2011

A1.6. Water

Table 22 shows values of energy and emissions factors for water from relevant EPDs.

Table 23: Water Cradle-to-Gate Emission and Energy Use

Material	Type	kg CO_2eq per metric tonne	Thousand BTUs per metric tonne	Location	Source	Year
	California Statewide Mix	0.59	4.4	California	Stokes-Draut et al. (21)	2010

[56] Note that these steel parameters already include recycled content. EPDs for rebar list around 97-98% recycled iron while light structural shapes and Merchant Bar are manufactured from 100% scrap steel sourced in U.S.
[57] American Galvanizers Association. Hot-dip Galvanized Steel after Fabrication. Centennial, CO; 2016.
[58] American Institute of Steel Construction. Fabricated Steel Plate. Chicago, Il; 2016.
[59] American Institute of Steel Construction. Fabricated Hot-Rolled Structural Sections. Chicago, Il; 2016.
[60] American Institute of Steel Construction. Fabricated Hollow Structural Sections. Chicago, Il; 2016.

Water	Imported water	1.1	17.1	California	Stokes & Horvath (20)	2009
	Desalinated ocean water, conventional pretreatment	2.5	39.8			
	Desalinated ocean water, membrane pretreatment	2.4	38.9			
	Desalinated brackish ground water	1.7	25.6			
	Recycled Water	1.0	16.1			
	Maximum	3.4	-	Europe	Meron et al. (19) (meta-analaysis)	2016
	Minimum	0.16	-			
	Average	0.85	-			
	Median	0.38	-			
	Maximum	6.7	-	Europe (Italy, Netherlands, Switzerland, Belgium, Average), South Africa, United States, Australia, Vietnam	Fantin et al. (18)	2014
	Minimum	0.1	-			
	Average	0.85	-			
	Median	0.4	-			

A1.7. Bitumen

Table 26 shows literature values for bitumen factors.

Table 24: Bitumen Cradle-to-Gate Emission and Energy Use

Material	kg CO_2eq per metric tonne	Thousand BTUs per metric tonne	Type	Location	Source	Year
Asphalt Binder	430.11	-	EPD/Grey	U.S. Average	Mukherjee(22)	2016
	509.3	5506.8	Thesis	East Coast	Yang(29)	2014
	324.1	4388.4	Thesis	Mid-West		
	378.1	4729.6	Thesis	Gulf Coast		
	250.6	4198.8	Thesis	Rockies		
	359.4	4919.2	Thesis	West		
	400.1	5156.1	Thesis	U.S Average		
	329.6	5686.8	Grey	Finland	Häkkinen, Mäkelä (24)	1996
	173.1	3445.7	Grey	Sweden	Stripple(25)	2001
	525.8	5216.6	Grey	Canada	Athena (26)	2001
	189.6	2744.7	Grey	Europe	Eurobitume (27)	2011
	374.8	4708.9	LCI Database	Europe	Ecoinvent (28)	2007

A1.8. Timber

Timber is a material category included in ICE1.0 but not used. It is not included in ICE2.1. However, EPD's for several types of wood used in construction were developed by the American and Canadian Wood Councils and identified. These are shown in Table 27.

Table 25: Timber Cradle-to-Gate Emission and Energy Use

Material	Type	kg CO_2e per metric tonne	Thousand BTUs per metric tonne	Source	Year
Wood	North American Softwood Lumber	167.54	6267.3	American Wood Council and Canadian Wood Council (30–32)	2011
Wood	Plywood	264.21	10889.1		
Wood	Glued Laminated Timber (Glulam)	370.75	10355.8		

A1.9. Soil

Similar to timber, soil was included as a primary material in ICE1.0 but not used. It is not included in ICE2.1. No factors were researched for this material.

A1.10. Fuel Use Factors

Table 25 shows the fuel usage factors by process category underlying ICE. These fuel usage factors are derived from survey responses of actual fuel usage during various construction processes.

Table 26: Fuel Usage Factors used in ICE

Category	Item of Work	Units	FUF
Clearing and Removal	Clearing	Gallons/Acre	191.2
	Pipe Removal	Gallons/L.F.	0.863
	Pavement Removal - Asphalt	Gallons/C.Y.	1.397
	Pavement Removal - Concrete	Gallons/C.Y.	0.562
	Structure Demolition (House/Building)	Gallons/Each	375
	Structure Demolition (Bridge per S.F. of Deck)	Gallons/S.F.	0.626
Excavation	Excavation - Earth - Off Road - Long Haul	Gallons/C.Y.	0.32
	Excavation - Earth - Off Road - Short Haul	Gallons/C.Y.	0.263
	Excavation - Earth - On Road - Long Haul	Gallons/C.Y.	0.687
	Excavation - Earth - On Road - Short Haul	Gallons/C.Y.	0.319
	Excavation - Rock - Off Road - Long Haul	Gallons/C.Y.	0.402
	Excavation - Rock - Off Road - Short Haul	Gallons/C.Y.	0.311
	Excavation - Rock - On Road - Long Haul	Gallons/C.Y.	0.74
	Excavation - Rock - On Road - Short Haul	Gallons/C.Y.	0.465
	Strip Topsoil	Gallons/C.Y.	0.167
	Roadway Finishing	Gallons/S.Y.	0.073
Base Stone	Base Stone - Short Haul (Haul and Place)	Gallons/Ton	0.406
	Base Stone - Long Haul (Haul and Place)	Gallons/Ton	0.558

Category	Item of Work	Units	FUF
Asphalt	Asphalt Production (Diesel)	Gallons/Ton	2.04
	Asphalt Production (Natural Gas)	Gallons (GGE)/Ton	2.144
	Asphalt Production (Natural Gas) (Support Equipment)	Gallons/Ton	0.09
	Warm Mix Asphalt Production (Diesel)	Gallons/Ton	1.632
	Warm Mix Asphalt Production (Natural Gas)	Gallons (GGE)/Ton	1.715
	Warm Mix Asphalt Production (Natural Gas) (Support Eqp.)	Gallons/Ton	0.072
	Asphalt Hauling (0-5 miles)	Gallons/Ton	0.183
	Asphalt Hauling (6-15 miles)	Gallons/Ton	0.293
	Asphalt Hauling (>15 miles)	Gallons/Ton	0.514
	Asphalt Placement	Gallons/Ton	0.273
Milling	Milling - 0-1" (0-5 mile haul)	Gallons/Ton	0.028
	Milling - 0-1" (6-15 mile haul)	Gallons/Ton	0.03
	Milling - 0-1" (>15 mile haul)	Gallons/Ton	0.038
	Milling - 2-4" (0-5 mile haul)	Gallons/Ton	0.062
	Milling - 2-4" (6-15 mile haul)	Gallons/Ton	0.071
	Milling - 2-4" (>15 mile haul)	Gallons/Ton	0.09
Structures	Reinforcing Steel	Gallons/Lbs.	0.004
	Steel Beams	Gallons/L.F.	0.18
	Substructure Concrete	Gallons/C.Y.	4.7
	Superstructure Concrete	Gallons/C.Y.	4.15
	Bridges	Gallons/Contract $	5.2
	Bridges (per S.F. of deck)	Gallons/S.F.	0.616
Misc. Concrete	Concrete Production (Support Equipment)	Gallons/C.Y.	0.09
	Concrete Hauling - Short Haul	Gallons/C.Y.	0.6
	Concrete Hauling - Long Haul	Gallons/C.Y.	1.1
	Concrete Placement	Gallons/C.Y.	0.267
	Concrete Curb/Gutter	Gallons/L.F.	0.152
	Concrete Sidewalk	Gallons/S.F.	0.09
	Retaining Wall (Cast in Place)	Gallons/S.F.	0.646
	Noise Wall (Pre-Cast)	Gallons/S.F.	0.304
	Concrete Median Barrier	Gallons/L.F.	0.309
Drainage Pipe and Structures	Large Pipe Crew	Gallons/L.F.	4.338
	Medium Pipe Crew	Gallons/L.F.	1.481
	Small Pipe Crew	Gallons/L.F.	0.871
	Drainage Structures	Gallons/Each	26.175
Specialty Items	Fence Gates	Gallons/Each	4.2
	Fencing	Gallons/L.F.	0.043
	Grassing (Hydro Seeding)	Gallons/Acre	3.497
	Grassing (Seedbed Preparation)	Gallons/Acre	10
	Sodding	Gallons/S.Y.	0.017
	Guardrail Posts	Gallons/Each	0.042
	Guardrail - Steel	Gallons/L.F.	0.037

Category	Item of Work	Units	FUF
	Guardrail - Wire/Cable	Gallons/L.F.	0.105
	Intersection Signalization (2 Lane)	Gallons/Each	170
	Intersection Signalization (4 Lane)	Gallons/Each	304
	Pavement Marking	Gallons/L.M.	4.5

Source: Skolnik J, Brooks M, Oman J. Fuel Usage Factors in Highway and Bridge Construction. Vol. 744. Transportation Research Board; 2013.

A1.11. Pavement Preservation Factors

We conducted a survey of academic and grey literature to estimate the impacts associated with pavement preservation activities. Our review identified several papers quantifying the impacts of various pavement preservation processes. Table 26 details the results of these studies.

Table 27: Pavement Preservation Emission and Energy Use.[61]

Description	kg CO_2eq/m^2	Thousand BTUs/m^2	Type	Location	Source	Year
Slurry Seal	0.33	13.77	Thesis	Not Specified	Gangaram (35)	2014
Chip Seal	0.46	15.36				
Crack Seal	0.06	0.09				
Crack Seal	0.17	1.45	Academic Literature	Nevada	Robinette & Epps (36)	2010
Slurry Seal	0.72	1.22				
Crack Seal	2.54		Academic Literature	Chile	Torres-Machi, Chamorro, Pellicer, Yepes, & Videla (37)	2015
Slurry Seal	6.65					
Single Chip	2.8					
Double Chip	2.54					
Crack Seal (.37m/m^2)	0.08	1.00	Academic Literature	Average	Chehovits & Galehouse (38)	2010
Crack Fill (.74m/m^2)	0.14	1.80				
Slurry Seal/Microsurfacing Type III, 12% Emulsion (13kg/m^2)	0.30	6.20				
Slurry Seal/Microsurfacing Type II, 14% Emulsion (16kg/m^2)	0.20	4.60				
Chip Seal Emulsion 2.0L/m^2, Aggregate 21 kg/m^2	0.50	8.40				

[61] Values defined by Gangaram and Toreres-Machi et al. were defined per lane-mile and per lane-kilometer respectively. A standard lane width of 3.6 meters (11.8 feet) was assumed to normalize their results to square meters.

Chip Seal Emulsion 1.6L/m^2, Aggregate 15 kg/m^2	0.40	6.10				

There is reasonable consistency across three separate studies and one study where the values defined for maintenance strategies seem to be outliers.[62, 63, 64, 65] Close inspection of Torres-Machi et al. could not identify a cause(s) of the discrepancy. Across the studies, Chehovits & Galehouse stands out as the most complete and highly cited piece of literature in the space of pavement preservation. The factors above are all per unit area of roadway.

A2. Tool Changes from version 2.0.2 to version 2.1

Version 2.0.2 was released November 1, 2019. This was the complete release version of ICE2.0. In 2020, ICF also updated ICE to be section 508 compliant and a small number of other corrections and improvements. This appendix lists the changes from version 2.0.2 to version 2.1.

Updates to version 2.0.2 of the tool largely revolved around adding aesthetic and functional modifications in line with 508 compliance guidance. The updates to the tool make it more accessible for people with disabilities and included:

1. Modifying charts to have individual data labels that include both the amount and series name.
2. Changed the foreground/background contrast on all command button, to indicate on, off, or disabled.
3. Changed the name of the file, to include the full name of the tool.
4. Added a "title" to the document properties.
5. Updated the link on the Introduction tab to include the name of the tool in the user's guide title.
6. Added the ability for users to toggle on/off 508 compliance formatting, this toggle was added to the Project Inputs tab and to the Print tab.
7. Added tab headers to all worksheets.
8. Changed the properties of all command buttons and charts so that when the user views the model at a very high zoom factor the objects do not move.
9. Added alternative text was to all charts and non-decorative images.

This update also included a small number of changes not related to Section 508 compliance. Those were

10. Simplification of the treatment of Culverts in Planning Mode to be consistent with comments on discrepancies between the level of detail requested by the tool and data available in planning operations.

[62] Gangaram R. Energy and emission impact quantification of pavement preservation using life cycle assessment. Rutgers University-Graduate School-New Brunswick; 2014.
[63] Robinette C, Epps J. Energy, emissions, material conservation, and prices associated with construction, rehabilitation, and material alternatives for flexible pavement. Transp Res Rec. 2010;2179(1):10–22.
[64] Torres-Machí C, Chamorro A, Pellicer E, Yepes V, Videla C. Sustainable pavement management: Integrating economic, technical, and environmental aspects in decision making. Transp Res Rec J Transp Res Board. 2015;(2523):56–63.
[65] Chehovits J, Galehouse L. Energy usage and greenhouse gas emissions of pavement preservation processes for asphalt concrete pavements. In: Proceedings on the 1st International Conference of Pavement Preservation. 2010. p. 27–42.

11. Updating the medium-sized sign to include two steel posts rather than the wooden posts listed in ICE2.0. Wood is not a material included in ICE (Appendix A1).

Finally, additional quality assurance of the tool based on user feedback was performed.

Version 2.1.1 was released 14 September 2020. This version made a correction to the reporting of GHG emissions in non-native units and made several small unit fixes to the calculations, including: fixing a calculation error in applying fuel use factors to materials; fixing a mismatch between metric and short tons in some material amounts; correcting a calculation error in "custom" applications of the Bridges and Overpasses done using the Project mode; and resolving an issue that kept the user's notes from being presented on the Print Results tab.

A3. Tool Change Summary from version 2.1 to version 2.2

The following is a high-level summary of the tool changes incorporated into version 2.2 of ICE. Details on thes are presented throughout this User's Guide.

1. Add Interchanges as a New Infrastructure Category
2. User Interface and Related Technical Changes, including adding graphics and reorganizing presentation of information and comments to guide users.
3. Changes to Roadway Rehabilitation in Short Term Projects
4. New factors from MOVES3 extend the calculation period for use-phase through 2060 and fix an issue identified in ICE2.1 for use phase emissions calculations past the end of the available data period.
5. Vehicle use-phase emissions and other analysis period extended to year 2060. We also identified and corrected an issue identified in ICE2.1 for use phase emissions calculations past the end of the available data period.
6. Lifecycle emission factors and energy consumption were developed for different transportation fuels, for usage in the tool as both default fleet fuels and for mitigation strategies. ICE2.2 adds several new alternative fuels for mitigation.
7. GREET factors for fuels and vehicles all updated to GREET 2022 to derive full lifecycle energy and emissions factors for light-duty, heavy-duty, and construction/off-road heavy-duty vehicles.
8. Lifecycle Emission Factors and Energy consumption were developed for electricity on a state-by-state basis and for projected period in the tool.
9. Modified Use Phase Emissions to accept external emissions calculations. This updated approach also allows input in either full-lifecycle or tailpipe values, with the ability to convert between the two options to accommodate different input and reporting approaches.
10. Use phase emissions allows separate light and heavy vehicle categories if using ICE calculations. Also reduces the number of years required for input from three to two.
11. Construction delay approach updated to correct a calculation issue. New approach isolates GHG emissions from construction-impacted VMT and multiplies this by the construction duration.
12. Updated Mitigation Calculations to add new fuels and adjust the impacts of electricity to be state-specific.
13. Multiple changes to internal tool operations to update methodologies and correct identified issues in ICE2.1.
14. Multiple changes to default values and approaches presented to users, including default approach for use phase, limiting presentation of results by material to individual infrastructure

types, and advancing summary table of results by infrastructure type to top of Summary Results to emphasize importance of different infrastructure.
15. Updated roadway rehabilitation maintenance schedule approach.
16. Updated reporting units to MMT (millions of metric tonnes) consistent with common reporting.

A4. Advanced Customization

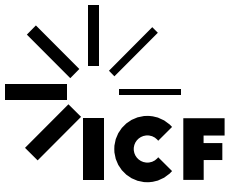
ICE2.1 included a completely reworked structure and functionality of the tool since ICE1.0. One part of that reorganization was the creation of a single tab that assembles all factors used in the calculations and the ability to overwrite those values with custom values if available. This was designed to also facilitate future updates by collecting factors that may be updated, for example when more advanced LCAs are available for a material. This new feature was requested by Panel members and discussed throughout the development process.

However, in practice many users found that while the *Advanced Customization* tab was interesting, it was of limited use. Concern was raised over where users would get local or updated values to use here, even though they recognized its utility to agencies interested in this level of detail. Some reviewers expected that access to this Advanced Customization tab would create confusion for the majority of users who input local or custom factors for building materials, users would need significant detail about system boundary assumptions to create framework for translating information from Environmental Product Declarations, and it would be easy for users with limited LCA experience to overlook details and enter values that would double-counted or omit certain processes.

Given the central aspect this tab plays in the tool's functionality, it's critical nature to future updates, and the potential need for the tool's manager to override default factors after release, it remains included in ICE2.2, but is locked from the user until further guidance is available on how to obtain and use relevant state- or locally specific values and guidance on appropriate system boundaries and underlying assumptions for the current factors is available.

A5. Documentation of Relevant other Tools

See attached memorandum: Final memo on ICE and other Lifecycle Models, to ICE Tool Oversight Group Panel, from Seth Hartley and Ramon Molina Garcia, ICF, January 3, 2023.



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