



FHWA Infrastructure Carbon Estimator Final Report and User's Guide

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16. Abstract This study developed a method of estimating energy and GHG emissions from construction and maintenance of transportation systems. Designed as a spreadsheet-based model for practitioners, FHWA's Infrastructure Carbon Estimator is based on data collected from state DOTs, a nationwide database of construction bid documents, and consultation with transportation engineers and lifecycle analysis experts. The new tool improves upon previously available methods, which often require complex inputs or are based on outdated research. The Estimator allows users to create "ballpark" estimates of energy and GHG emissions using limited data inputs. This approach allows the tool to be used in transportation planning processes before details about specific facility dimensions, materials, and construction practices are known. The User's Guide component of this document provides a step-by-step guide to using the tool. Detailed instructions and explanations of key input parameters are also provided in the tool itself.		

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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. One study estimates that energy from construction and maintenance activities is equivalent to nearly one-third of the energy used by light-duty cars and trucks traveling on the roadways, when prorated on a per vehicle lifetime basis.¹ However, assessments of energy and GHG emissions from transportation typically focus on the energy and fuel used by vehicles in travel. 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.²

Some state Departments of Transportation (DOTs) and metropolitan planning organizations (MPOs) have already estimated construction and maintenance emissions of their long range transportation plans and of individual projects, for inclusion in Environmental Impact Statements (EISs). But the methods used have generally been simplistic.

This study developed the Infrastructure Carbon Estimator, a spreadsheet model to estimate lifecycle energy and GHG emissions from transportation infrastructure. Designed as a spreadsheet-based system, the Estimator is based on data collected from state DOTs, a nationwide database of construction bid documents, and consultation with transportation engineers and lifecycle analysis experts. The new tool improves upon previously available methods, which generally require complex data inputs or are based on limited and outdated research. The Estimator is designed to allow users to create “ballpark” estimates of energy and GHG emissions using limited data inputs. It avoids asking for 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 processes, before details about specific facility dimensions, materials, and construction practices are known. The tool is not appropriate to inform engineering analysis and pavement selection.

State DOTs and MPOs can use the Estimator for planning level analysis to help answer the following types of questions:

- *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?
- *Transportation Emission Reduction Strategies:* How do emissions generated by constructing projects compare with the operational emissions that those projects are expected to reduce? What is the payback period for the measure to generate a net reduction in emissions?

¹ Estimate adapted from Chester, Mikhail, Life-cycle Environmental Inventory of Passenger Transportation in the United States, Institute of Transportation Studies, Dissertations, University of California, Berkeley, 2008.

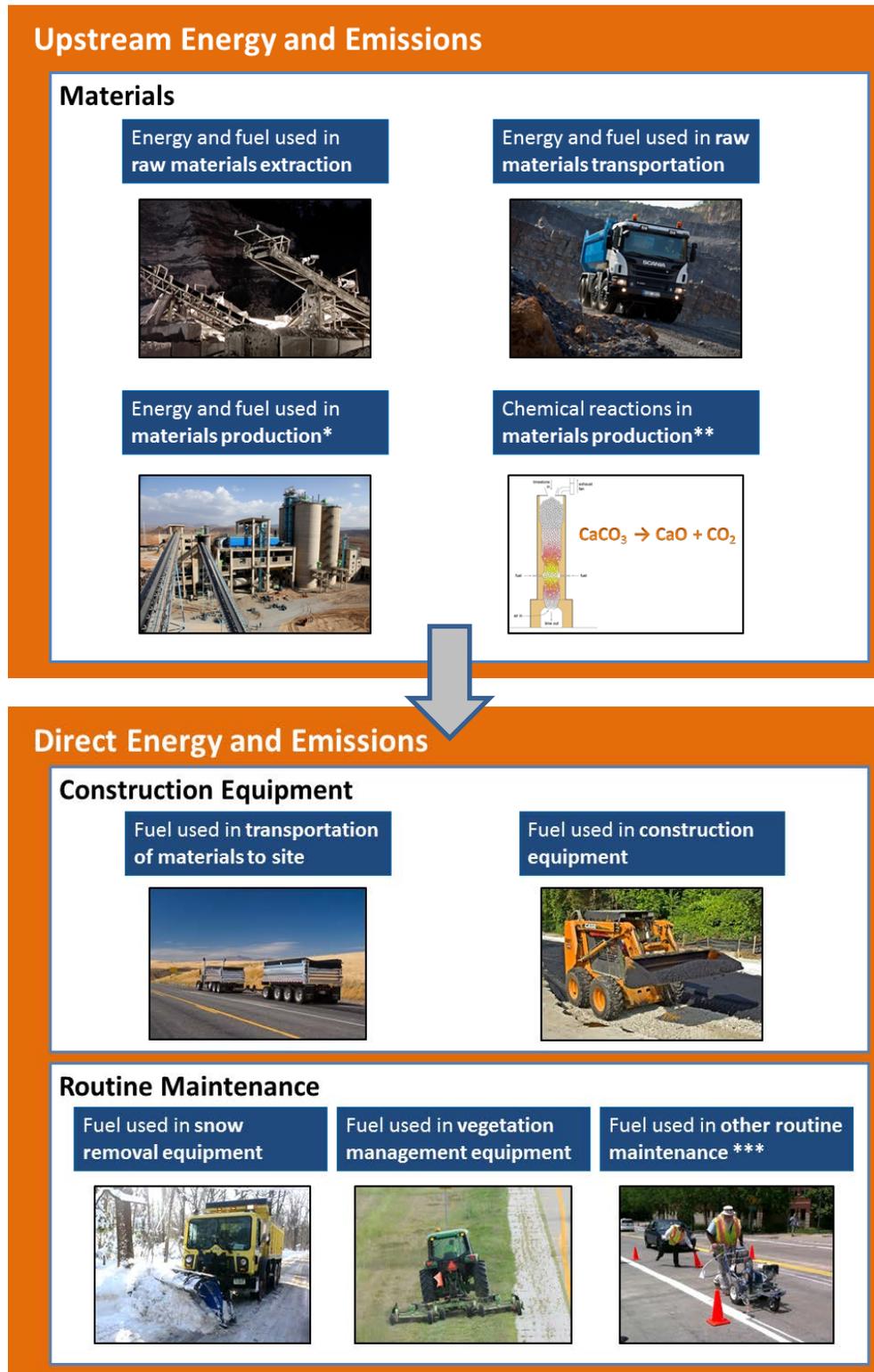
² Office of Highway Policy Information. Highway Statistics 2012 (Report). Federal Highway Administration. <https://www.fhwa.dot.gov/policyinformation/statistics/2012/>.

- *Construction & Maintenance Mitigation Measures:* What types of strategies are most effective to reduce energy use and GHG emissions in construction and maintenance? How much can mitigation measures reduce emissions relative to the total?

The Estimator takes a lifecycle approach to accounting for energy use and emissions. Figure ES1 shows the upstream and direct activities included in the factors used to estimate impacts. The activities and emission sources covered include:

- Construction/Rehabilitation – Construction of a new facility or rehabilitation of an existing facility, including reconstruction and repaving.
 - 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 crack sealing.
 - Construction equipment and transportation – Fuel used in maintenance equipment.
- Facility Use (partial) –
 - Efficiency gains from pavement smoothness – Fuel saved in vehicles traveling on recently improved roadway surfaces.

Figure ES1: Components included in lifecycle 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

The Estimator accepts project inputs for roadways, parking facilities, bridges, rail and bus rapid transit infrastructure, and bicycle and pedestrian facilities. Project types accepted vary by facility type, but generally include both new construction and repair or upgrading of existing facilities. A complete list of facility and project types accepted is provided in Table ES1.

Table ES1: Facility types and construction/rehabilitation activities included in tool

Category	Facility type	Project type
Roadways	Rural interstates Rural principal arterials Rural minor arterials Rural collectors Urban interstates / expressways Urban principal arterials Urban minor arterials / collectors	Roadway construction New facility Re-alignment Construct additional lane Lane widening Shoulder improvement Roadway rehabilitation Re-construct pavement Resurface pavement
Parking	Surface parking Structured parking	New construction
Bridge structures	Single-span Two-span Multi-span (over land) Multi-span (over water)	New construction Reconstruction Lane addition
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)
Bus rapid transit	BRT lane or right-of-way BRT station	New construction Convert/upgrade lane
Bicycle	Off-street paths On-street bicycle lanes	New construction Resurfacing Restriping (on-street only)
Pedestrian	Off-street paths On-street (sidewalks)	New construction Resurfacing (off-street only)

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:

- Alternative fuels and vehicle hybridization
- Alternative vegetation management
- Alternative snow management

- In-place roadway recycling
- Warm mix asphalt
- Recycled and reclaimed materials
- Preventive maintenance

FHWA used the tool to estimate the impacts for a hypothetical project to add a truck climbing lane to a four-mile stretch of highway on mountainous terrain with three lanes in each direction in order to reduce occasional congestion associated with slowly-climbing trucks. This example project would also involve rebuilding and widening overpass bridges at two points along the project site. Additionally, FHWA used EPA's Motor Vehicle Emissions Simulator (MOVES) to calculate the reduction in GHG emissions resulting from reduced congestion for vehicles traveling along this section of highway.

Using the Estimator, FHWA calculated a construction and maintenance impact of 94 MT per year over 20 years, or 1880 MT total, from the project. Using MOVES, FHWA calculated a reduction in vehicle operational emissions of 325 MT per year. Thus, it would take over 5 years of operational energy savings from reduced congestion to offset the construction and maintenance impact of the project.

The User Guide component of this document provides a step-by-step guide to using the Infrastructure Carbon Estimator. Detailed instructions and explanations of key input parameters are also provided in the tool itself.

1. Introduction to Planning-Level Analysis of Construction and Maintenance

The impacts of the transportation system on energy use and greenhouse gas (GHG) emissions are increasingly important to transportation planners and decision makers. Climate action plans (CAPs) routinely analyze the potential to reduce fuel use and GHG emissions from on-road transportation as well as other modes. Some state departments of transportation (DOTs) and metropolitan planning organizations (MPOs) have goals to reduce energy and GHG emissions from transportation. Until recently, these impacts were considered mainly with regard to the operation of the transportation system: energy used in vehicles traveling on roadways and emissions from their tailpipes. However, the construction of transportation systems also uses energy and produces GHG emissions. Materials used, 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 sources of energy use and GHG emissions must be considered to make a full account of the transportation system's impacts.

Traditional transportation air quality analysis does include construction equipment, but only short-lived, localized impacts of pollutants like particulate matter are considered. These impacts only last for the duration of the construction project, as carbon monoxide and other criteria pollutants break down quickly in the atmosphere. In contrast to these traditional pollutants, GHG emissions' impacts are cumulative. GHG emissions persist in the atmosphere for decades. 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.

Energy and emissions associated with constructing and maintaining transportation systems are an important component of the total impact of transportation. For example, constructing and maintaining transportation infrastructure used by light-duty cars and trucks uses almost one-third as much energy as the vehicles themselves, when prorated on a per vehicle lifetime basis.³ The GHG emissions impacts of construction and maintenance are roughly proportional to the energy impacts. Estimating impacts from construction and maintenance ensures that the total impacts of transportation strategies are accounted for. CAPs often analyze the potential for transportation projects to reduce energy use and emissions once operational, but the initial use of energy to construct projects should be incorporated in analyses as well.

Some transportation agencies are already analyzing energy and GHG emissions in construction and maintenance. For example, MPOs in New York State have included this type of analysis in their long range transportation plans. The Oregon and Washington state DOTs included an analysis of the GHG emissions impacts of the Columbia River Crossing project in the Environmental Impact Statement (EIS) for that project. To date these analyses have been relatively simplistic and based on emissions factors developed many years ago. The primary challenges associated with existing methods are:

³ Estimate adapted from Chester, Mikhail, Life-cycle Environmental Inventory of Passenger Transportation in the United States, Institute of Transportation Studies, Dissertations, University of California, Berkeley, 2008.

- *Complex input data requirements* – Existing estimation methods require detailed inputs about the tons of materials and hours of equipment used in construction. This information is only available when project engineering and design is completed, and can be difficult to obtain even then.
- *Assumptions based on limited research* – Existing estimation methods have generally been based on data from a small sample of projects.
- *Assumptions based on outdated research* – Existing estimation methods have generally been based on data that are decades old, and do not capture more recent changes in construction methods, materials, and equipment.

The FHWA Infrastructure Carbon Estimator is designed for a planning-level analysis of the energy and GHG emissions impacts of constructing and maintaining transportation systems. 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 facility design and construction parameters. A planning level analysis necessitates the use of high level estimates of construction activity in terms of lane miles or track miles. It is appropriate to analyze decisions that are made in the long range planning process or project development process, before details about specific facility dimensions, materials, and construction practices are known.

The Estimator 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 analyzes the decision to build or not build a certain type of facility, such as a freeway, bike path, or subway station. Specifically, the planning level analysis in the Estimator can help answer the following types of questions:

- *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?
- *Transportation Emission Reduction Strategies:* How do emissions generated by constructing projects compare with the operational emissions that those projects are expected to reduce? What is the payback period for the measure to generate a net reduction in emissions?
- *Construction & Maintenance Mitigation Measures:* What types of strategies are most effective to reduce energy use and GHG emissions in construction and maintenance? How much can mitigation measures reduce emissions relative to the total?

1.1 Project History

The Infrastructure Carbon Estimator is the product of extensive research, data analysis, and stakeholder consultation. The core tasks in the project comprised:

- *Literature Review* – The research team reviewed the literature on existing methods to estimate energy use and GHG emissions associated with construction equipment, materials, and maintenance activities, as well as limited operational impacts of roadway construction and

maintenance due to construction delay and improvements to roadway smoothness. Literature on the energy and GHG benefits of alternative construction and maintenance practices were also reviewed. Finally, a sample of planning and programming documents from transportation agencies were reviewed to determine key categories that could be used as inputs in the Estimator.

- *Development of Estimation Methodology* – Based on information gathered in the literature review, the research team proposed categories of inputs in the calculator tool. The team then developed a series of methodologies that could be used to quantify energy and GHG emissions impacts of construction and maintenance using existing research as well as original analysis of primary data. (More information on these methodologies is provided in Section 5 and in the Appendix).
- *Data Analysis* – The research team applied the methodologies designed to develop a series of energy and emissions factors that drive results in the Estimator. Additional research was conducted to quantify the potential impact of strategies that mitigate energy use and GHG emissions in construction and maintenance, and cost estimates for these practices were created.
- *Design of the Estimator* – An Excel-based calculator tool was designed to provide a user interface that collects inputs and presents the analysis of energy and emissions impacts in a series of discrete steps. The tool was piloted by several state DOTs and MPOs, and feedback from these agencies was incorporated in a revised tool.

An extensive group of stakeholders have guided the research and development of the tool. Key contributors have included:

- FHWA Office of Environment, Planning, and Realty
- FHWA Office of Infrastructure
- FHWA's Resource Center
- State DOTs in New York, California, and Washington
- MPOs in San Diego, Dallas, and Colorado Springs
- Researchers at Arizona State University, Michigan State University, and other academic institutions

1.2 Organization of this Report

The remainder of this report is organized in four sections:

- Section 2 describes the Estimator and its capabilities in greater detail
- Section 3 provides a full step-by-step user guide to the Estimator
- Section 4 provides two brief case studies of the tool's application
- Section 5 provides a summary of the methodology behind the tool's calculations

The Appendix provides an exhaustive description of the methodology and emission factors that drive the tool's calculations.

2 The Infrastructure Carbon Estimator: An Introduction

The Infrastructure Carbon Estimator is a Microsoft Excel-based sketch planning application for estimating the energy and GHG emissions impacts of maintaining existing transportation systems or of constructing and maintaining new transportation facilities. The tool provides a new method to account for construction and maintenance emissions that are not typically calculated, so that these can be considered in long range planning, corridor analysis, or development of energy and GHG emission reduction strategies.

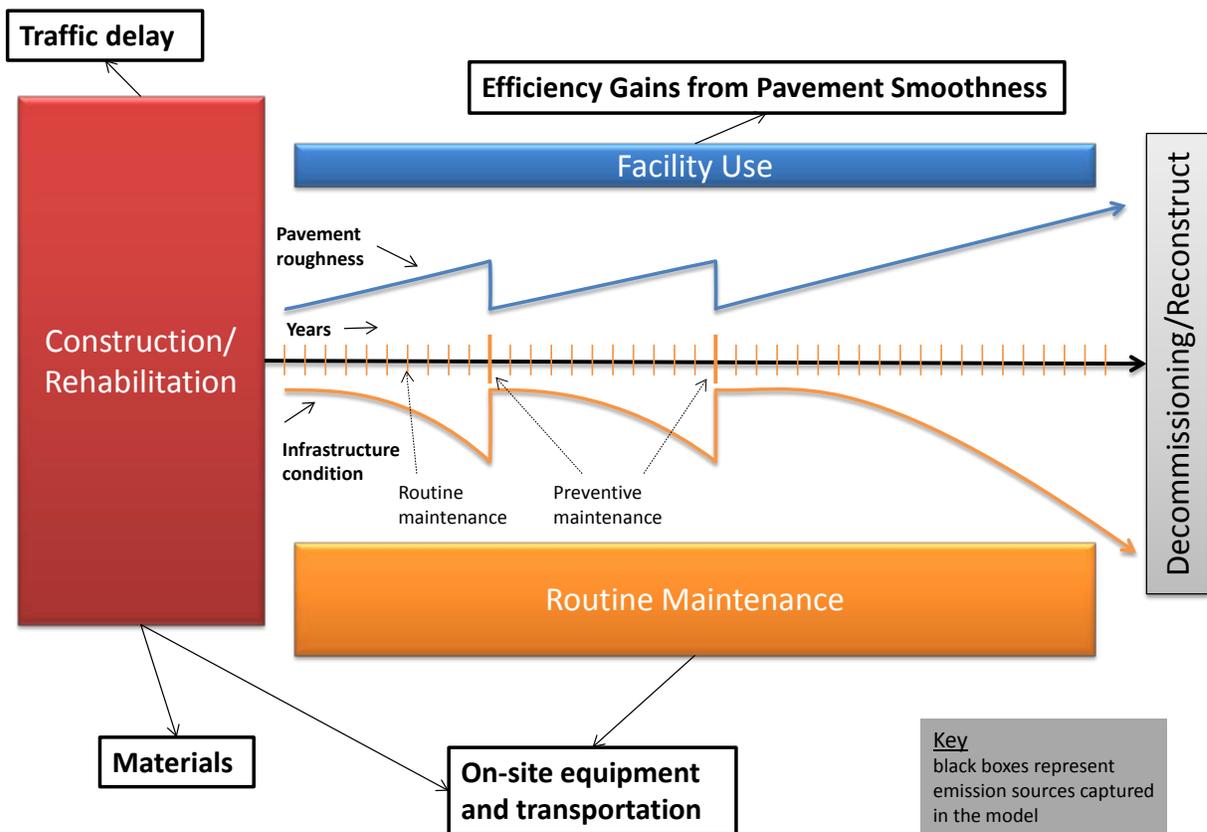
2.1 Capabilities of the Tool

The Estimator captures information about construction and maintenance of the following types of transportation facilities:

- Roadways and parking facilities
- Bridges
- Public transportation (rail infrastructure and dedicated bus infrastructure)
- Bicycle and pedestrian facilities

Figure 1 below illustrates the activities and emissions sources associated with roadway construction, rehabilitation, and maintenance of road-based transportation systems that are captured within the Estimator. Parallel activities and emissions sources are captured for the other modes incorporated in the tool.

Figure 1: Scope of Activities Captured in the Estimator



The tool is capable of estimating energy use and GHG emissions associated with the full lifecycle of transportation infrastructure, as illustrated in Figure 1. Specifically, the activities and emission sources covered include:

- Construction/Rehabilitation – Construction of a new facility or rehabilitation of an existing facility, including reconstruction and repaving. The user is responsible for inputting all construction and rehabilitation activity.
 - Materials – Embodied energy and emissions associated with the extraction and processing of raw materials.⁴
 - 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.⁵

⁴ Embodied, or upstream, energy and emissions refers to the requirements to produce and acquire the materials used in construction and maintenance. The factors used in the tool account for: the extraction of the raw resources used to produce the construction materials; the transportation of the raw materials to the production facilities; the production of the construction materials from the raw resources (e.g., crushing of aggregate for roadway materials, batch plant for asphalt production); and the release of carbon dioxide in a calcination reaction to produce cement from limestone.

⁵ The tool accounts for routine maintenance activities such as snow removal, vegetation management, and other activities (e.g., sweeping, lane striping, bridge deck repair, litter pickup, and maintenance of appurtenances).

- 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 maintenance of appurtenances. The tool automatically estimates routine maintenance activity based on the extent of the existing system.
 - Construction equipment and transportation – Fuel used in maintenance equipment.
- Facility Use (partial) –
 - Efficiency gains from pavement smoothness – Fuel saved in vehicles traveling on recently improved roadway surfaces. The tool automatically estimates fuel savings based on traffic volumes provided by the user.

2.1.1 Pavement Material Neutrality

The tool incorporates 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. The assumptions are based on data from a broad sample of projects. With a few exceptions related to mitigation strategies, the tool does not analyze the impacts of any project elements that would be specified during development of detailed design, engineering, and construction plans.

With regard to pavement surfaces, the tool is designed 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.

2.1.2 Mitigation Strategies

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

- Alternative fuels and vehicle hybridization
- Alternative vegetation management
- Alternative snow management
- In-place roadway recycling
- Warm mix asphalt
- Recycled and reclaimed materials
- Preventive maintenance

The tool assesses the impact of these strategies on total lifecycle energy and GHG emissions associated with construction and maintenance. Many of these strategies relate to construction materials and practices that would be specified during detailed design, engineering, and construction planning. Their use is incorporated in the tool in order to allow planners to estimate the relative impact that these strategies can have on baseline emissions and help to determine which strategies are the most effective for their particular context. Use of these strategies in actual projects should in all cases be specified by a qualified engineer or construction manager, as there may be details specific to individual projects or facilities that limit the deployment of mitigation strategies.

2.2 How to Use the Tool

Key steps in using the Estimator are:

- *Step 1: Input general information about your project(s)* – Including existing lane miles and track miles of facilities.
- *Step 2: Input information about construction and maintenance activities* – Including lane miles of various construction and rehabilitation projects.
- *Step 3: Input information about construction delay* – Including average traffic volumes on existing facilities.
- *Step 4: Input mitigation strategies* – Including baseline and projected deployment levels.
- *Step 5: View results* – Tables and bar charts are provided to view results for construction materials, construction equipment, and maintenance activity.
- *Step 6: View impacts on vehicle operation results* – A separate table is provided to view impacts related to vehicle operation (traffic delay and efficiency gains due to improved roadway smoothness).

The inputs to the tool 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 are lane miles and track miles of various project types, such as constructing a new urban freeway, repaving a rural arterial road, or converting existing roadway space to a dedicated bike lane.

Detailed instructions and explanations of key input parameters are provided in the tool itself. The User Guide in Section 3 also provides a step-by-step guide to using the tool.

Factors and assumptions incorporated in the tool are summarized in Section 5 and explained in more detail in the Appendix. The tool itself is locked and assumptions hidden, but an unlocked version may be requested from FHWA. Please contact John Davies (johng.davies@dot.gov) or Jeff Houk (jeff.houk@dot.gov).

In 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 accounted for.

- *Users should make reasonable assumptions based on their knowledge of the project area in order to fill any data gaps.* More guidance on reasonable assumptions is included in the detailed User Guide in Section 3.
- *If desired, a more detailed analysis can be conducted on specific projects once additional information is known, using tools designed for that purpose.* More guidance on other tools is included below.

2.3 Relationship to Other Tools

Users may want to consider the relationship of other analysis tools to the Infrastructure Carbon Estimator.

2.3.1 Construction Emission Models

- **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.
- **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.
- **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.
- **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.
- **The Greenhouse-Gas Assessment Spreadsheet for CAPital Projects (GasCAP)** – GasCAP is a new 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.

2.3.2 On-Road Vehicle Emission Models

- 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. A MOVES analysis can be used to 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. An example of a MOVES analysis is discussed in Section 4.
- 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

2.3.3 Off-Road Vehicle Emission Models

- NONROAD – 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. Emission factors from NONROAD are applied in the GreenDOT tool (discussed below).
- OFFROAD – OFFROAD is California’s emission model for nonroad engines, equipment, and vehicles. Like NONROAD, it contains emission factors that are unique to specific equipment types and fuel types.

3 User's Guide

The Infrastructure Carbon Estimator consists of four different 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 **Results Summary** 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.
4. An **Impacts on Vehicle Operations** sheet that estimates some of the impacts that the project will have on energy and GHG emissions from passenger vehicles.

Users can navigate between sheets using the buttons that are embedded throughout the tool or the tabs at the bottom of the Excel window. The following subsections provide descriptions and instructions on using each of the above four sheets.

3.1 Project Inputs Sheet

The *Project Inputs* sheet is the primary sheet through which users input information on their existing transportation network and the project that they are analyzing. The tool uses the term “project” not just to refer to individual projects, but also to long range transportation plans or other plans that consist of a suite of projects, and this sheet is designed to accommodate inputs on both individual projects and comprehensive transportation plans. The *Projects Input* sheet contains five sections:

- A General Information section for overarching information about the project and about the existing transportation system.
- Three sections where users enter information on construction and maintenance activities, categorized by facility type:
 - Roadways
 - Bridges
 - Rail, Bus, Bicycle, and Pedestrian Facilities
- A Construction Delay section where users enter estimates of the delay caused by the roadway project.

Cells where users can input information are filled in **orange**; cells that calculate automatically are filled in **gray**.

The *Project Inputs* sheet asks about transportation projects at a high level of detail in order to allow users with sufficient information to calculate the impact of building specific facilities or project types. However, the tool will still produce estimates if some inputs are left blank, so that users with less detailed information can still use the tool. As we describe the steps for inputting information into the tool, we highlight methods and assumptions that users with less detailed information can use to

complete the inputs and receive the most accurate and consistent estimates of energy and GHG impacts.

3.1.1 Step 1: Input general information about your project

The Estimator begins by asking for two pieces of general information about your project:

The state in which the project is located. A drop-down menu contains a list of all U.S. states. This information is used to estimate the level of effort associated with vegetation and snow management.

The lifetime of your plan or project, in years. This is used to estimate average annual emissions associated with construction projects that span multiple years. If you only want to estimate the total emissions associated with a construction project, set this cell to 1. However, we recommend filling in this cell if you are interested in estimating impacts related both to construction and routine maintenance. Since the tool estimates annual routine maintenance needs and impacts, it is necessary to annualize construction impacts in order to enable comparisons between construction and maintenance emissions and energy use.

The following examples illustrate how users might enter information on project lifetimes:

- Example 1: User wants to estimate emissions occurring during the time horizon of a long range transportation plan (LRTP): 30 years. User enters '30' as time period. Activities entered are all construction and rehabilitation activities planned in the region during that period. The tool estimates an average level of routine maintenance activity during each year. The outputs represent the average annual emissions from C&M activities in the region over 30 years.
- Example 2: User wants to estimate emissions associated with the full lifetime of a new road that is planned for construction. The facility has an assumed lifetime of 40 years. User enters '40' as time period. Activities entered are the construction of the facility and planned rehabilitation, e.g., every 10 years. The tool estimates an average level of routine maintenance activity during each year. The outputs represent the average annual emissions form C&M activities over the 40-year lifetime of the facility.

Figure 2: Sample input of general project information

Infrastructure location (state)	WA
Analysis timeframe (years)	20

The tool also asks the user for *Average daily traffic per lane mile*, for facilities that will be reconstructed or resurfaced. This information is used to calculate fuel savings from vehicle operations on resurfaced and reconstructed roadways due to improved pavement smoothness. A regional average value can be used as a proxy. If this cell is left blank, the tool will not calculate pavement smoothness benefits.

3.1.1.1 ROADWAY SYSTEM INPUTS

The tool then asks for the existing (i.e., prior to the construction of the project) centerline, track, or lane miles of roadway, rail, bus, and bicycle facilities. The centerline and lane miles of existing

roadways are used to calculate snow removal, vegetation management, and other maintenance required, based on average fuel required for each maintenance strategy in a given climatic region. Roadway maintenance fuel factors for strategies that apply to the roadside (e.g., vegetation management along shoulders) are based on the number of centerline miles, while factors for strategies that apply to the roadway surface (e.g., snow removal) are based on the number of lane miles. Maintenance impacts of light and heavy rail are based on average fuel use per track mile, and BRT and bicycle lane maintenance is per lane mile. Roadway maintenance estimates will also capture the routine maintenance of the roadway surface on bridges.

This information is used to calculate routine maintenance associated with the existing transportation system. The tool also accounts for newly-constructed facilities in its GHG/energy estimates; the total amount of newly-constructed facilities is shown for informational purposes. In some cases, such as long range plans in areas where the transportation system is largely built out, the energy and GHG impacts associated with maintaining the existing system will be a substantial share of the total, and many of the mitigation strategies included in the tool focus on reducing fuel used for routine maintenance. Though the tool will produce GHG/energy estimates in the absence of information about the existing system, including this information will yield more comprehensive estimates of GHG and energy impacts and allow the user to see results from a wider variety of mitigation strategies.

Figure 3: Sample inputs to calculate impacts of routine maintenance

Roadway System	
Total existing centerline miles	20
Total existing lane miles	80
Total newly-constructed centerline miles	1.25
Total newly-constructed lane miles	5

3.1.2 Step 2: Input information about construction and maintenance activities

The Estimator evaluates emissions associated with three categories of facilities: roadways; bridges; and rail, bus, bicycle, and pedestrian facilities. In each category, the tool allows users to input the amount of construction and maintenance activities for different combinations of activities (e.g., new construction, rehabilitation) and transportation facilities of different types, in terms of the amount of facilities that are subject to each activity (e.g., lane miles, track miles). Below we describe activities, facility types, and inputs for each category.

3.1.2.1 ROADWAYS

The main input table in the Roadway section allows users to enter the amount of construction and rehabilitation, in terms of lane or centerline miles, for a combination of activities and roadway facilities. The seven activities in the Roadway section are broken out into two categories:

- Roadway construction:
- New facility
- Re-alignment

- Construct additional lane
- Lane widening
- Shoulder improvement
- Roadway rehabilitation:
- Re-construct pavement
- Resurface pavement

The activities above are listed in order of decreasing energy/GHG intensity. For example, new roadway construction is more energy/GHG intensive than realignment or adding a lane. When in doubt about how to categorize a project that includes multiple activities, the conservative approach is to enter it in the inputs associated with the most energy and GHG-intensive activity.

Though many transportation plans focus on new construction, a full accounting of the energy/GHG impacts over the lifecycle of transportation facilities also requires consideration of ongoing rehabilitation needs. In addition, many of the mitigation strategies included in this tool are focused on reducing the energy/GHG impacts associated with rehabilitation and maintenance. It is therefore recommended that users estimate the rehabilitation needs that are associated with new construction, as well as with existing facilities, if sufficient information is available. (See text box *Accounting for the Full Roadway Lifespan* below for more information). As a general rule of thumb, new roadways require resurfacing after 15 years and reconstruction after 30 years. Figure 4 below shows the 60-year maintenance cycle for a typical roadway. This typical cycle was developed using expert input. It is not a recommended cycle, since the resurfacing and rehabilitation needs of roadways vary widely based on climate, design, and use levels. Rather it is a starting point for estimating resurfacing and reconstruction activities if no other information is available.

Figure 4: 60-year Maintenance Cycle for a Typical Roadway

Year	Activity
0	New Construction
15	Resurfacing
30	Reconstruction
45	Resurfacing
60	Reconstruction

Accounting for the Full Roadway Lifespan

The Infrastructure Carbon Estimator accounts for construction, rehabilitation, routine maintenance, and preventive maintenance in different ways:

New Construction (user provided): The user enters lane miles of construction projects.

Rehabilitation (user provided): The user enters expected reconstruction and resurfacing projects on all existing and new roadways for the length of the analysis period. As a general rule of thumb, new roadways require resurfacing after 15 years and reconstruction after 30 years.

Routine Maintenance (automatically estimated): The tool automatically estimates routine maintenance activity, such as sweeping, striping, bridge deck repair, litter pickup, and maintenance of appurtenances, per lane mile of existing and new roadway.

Preventive Maintenance (user provided): The user has the option to specify a preventive maintenance program as a mitigation strategy. Preventive maintenance techniques include crack sealing, patching, chip seals, and micro-surfacing.

Example: The user enters new construction of 10 lane miles of new freeway, with an analysis period of 40 years. Assuming that all construction takes place in year 1, the user enters 10 lane miles of freeway resurfacing (assumed to take place in year 15) and 10 lane miles of freeway reconstruction (assumed to take place in year 30). The tool automatically includes routine maintenance of the 10 newly constructed lane miles. The user has the option of specifying a preventive maintenance strategy, which will increase the longevity of the pavement surface and therefore reduce the amount of energy and emissions associated with resurfacing and rehabilitation.

The Roadway input table contains seven different facility types, divided between urban and rural:

- Rural facilities:
- Rural interstates
- Rural principal arterials
- Rural minor arterials
- Rural collectors
- Urban facilities:
- Urban interstates / expressways
- Urban principal arterials
- Urban minor arterials / collectors

These facility types are used by the tool to distinguish between facilities that involve different levels of energy use and GHG emissions during construction and rehabilitation, and generally align with the functional classifications used by FHWA.⁶ The facilities above are listed in order of decreasing energy/GHG intensity. For example, interstates are generally more energy/GHG intensive to build and maintain than collectors or arterials. When in doubt about how to categorize a project, the conservative approach is to enter it in the inputs associated with the most energy and GHG-intensive facility type. If you are assessing a transportation plan for an area that contains a mix of urban and rural areas and lack information about the breakdown between urban and rural facilities, either estimate an approximate split or use the predominant classification for your area.

Figure 5: Sample input of roadway project information

Roadway Projects							
Facility type	Roadway Construction					Roadway Rehabilitation	
	New Roadway (lane miles)	Construct Additional Lane (lane miles)	Re-Alignment (lane miles)	Lane Widening (lane miles)	Shoulder Improvement (centerline miles)	Re-construct Pavement (lane miles)	Resurface Pavement (lane miles)
Rural Interstates	0	0	0	0	50	0	10
Rural Principal Arterials	5	0	0	10	0	0	30
Rural Minor Arterials	0	0	20	0	0	0	0
Rural Collectors	0	0	0	20	0	0	0
Urban Interstates / Expressways	0	0	0	0	40	20	30
Urban Principal Arterials	0	0	0	0	0	0	10
Urban Minor Arterials / Collectors	0	0	0	0	0	0	0

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.

The Roadway section contains two additional tables: one where users can input the total amount of structured and surface parking that will be created under the project, and one for the percentage of project activities that take place on rocky or mountainous terrain. Rocky or hilly terrain generally increases the energy and GHG emissions impacts of construction because it requires more fuel for earthwork and more materials for the base and structural elements of the road. Though there are no specific guidelines for determining whether terrain is rocky or mountainous, users should input an estimated value based on the percentage of a project that will require additional fuel and materials due to the nature of the terrain.

⁶ Federal Highway Administration, 2012, *Flexibility in Highway Design*, Chapter 3: Functional Classification, <http://www.fhwa.dot.gov/environment/publications/flexibility/ch03.cfm>.

Figure 6: Sample input of parking information and rocky/mountainous terrain option

Parking	
Surface Parking (spaces)	50
Structured Parking (spaces)	100

Options	
% roadway construction on rocky / mountainous terrain	10%

3.1.2.2

3.1.2.3 BRIDGES

The Bridge section of the tool focuses on construction of bridge structures, rather than the construction and maintenance of the roadway surfaces of the bridges; those surface facilities are covered under the Roadway section described previously.

The input table in the Bridge section allows users to enter the amount of new construction and reconstruction for bridges of varying size, in terms of number of spans, and whether crossing over land or water. A span refers to a section of bridge between two supports. Bridge construction inputs are characterized by number of spans rather than specific lengths. Specifically, users can input for the following bridge types:

- Single-span
- Two-span
- Multi-span (over land)
- Multi-span (over water)

The tool distinguishes between the types of terrain because bridges spanning water require either larger lengths between supports or supports built into the floor of the body of water, which is more materials- and labor-intensive than an equivalent land crossing.

The inputs include three options for construction project types, which require different levels of materials and energy:

- Constructing a new bridge
- Reconstructing a bridge
- Adding a lane to a bridge

Figure 7: Sample input of bridge project information

Bridge Structure	Construct New Bridge				Reconstruct Bridge			
	Number of bridges	Average number of spans per bridge	Average number of lanes per bridge	Total number of lane-spans	Number of bridges	Average number of spans per bridge	Average number of lanes per bridge	Total number of lane-spans
Single-Span	1	1	1	1	0	1	0	0
Two-Span	0	2	0	0	2	2	4	16
Multi-Span (over land)	0	0	0	0	0	0	0	0
Multi-Span (over water)	0	0	0	0	0	0	0	0

For each bridge construction type, the user inputs the number of planned projects, the average number of spans per project, and the average number of lanes per bridge span. Based on these inputs, the tool calculates the number of lane-spans (i.e., the total number of lanes on all project bridge spans) for each project type. The energy and GHG impacts of construction are calculated based on the number of new lane-spans for an average bridge. However, it should be noted that the material and energy factors in the calculations do not apply to bridge projects greater than 1000 feet in length, due to the different types of materials and construction practices involved in those projects. Energy and GHG impacts for those projects are best captured in separate assessments specific to each individual project.

How Many Bridge Spans?

Approximately half of short bridges in the U.S. (less than 1000 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. You may want to test a few different assumptions to see the effects.

3.1.2.4 INTERCHANGES

While many MPO transportation plans list new or modified interchanges as projects, the tool does not include a separate data entry table for interchanges. Since interchanges are a combination of roadways and bridges, the relevant infrastructure can be entered in those tables. It may be necessary to consult with the State DOT or other project sponsor to determine the number and type of bridges involved in each interchange and the type of construction activity involved (e.g., new construction, reconstruction, adding lanes). Large “flyover” bridges can be represented as “Multi-span (over land).”

3.1.2.5 RAIL, BUS, BICYCLE, AND PEDESTRIAN FACILITIES

The Rail, Bus, Bicycle, and Pedestrian Facilities section include input tables for each type of facility. In general, each table allows for inputting new construction or conversions/improvements.

Rail facilities are divided into light and heavy rail projects. Each type of rail is distinguished by four new construction project types: underground – hard rock; underground – soft rock; elevated; or at

grade. There is also an option for converting or upgrading existing light rail segments. All rail construction is entered in terms of track miles. The project types are listed in order of decreasing energy/GHG intensity. For example, constructing underground rail lines through hard rock is generally more energy/GHG intensive than building the same number of track miles at grade. When in doubt about whether underground construction is in hard or soft rock or how to categorize a project that includes multiple activities, the conservative approach is to enter it in the inputs associated with the most energy and GHG-intensive activity. The tool also allows for assessing the impacts of building new underground, elevated, or at grade stations for light or heavy rail.

Figure 8: Sample input of rail project information

Rail construction		
Project Type	Light rail	Heavy rail
New construction (underground - hard rock) - track miles	0	0
New construction (underground - soft soil) - track miles	0	10
New construction (elevated) - track miles	5	0
New construction (at grade) - track miles	5	10
Converted or upgraded existing facility - track miles	5	N/A
New rail station (underground) - stations	0	0
New rail station (elevated) - stations	2	0
New rail station (at grade) - stations	0	1

The bus facility portion of the tool is only for construction or conversion of bus rapid transit (BRT) facilities. This refers to the construction of lanes dedicated to bus transit rather than lanes shared with general traffic. Dedicated BRT lanes are entered in terms of lane miles. The tool also calculates impacts of BRT station construction.

Figure 9: Sample input of BRT project information

Bus rapid transit construction	
New lane or right-of-way - lane miles	40
Converted or upgraded lane/facility - lane miles	20
New BRT Stations	2

The inputs for construction of bicycle and pedestrian facilities are combined in the final table of this section. Bicycle facility construction impacts can be calculated for new construction of off-street bicycle and pedestrian paths and for new construction of on-street bicycle lanes. The latter case applies where new roadway service is constructed for a bicycle lane. Resurfacing of existing roadway surface to create a bicycle lane should be included under ‘Resurfacing’. If bicycle lanes are created simply by restriping existing roadway space, these can 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, if your plan includes sidewalks on all new roads constructed, 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 any sidewalk repairs.

Figure 10: Sample input of bicycle and pedestrian project information

Bicycle and Pedestrian Facilities			
Project Type	New Construction	Resurfacing	Restriping
Off-Street Bicycle or Pedestrian Path - miles	15	45	N/A
On-Street Bicycle Lane - lane miles	25	25	50
On-Street Sidewalk - miles	30	N/A	N/A

3.1.3 Step 3: Input information about construction delay

In addition to direct energy and GHG emissions impacts due to fuel and materials use, roadway construction can indirectly impact emissions by creating traffic delays, which cause vehicles using roads to operate less efficiently. In order to estimate these impacts, users need to fill in three inputs:

- Total project-days of lane closure: this is the total number of days that travelers will experience delays due to the proposed project.
- Average daily traffic per directional segment for facilities requiring lane closure: this is the average daily traffic across each directional roadway segment affected by the project. For long range transportation plans and other projects that address many transportation facilities across a state or metropolitan area, this should be the systemwide average daily traffic across all traffic segments in the project area.
- Percentage of facility lanes closed during construction: the average percentage of a facility's lanes that are expected to be closed for a construction project. For example, on a facility with four lanes in each direction that will close two lanes at a time, select 50%.

Figure 11: Sample input of construction delay information

Total project-days of lane closure	50%
Average daily traffic per directional segment for facilities requiring lane closure	
Percentage of facility lanes closed during construction	

Estimates of the operational energy and GHG impacts due to construction delay as well as to smoother pavement are presented in the *Impacts on Vehicle Operation* sheet, which is separate from the *Results Summary* sheet. These results are not comparable with the results in the summary sheet because they come from a different source—roadway vehicles—than the construction materials and construction and maintenance vehicles that are the focus of the other sections of the tool.

Estimating Project-Days of Lane Closure

Estimates of project-days of lane closure may be available from project documents. The tool assumes that lane closures occur in one-mile increments. Average values for construction schedules (e.g., daytime versus overnight) are incorporated in the calculations. Estimates of emissions from construction delay are meant to provide a rough sense of the scale of emissions relative to the construction processes themselves and are not meant to replace estimates derived from traffic modeling software. Planned construction projects that will result in significant lane closures on high volume roads should be evaluated using traffic modeling software.

3.2 Mitigation Inputs Sheet

3.2.1 Step 4: Input mitigation strategies

After entering information on your project using the *Project Inputs* sheet, use the buttons or tabs to navigate to the *Mitigation Inputs* sheet. This sheet allows users to enter information on 19 strategies, organized into seven categories, that reduce energy use and GHG emissions due to construction and maintenance. Cells where users can input information are filled in **orange**; cells that calculate automatically are filled in **gray**. The input table on this sheet has five columns:

- Strategy: a brief description of the mitigation strategy.
- Baseline deployment: use this column to input the baseline (i.e., pre-project) deployment of the strategy.
- Planned deployment: use this column to input the planned deployment of the strategy under the project. The tool estimates the impact of mitigation strategies based on the difference between baseline and planned deployment. If the planned deployment of a strategy is less than the baseline deployment, energy use and GHG emissions will increase.
- Maximum potential deployment: this column displays the maximum potential deployment of the strategy, based on research. If you enter a value in the baseline or planned deployment column that is greater than this value, the input cell will appear highlighted in light red with dark red text as a warning. The calculations in the sheet will continue to function. Note that the tool does not check for reasonable inputs across multiple overlapping strategies; for example, the warning will not show if combined usage of B20/B100 in the maintenance fleet exceeds 100%.
- Applied to: this column displays information on the application of strategies to materials or fuel used in the construction process in order to guide users in entering deployment levels and interpreting results. For example, if your agency has a policy to encourage the usage of a certain percentage of industrial substitutes for portland cement in roadway facilities, but the project that you entered focuses on transit facilities, it may not be correct to assume that the policy applies to your project. If you did not enter information on existing facilities, strategies that

primarily affect fuel use in maintenance vehicles, such as vegetation and snow management, will not produce much of an impact on the final results.

Figure 12: Sample of reduction strategy options

Energy / GHG reduction strategies				
Strategy	Baseline deployment	Planned deployment	Maximum potential deployment	Applied to
Alternative fuels and vehicle hybridization				
Hybrid maintenance vehicles and equipment	0%	10%	44%	Fuel use by maintenance equipment
Switch from diesel to B20 in maintenance vehicles and equipment	0%	10%	100%	Fuel use by maintenance equipment
Switch from diesel to B100 in maintenance vehicles and equipment	0%	10%	100%	Fuel use by maintenance equipment
Combined hybridization/B20 in maintenance vehicles and equipment	0%	10%	44%	Fuel use by maintenance equipment
Vegetation management				
Alternative vegetation management strategies (hardscaping, alternative mowing, integrated roadway/vegetation management)	No	Yes	N/A	Fuel use by vegetation management equipment
Snow fencing and removal strategies				
Alternative snow removal strategies (snow fencing, wing plows)	No	Yes	N/A	Fuel use by snow removal equipment
In-place roadway recycling				
Cold In-place recycling	0%	0%	99%	Asphalt and fuel use by construction equipment in roadway resurfacing and BRT conversions

Below we present information on the mitigation strategies in each category, the units used to input information on deployment, and the applicability of strategies. Refer to Section 4.1 for more information on the data sources used to assess the reduction potential and maximum potential deployment of each strategy.

3.2.1.1 ALTERNATIVE FUELS AND VEHICLE HYBRIDIZATION

Strategies in this category include the use of hybrid vehicles, varying grades of biodiesel, and combined use of biodiesel in hybrid vehicles. Hybrid vehicles operate more efficiently and burn less fuel, reducing energy use and GHG emissions, while biodiesel produces fewer GHG emissions but consumes more energy than conventional diesel on a lifecycle basis. The tool separates the application of these strategies in maintenance vehicles from construction vehicles because transportation agencies are more likely to own their own maintenance fleets, and therefore have a higher level of control over the use of biodiesel and hybrid vehicles for maintenance purposes. Users input information on deployment of these strategies in terms of either the percent of vehicles used in the construction or maintenance of facilities that are hybrids or the percent of all diesel fuel used that is biodiesel.

3.2.1.2 VEGETATION MANAGEMENT

The use of hardscape and native plants in lieu of traditional roadside landscaping, as well as more efficient landscaping practices such as integrated roadway and vegetation management, reduce the amount of fuel used for vegetation management. The tool estimates the overall energy and GHG

impacts of a single vegetation management strategy that draws on a variety of these approaches. Users input whether they are using efficient vegetation management practices on their roadway system (yes/no).

3.2.1.3 SNOW MANAGEMENT

The use of snow fencing to block roads from snowdrifts or of wing plows that increase the width of roadway that can be cleared by a single plow reduce the amount of fuel used for snow management. The tool estimates the overall energy and GHG impacts of a single snow management strategy that draws on a variety of more efficient approaches. Users input whether they are using efficient snow management practices on their roadway system (yes/no).

3.2.1.4 IN-PLACE ROADWAY RECYCLING

The two strategies in this category reduce asphalt and construction fuel use by recycling the existing roadway to resurface or reconstruct a new roadway. Users input the deployment of these strategies in terms of the percent of total lane miles of roadway resurfacing or reconstruction projects that are subject to in-place recycling. Note that in-place recycling may limit the use of recycled substitutes for virgin asphalt or base stone. Use of in-place recycling may also be limited by the use of preventive maintenance, which reduces the frequency of roadway reconstruction and resurfacing through more frequent roadway surface treatments.

3.2.1.5 WARM MIX ASPHALT

Warm mix asphalt reduces the fuel required to heat asphalt mixes. Users input the deployment of this strategy in terms of the percent of total asphalt used that is warm mix asphalt.

3.2.1.6 RECYCLED AND RECLAIMED MATERIALS

Using recycled and reclaimed materials as substitutes for virgin materials in the construction of transportation facilities reduces lifecycle energy use and GHG emissions. The Estimator considers four different recycled or reclaimed substitutes for virgin materials. Users input the deployment of these strategies in terms of the percent of total materials used that are recycled or reclaimed. Furthermore, the use of in-place recycling may limit opportunities to use recycled substitutes for asphalt.

3.2.1.7 PREVENTIVE MAINTENANCE

Preventive maintenance reduces construction fuel and materials use associated with roadway reconstruction and resurfacing by applying preventive surface treatments to forestall the deterioration of roadways. Preventive maintenance techniques include crack sealing, patching, chip seals, and micro-surfacing. Users input the deployment of this strategy in terms of the percent of total lane miles that are subject to preventive maintenance. Note that preventive maintenance may limit the applicability of in-place recycling because it reduces the frequency of the reconstruction and resurfacing projects that are candidates for in-place recycling.

3.3 Results Summary Sheet

3.3.1 Step 5: View results

After entering project and mitigation inputs, use the tabs or buttons to navigate to the *Results Summary* sheet. This sheet contains two tables: one showing annualized energy use in millions of British thermal units (mmBTU) and one showing annualized greenhouse gas emissions in metric tons of carbon dioxide equivalents (MT CO₂e).

Figure 13: Sample results of energy use associated with the activities

Annualized energy use (mmBTUs), per year over 20 years						
Unmitigated						
	Roadway - new construction	Roadway-rehabilitation	Roadway - total	Bridges	Rail, bus, bicycle, ped.	Total
Upstream Energy						
Materials	89,975	152,838	242,813	24,643	178,067	445,523
Direct Energy						
Construction Equipment	33,942	27,079	60,021	10,747	61,606	132,374
Routine Maintenance						158,585
Total	123,917	179,917	302,834	35,390	239,673	736,482
Mitigated						
	Roadway - new construction	Roadway-rehabilitation	Roadway - total	Bridges	Rail, bus, bicycle, ped.	Total
Upstream Energy						
Materials	62,980	43,026	106,006	24,643	158,592	289,241
Direct Energy						
Construction Equipment	32,942	9,070	42,012	10,747	61,606	114,365
Routine Maintenance						158,585
Total	95,922	52,096	148,018	35,390	220,198	562,191

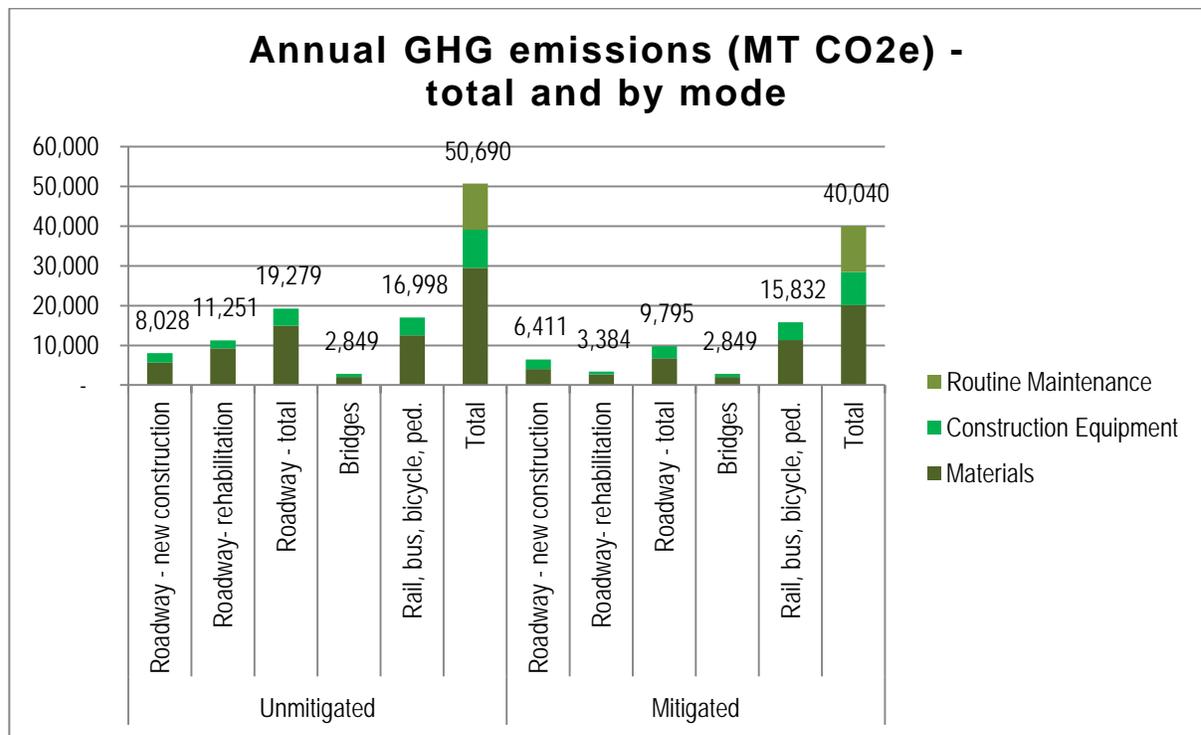
Figure 14: Sample results of GHG emissions associated with the activities

Annual GHG emissions (MT CO ₂ e), per year over 20 years						
Unmitigated						
	Roadway - new construction	Roadway-rehabilitation	Roadway - total	Bridges	Rail, bus, bicycle, ped.	Total
Upstream Emissions						
Materials	5,626	9,276	14,902	2,065	12,507	29,474
Direct Emissions						
Construction Equipment	2,402	1,975	4,377	784	4,491	9,652
Routine Maintenance						11,564
Total	8,028	11,251	19,279	2,849	16,998	50,690
Mitigated						
	Roadway - new construction	Roadway-rehabilitation	Roadway - total	Bridges	Rail, bus, bicycle, ped.	Total
Upstream Emissions						
Materials	4,009	2,711	6,720	2,065	11,341	20,126
Direct Emissions						
Construction Equipment	2,402	673	3,075	784	4,491	8,350
Routine Maintenance						11,564
Total	6,411	3,384	9,795	2,849	15,832	40,040

Each of these tables shows both unmitigated results and mitigated results that take into account the mitigation strategies entered under the previous step. The columns of each chart include the categories that are used on the project inputs page—roadway (broken down into new construction, rehabilitation, and total): bridges; and rail, bus, bicycle and pedestrian—as well as the total across all categories. The rows are organized according to the sources of energy use and emissions considered by the tool: lifecycle emissions and energy use from construction materials; fuel used in construction equipment; and fuel used in maintenance equipment. Note that routine maintenance is not broken out by project category, but only presented as a total.

The stacked column charts to the right of the tables can also be used to compare mitigated and unmitigated GHG emissions, either total or by project category (see example in Figure 15). They can also be used to assess the breakdown of energy/emissions sources.

Figure 15: Sample chart of GHG emission impacts associated with the activities



To convert mMBTU to gallons of conventional diesel, use a conversion factor of 7.785 gallons of diesel per mMBTU. However, keep in mind that this conversion represents lifecycle energy use for informational purposes and does not estimate actual diesel consumption.

3.4 Impacts on Vehicle Operation Sheet

3.4.1 Step 6: View impacts on vehicle operation results

In addition to increasing energy use and GHG emissions associated with constructions and maintenance vehicles and materials, transportation projects can also affect the energy use and

emissions associated with vehicles using the roadway. The *Impacts on Vehicle Operation* sheet estimates energy and GHG emissions impacts due to vehicle delay associated with construction projects and increased pavement smoothness following resurfacing and reconstruction projects. However, these results are not comparable with those shown in the *Results Summary* sheet because they come from a different source – roadway vehicles – than the construction materials and construction and maintenance vehicles that are the focus of the other modules in the tool. The results shown in this sheet should be considered in the context of a comprehensive evaluation of a plan or project's impact on roadway vehicles, including not only delay and pavement smoothness, but also travel patterns and demand.

This sheet contains three tables, all of which populate automatically based on information entered elsewhere in the sheet. The first estimates energy and GHG emissions impacts due to construction delay based on the construction delay inputs entered by the user in the *Project Inputs* sheet. Results are shown in terms of the daily, annual, and total energy and GHG emissions impacts over the course of the project.

The second table estimates the energy and GHG emissions impacts of smoother pavement, which improves the operating efficiency of vehicles by reducing rolling resistance. The tool applies smoothness benefits based on the total amount of resurfacing and reconstruction lane miles the user enters in the *Project Inputs*; the benefits accrue after completion of the project. The table presents both total and annualized results.

The third table presents the total net impact of both construction delay and pavement smoothness on an annual basis.

Figure 16: Sample results from vehicle operations activities

Construction delay		Result	Energy use (mmBTUs)	GHG emissions (MT CO2e)
Total project-days of construction/lane closure		20		
Project lifetime (years)		20		
Additional energy use / emissions due to delay (per project-day)			2.8	0.2
Total energy use / GHG emissions due to construction delay			56	5
Annual energy use / GHG emissions due to construction delay, per year			2.8	0.2
Pavement smoothness		Result	Energy use (mmBTUs)	GHG emissions (MT CO2e)
Total lane miles of roadway reconstruction / resurfacing		100		
Project lifetime (years)		20		
Reduced Energy use / GHG emissions due to smooth pavement			28	2
Annual energy / emissions savings due to pavement smoothness			1.4	0.1
Total			Energy use (mmBTUs)	GHG emissions (MT CO2e)
Total Annualized Delay and Pavement Smoothness Impacts			1.4	0.1

4 Example Use Cases

4.1 Using the Estimator to Assess a Plan: North Central Texas Council of Governments

The North Central Texas Council of Governments (NCTCOG) used the Estimator to examine the energy and GHG impacts of its long range regional transportation plan, Mobility 2035, which defines a vision for the greater Dallas-Fort Worth region's multimodal transportation system. NCTCOG's plan served as an ideal test case of the tool's ability to estimate energy and GHG impacts across a variety of modes, facilities, and project types.

NCTCOG gathered data from the 2013 update to Mobility 2035 to complete the tool's inputs on new construction of roadways, rail, bus rapid transit, and bridges.⁷ Since long range transportation plans are high-level documents that focus on new construction and major capital projects, NCTCOG drew on several supplemental sources to fill in other inputs in the tool, including:

- The City of Dallas' Dallas Bike Plan for new construction of on-street bicycle/pedestrian facilities.⁸
- The TXDOT Four Year Pavement Management Plan⁹ for information on existing roadway facilities and planned roadway resurfacing projects.

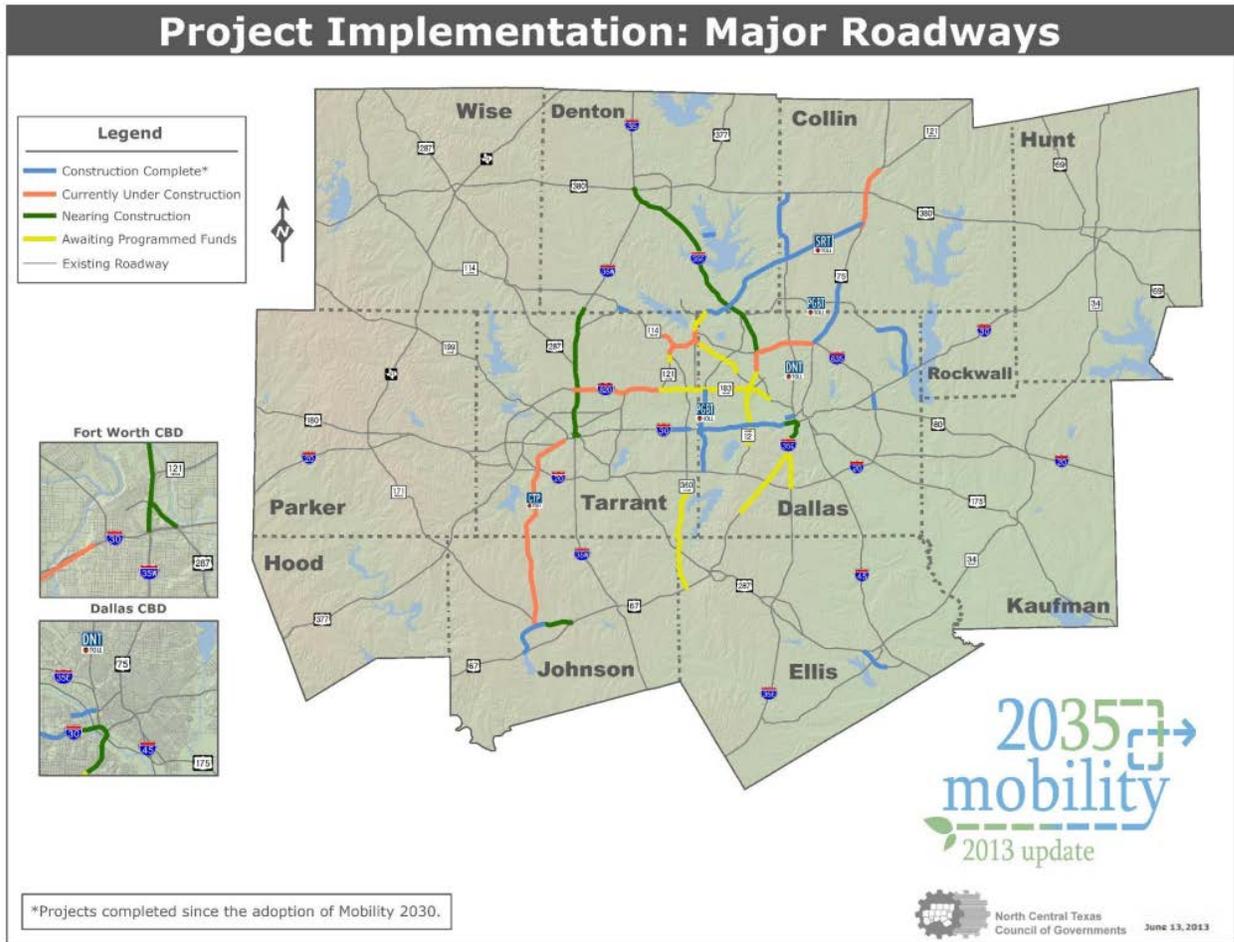
Though other agencies have the primary responsibility for developing and implementing these plans, NCTCOG works closely with these agencies, and felt justified in counting these activities as part of their plan in order to gain a more comprehensive picture of the energy and GHG impacts from constructing and maintaining the transportation system.

⁷ North Central Texas Council of Governments, Mobility 2035 – 2013 Update, <http://www.nctcog.org/trans/mtp/2035/index.asp>.

⁸ City of Dallas, 2011 Dallas Bike Plan, http://dallascityhall.com/public_works/bikePlan/pdf/2011_Dallas_Bike_Plan.pdf.

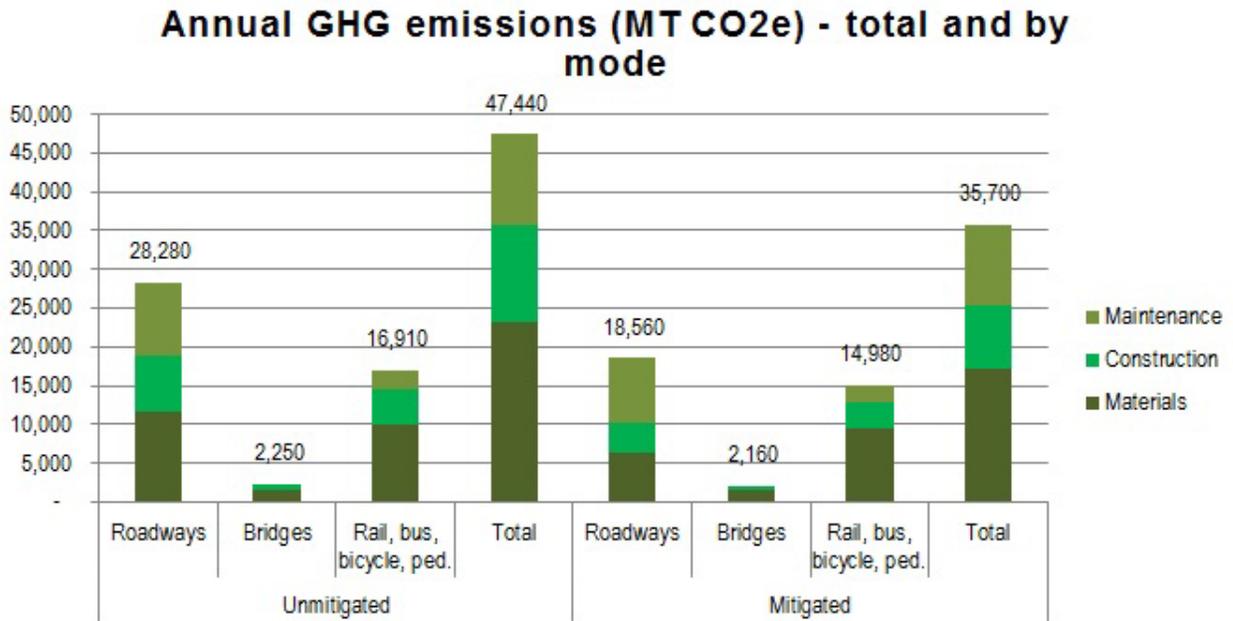
⁹ Liu, W., et. al., A Four-Year Pavement Management Plan (FY 2011-FY 2014), TxDOT Project 5-9035,01-P5, July 2012, http://www.utexas.edu/research/ctr/pdf_reports/5_9035_01_P6.pdf.

Figure 17: Major Roadway Construction in NCTCOG’s Mobility 2035 Plan



Overall, the tool estimated that NCTCOG’s plan, which calls for over 1,400 lane miles of roadway rehabilitation, over 300 lane miles of road re-alignment, 300 track miles of rail, and a major bridge reconstruction effort over the next 20 years, would consume almost 700,000 mmBTU of energy per year and produce almost 50,000 MT of GHG emissions per year due to construction and maintenance. Roughly 50 percent of these impacts are due to material usage, while the remaining half is split roughly evenly between construction equipment and maintenance fuel usage. Roadways account for almost two-thirds of energy use and GHG emissions; rail construction accounts for most of the remainder.

Figure 18: GHG emissions results from NCTCOG's analysis of its long-range transportation plan



NCTCOG used the tool to estimate the benefits of five energy and GHG mitigation strategies: hybrid vehicles and equipment, in-place recycling and full-depth reclamation, warm mix asphalt, recycled and reclaimed materials, and preventive maintenance.¹⁰ Collectively, these strategies were estimated to reduce energy use and GHG emissions by roughly 25 percent, with the biggest reductions associated with fuel use in roadway construction.

4.2 Using the Estimator to Assess a Project: Truck Climbing Lane

FHWA used the Estimator, in conjunction with other analysis tools, to examine the impact of a hypothetical project to add a truck climbing lane to a four-mile stretch of highway on mountainous terrain with three lanes in each direction in order to reduce occasional congestion associated with slowly-climbing trucks.¹¹ This example project would also involve rebuilding and widening overpasses at two points along the project site (see Figure 19): the Lookout Mountain Road overpass would be a reconstruction of a two-span bridge with two lanes; the project at CO93 would be to add an additional lane to the single-span bridge.

¹⁰ NCTCOG was using a pilot version of the tool, which contained a slightly different set of mitigation strategies than those discussed elsewhere in this report.

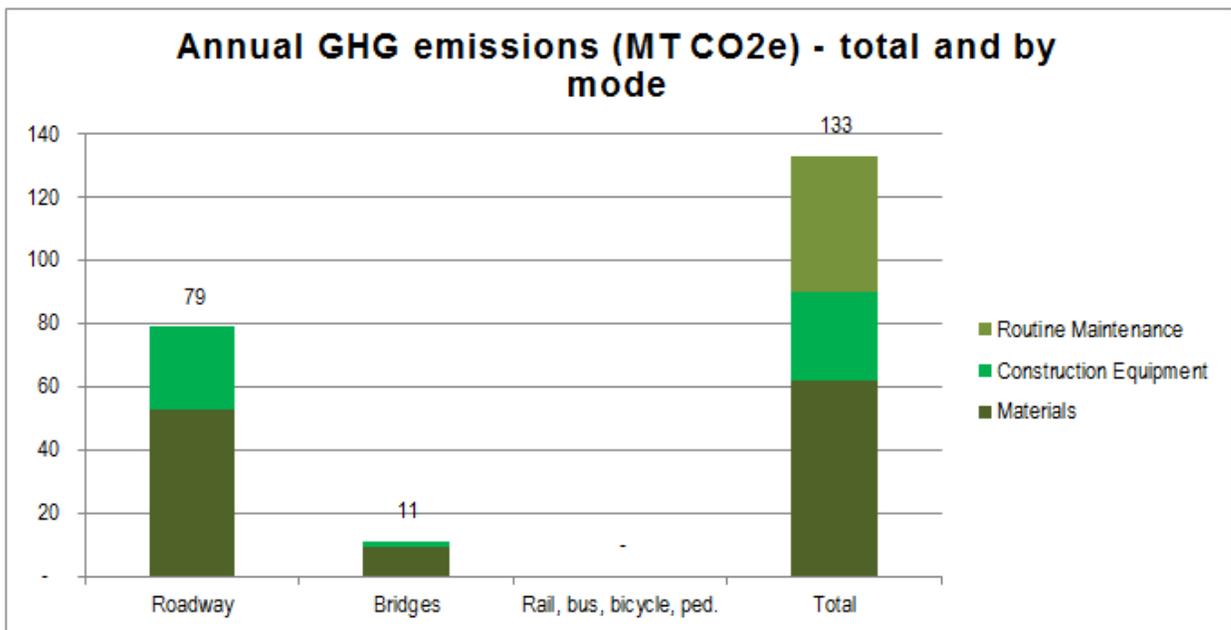
¹¹ This is a strictly hypothetical example developed to test the tool; it does not represent an actual or planned Colorado Department of Transportation project.

Figure 19: Map of hypothetical truck climbing lane project



FHWA used the tool to estimate construction emissions and the change in maintenance emissions due to the project. The construction activity consists of four lane miles of highway widening, one widened bridge and one reconstructed bridge, and occurs on mountainous terrain, which increases the energy required for roadways and the resulting GHG emissions. Without the additional lane, the maintenance of this roadway would generate 39 MT of GHG emissions per year; the combined annual emissions to build and maintain the road with the truck climbing lane would be 133 MT, assuming that construction emissions are annualized over 20 years.

Figure 20: GHG emissions results from hypothetical truck climbing lane project



FHWA also used MOVES to analyze the GHG impacts on vehicles using the road. Capacity/speed relationships developed by the Texas Transportation Institute were used along with estimated 2020 and 2040 traffic volumes to assess the congestion benefit of adding an extra lane of capacity. FHWA

estimated that travel speeds for vehicles other than trucks would increase by 13 mph in 2020 and 24 mph in 2040 if the truck lane were constructed, while truck speeds would remain constant at 40 mph because of the steepness of the roadway. Based on these assumptions, MOVES estimates that the project would reduce operational GHG emissions from vehicles using the road by 325 MT per year, which represents a slight (0.2%) decrease below the baseline.

FHWA used these results to calculate the payback period of the proposed project in terms of GHG reductions. The total construction and maintenance impact of the project is 94 MT per year over 20 years, or 1880 MT total; the project reduces operational emissions by 325 MT per year. Thus, it would take over 5 years of operational energy savings to offset the construction and maintenance impact of the project. In other words, if the project's additional lane was completed in 2020, it would not begin producing a net reduction in GHG emissions until sometime in 2025. Thus, while this hypothetical project would have congestion benefits, it would not be an ideal GHG mitigation project if near-term reductions in GHGs were considered important. The results also serve to illustrate the relative magnitude of the GHG and energy impacts of construction and maintenance compared to those of vehicles using the road. Since operational impacts are so much greater than impacts due to construction and maintenance, a small percentage reduction in the former may offset a large percentage increase in the latter. Users should consider impacts on GHG emissions and energy use, as analyzed by MOVES or another tool, alongside the results produced by the Estimator where feasible.

5 Background on the Tool: Estimation Methods and Research

This section describes the research and calculation methodologies behind the Infrastructure Carbon Estimator. In general, the tool works through the following three steps:

1. The tool applies factors to the project inputs entered by the user to estimate total materials use, construction fuel use, and routine maintenance fuel use, and then applies energy and GHG conversion factors to estimate total unmitigated energy use and GHG emissions.
2. The tool estimates the energy and GHG reductions due to mitigation strategies entered by the user and applies these to energy use and GHG emissions from the appropriate sources to estimate total mitigated energy use and GHG emissions.
3. The tool separately estimates the energy and GHG emissions impacts due to the effect of construction delay and pavement smoothness on vehicle operations.

Below we describe the data sources and calculations behind each step. Further detail on estimation methods and factors is contained in the Appendix.

5.1 Materials, construction, and routine maintenance factors

The Estimator focuses on three sources of energy demand and GHG emissions that are common across transportation facilities:

- **Materials** used in the construction of transportation facilities. The materials considered by the tool include asphalt, concrete, base stone, and steel.
- **Construction fuel** used in the construction of new facilities and the rehabilitation of existing ones.
- **Routine maintenance fuel** used to keep both existing and new facilities functional and well-preserved.

The tool estimates the quantity of materials and fuel that a project will use by applying usage factors (e.g., materials/fuel used per lane/centerline/track mile) for each activity/facility combination contained in the tool to the project information entered by the user. The next three subsections describe how these factors were derived for each of the three project categories considered by the tool. The following subsection describes the factors that are used to convert materials and fuel use into energy use and GHG emissions.

5.1.1 Roadway

5.1.1.1 MATERIALS

5.1.1.1.1 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 facility types used in the Estimator.¹²
- 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.¹³
- Mikhail Chester’s research on the lifecycle environmental impacts of parking infrastructure.¹⁴

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.

5.1.1.1.2 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.

Surface and structure parking were also estimated, using Chester’s research, to establish a profile of materials required to construct surface parking and structure parking facilities on a per-space basis. Major materials estimated were asphalt and base course stone.

5.1.1.2 CONSTRUCTION FUEL

5.1.1.2.1 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.¹⁵

¹² These reports, produced between 2002 and 2006 and identified by the team only in paper form, were entitled “Updating the Highway Improvement Cost Model.”

¹³ This database is proprietary, and held by Oman Systems, Inc. in Nashville, Tennessee.

¹⁴ 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).

¹⁵ 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>.

5.1.1.2.2 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 diesel.

5.1.1.3 ROUTINE MAINTENANCE FUEL

5.1.1.3.1 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.¹⁶
- Data on state snowfall and rainfall from the National Oceanic and Atmospheric Administration's National Climatic Data Monitoring Center.¹⁷

5.1.1.3.2 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.

¹⁶ 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>

¹⁷ <http://www.ncdc.noaa.gov/climate-monitoring/>.

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.
- High LOE (between 0 and 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.

For parking, we drew on the analysis of roadway maintenance costs to estimate the energy use associated with parking lots, which share the same basic pavement characteristics as vehicular travel lanes and are maintained using similar equipment and approaches. However, parking is not measured in terms of lane miles, but in terms of surface area. We divided total maintenance costs per lane mile by the difference in square footage between a lane mile and a parking space (approximately 60,000 vs. approximately 150) in order to estimate the gallons of fuel used per square foot for maintenance activities.

5.1.2 Bridges

5.1.2.1 MATERIALS

5.1.2.1.1 Data sources

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

- 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.
- 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.¹⁸

¹⁸ 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>.

5.1.2.1.2 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.

5.1.2.2 CONSTRUCTION FUEL

5.1.2.2.1 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.¹⁹ 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.

5.1.2.2.2 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.

5.1.2.3 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

¹⁹ 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>.

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 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.

5.1.3 Rail, Bus, Bicycle, and Pedestrian Facilities

5.1.3.1 MATERIALS

5.1.3.1.1 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.

- 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.
- 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.
- 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.

5.1.3.1.2 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.

5.1.3.2 CONSTRUCTION FUEL

5.1.3.2.1 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).

5.1.3.2.2 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.

5.1.3.3 ROUTINE MAINTENANCE FUEL

5.1.3.3.1 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.

5.1.3.3.2 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.

5.1.4 Energy and GHG Conversion Factors

5.1.4.1.1 Data sources

Factors for converting materials and fuel use to energy and GHG emissions were drawn from two sources:

- The NCHRP GreenDOT tool, which allows users to estimate the GHG and energy impacts of roadway construction and operations, and contains conversion factors for materials and fuel.²⁰
- The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) developed by the Consortium on Green Design and Manufacturing at the University of California Berkeley, which was the underlying source of emissions factors in GreenDOT, and contains detailed lifecycle energy and emissions factors for pavements.²¹

5.1.4.1.2 Calculation methods and assumptions

We drew most conversion factors in the tool directly from GreenDOT. However, we used PaLATE to estimate additional emissions from concrete and asphalt batch plants, which are not incorporated into the materials emissions factors used in GreenDOT.

5.2 Mitigation Strategies

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:

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

²⁰ NCHRP 25-25/Task 58 [Final], available at <http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2621>. Developed by ICF International.

²¹ <http://www.ce.berkeley.edu/~horvath/palate.html>.

- 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.

5.2.1 Alternative fuels and vehicle hybridization

5.2.1.1.1 Data sources

Data for the energy and GHG reductions related to alternative fuels and vehicle hybridization came from the following sources:

- Assumptions about the types of equipment associated with different construction processes were drawn from NCHRP's Fuel Factors.²²
- GreenDOT was used to estimate energy and emission reductions from hybridization of each type of equipment. GreenDOT also provided emission factors for different fuel types.
- U.S. Department of Energy's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model was used to determine reduction factors for GHG emissions and energy use from biodiesel use.²³

5.2.1.1.2 Calculation methods and assumptions

The emission reduction from hybridization is a direct result of the reduced fuel consumption by hybrid vehicles. The replacement of conventional diesel with biodiesel blends does not reduce energy consumption but reduces GHG emissions because of the lower carbon intensity associated with biodiesel.

Reductions from biodiesel use and hybrid replacements were calculated using the following steps:

- In order to calculate GHG emission reductions, we multiplied the fuel use for a given piece of diesel equipment by the GreenDOT emissions factors for conventional diesel and applied GREET GHG reduction factors for B20 and B100 biodiesel blends.
- In order to calculate the energy impacts due to biodiesel, we applied energy factors for B20 and B100 derived from GREET to the fuel use for a given piece of diesel equipment.

5.2.2 Vegetation management

5.2.2.1.1 Data sources

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

²² 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>.

²³ Argonne National Laboratory, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model 1, 2012, rev 1, U.S. Department of Energy, 2012.

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.

5.2.2.1.2 Calculation methods and assumptions

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

- 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.
- 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:

- 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.
- 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.

5.2.3 Snow fencing and removal strategies

5.2.3.1.1 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.

5.2.3.1.2 Calculation methods and assumptions

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

- 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.

- 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.
- 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.

5.2.4 In-place Roadway Recycling

5.2.4.1.1 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.²⁴

5.2.4.1.2 Calculation methods 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:

- 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.
- We took the midpoint of the range of GHG reductions identified for various in place recycling techniques surveyed in NCHRP 421.
- We took the average of the average reduction values from the NYSDOT report and from NCHRP 421.

²⁴ 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.

5.2.5 Warm Mix Asphalt

5.2.5.1.1 Data sources

Data on the mixing temperatures and energy consumption from warm mix asphalt technologies were pulled from Kristjansdottir et al.²⁵

5.2.5.1.2 Calculation methods 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.

5.2.6 Recycled and reclaimed materials

5.2.6.1.1 Data sources

We drew on two key data sources in order to quantify the GHG and energy reductions due to the use of recycled and reclaimed materials:

- GreenDOT, which is the primary source for the materials energy and emissions factors used in the Estimator and also contains factors for recycled and reclaimed materials.
- Data from Caltrans, which is a leader in the use of recycled and reclaimed materials in the roadway system, on the maximum potential deployment of these strategies. We also received additional information from Caltrans staff on the applicability of recycled and reclaimed materials.

5.2.6.1.2 Calculation methods and assumptions

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:

- 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.

²⁵ Kristjansdottir, O., Muench, S., Michael, L., & Burke, G. (2007). "Assessing Potential for Warm Mix Asphalt Technology Adoption." *Transportation Research Record* 2040, 91-99.

- 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.
- 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.

5.2.7 Preventive maintenance

5.2.7.1.1 Data sources

Preventive maintenance impacts were calculated using two sources of information:

- Typical cycles for roadway maintenance and rehabilitation were developed for two treatment regimes using expert input:
 - Pavement lifecycle without preservation
 - Pavement lifecycle with preservation
- Energy usage associated with each activity in the pavement lifecycle was drawn from Chehovits and Galehouse²⁶

5.2.7.1.2 Calculation methods and assumptions

We calculated average annual energy use associated with roadway maintenance and rehabilitation (following new roadway construction) for both cycles, in order to estimate the relative energy and emissions savings from a preventive maintenance cycle.

²⁶ Chehovits, J. and L. Galehouse, 2010, "Energy Usage and Greenhouse Gas Emissions of Pavement Preservation Processes," Compendium of Papers from the First International Conference on Pavement Preservation, http://techtransfer.berkeley.edu/icpp/papers/65_2010.pdf.

5.3 Impacts on Vehicle Operation

5.3.1.1.1 Data Sources

We estimated the impact of construction delay and pavement smoothness on GHG emissions and energy use due to vehicles operating on roadways subject to construction and resurfacing using the following data sources:

- A 2001 study completed by the Texas Transportation Institute (TTI) on the emissions impacts of delay due to construction projects.²⁷ The report estimates delay on roads of varying width and traffic volumes that are subject to varying levels of lane closures based on data from four locations around Texas.
- A scenario of excess traffic delay generated using the Highway Capacity Software.
- Two studies, one by the State of Missouri and the other by WesTrack, to estimate fuel savings resulting from road resurfacing, which involved driving vehicles over a section of road before and after resurfacing was completed and comparing fuel efficiency results.^{28,29}
- The 2013 Department of Energy Annual Energy Outlook, which contains projected fleetwide fuel efficiency averages for light-duty vehicles and for heavy-duty trucks.³⁰
- FHWA 2010 Highway Statistics, which contains information on the mix of vehicle miles traveled from light- and heavy-duty trucks.

5.3.1.1.2 Calculation methods and assumptions

For construction delay, the TTI report contained data on emissions of CO, NO_x, and VOC on a one-mile roadway segment during construction delay for multiple scenarios of construction schedules, annual average daily travel (AADT), and number of lanes closed; we calculated average emissions per AADT using data from a single scenario—a four-lane road with 56,000 AADT with one of two lanes per direction closed for construction work. Adjustment factors were developed from the various scenarios to account for closures of different numbers of lanes.

We apply the report's estimates of CO emissions using a rough equivalency of 20 grams of CO₂ to one gram of CO. Fuel consumption was derived using standard ratios of CO₂ emissions per gallon of fuel.³¹

²⁷ Benz, Robert and Fenno, David. "Emissions Due to Construction Equipment and Traffic Delays – Task 6: Contribution of Vehicular Emissions Caused by Reduction in Capacity During Roadway Construction." Texas Transportation Institute (TTI), 2001.

²⁸ Missouri Department of Transportation, "Pavement Smoothness and Fuel Efficiency: An Analysis of the Economic Dimensions of the Missouri Smooth Road Initiative." 2006. Available at <http://library.modot.mo.gov/RDT/reports/Ri05040/or07005.pdf>.

²⁹ FHWA, "Smoother Pavements Add Up to Savings at WesTrack," April 2000, available at <http://www.fhwa.dot.gov/publications/focus/00apr/smooother.cfm>

³⁰ Energy Information Administration, "Annual Energy Outlook 2013." April 2013. Available at [http://www.eia.gov/forecasts/aeo/pdf/0383\(2013\).pdf](http://www.eia.gov/forecasts/aeo/pdf/0383(2013).pdf).

³¹ To validate this method, the research team used an analysis approach specified by the Highway Capacity Manual to analyze the same parameters of the roadways in the TTI study. Similar results were obtained.

For road smoothness impacts, we took the average vehicle efficiency improvements from the Missouri and WesTrack studies, which were 1 percent for light-duty vehicles and 3.4 percent for heavy- and medium-duty vehicles. We applied these improvements to the average fuel efficiency for light- and heavy/medium-duty vehicles, weighted according to the proportion of U.S. VMT for each vehicle type, to calculate average reductions in energy and GHG emissions per vehicle. In order to use a consistent basis for estimating construction delay and road smoothness impacts, we calculated annual impacts by multiplying the per vehicle reductions in fuel use and emissions due to resurfacing by the traffic volume estimates from the TTI report on construction delay. Finally, we calculated total impacts of resurfacing projects over time assuming a declining efficiency-gain effect over a ten-year period based on work conducted by Mikhail Chester and the FHWA Long-Term Pavement Project.^{32, 33}

³² Chester, Mikhail, Life-cycle Environmental Inventory of Passenger Transportation in the United States, Institute of Transportation Studies, Dissertations, University of California, Berkeley, 2008.

³³ FHWA TechBrief, "Roughness Trends of Flexible Pavements." Publication #FHWA-RD-97-147. 1998. Last accessed August 30, 2012 at <http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltp/98132/98132.pdf>.

Appendix

This appendix summarizes the results developed for the energy use and emissions generated from construction project types and alternative construction and maintenance strategies. Those project types cover four major roadway project types, including the construction, reconstruction, expansion, and resurfacing of all sizes of roadways, new construction of a wide variety of alternative mode infrastructure including rail transit, bus rapid transit (BRT), bicycle lanes, and pedestrian walkways, as well as bridges of varying lengths. In addition to those major categories, the estimates also cover a range of common maintenance activities as well as estimates of the potential energy use and emissions reductions from alternative methods of construction and maintenance.

In general, the ICF team began the estimate development process with an analysis of the materials requirements necessary to complete each project over a single lane mile (or track mile) of a facility. Based on the estimate of the quantities of these major materials needed for each type of project, the team estimated the amount of fuel required by the equipment necessary to complete the work. Once the materials and fuel estimates were complete, the team estimated the energy and emissions associated with the fuel use, as well as the embodied energy and emissions associated with the production and transportation of the required construction materials. The following sections describe the process by which the ICF team estimated impacts for each type of activity.

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1. Roadways

The roadway component comprises six project types – resurfacing, reconstructing, adding a lane, lane widening, re-alignment, and constructing a new roadway – over seven roadway sizes. These roadway sizes include three distinct urban roadways ranging from local roads to highways, and four rural roadways ranging from local roads to interstates in rural settings. Additionally, the analysis developed estimates for a “toggle” to apply to projects in rocky or mountainous soil.

The roadway analysis focused on specific materials and specific activities already identified as important to roadway construction projects in the Battelle research. These key elements are:

➤ Materials

- Asphalt
- Concrete
- Base Stone
- Drainage Pipe
- Gate and Guardrail

➤ Activities

- Placement of all key materials
- Erosion Control and Landscaping
- Earthwork (rolling and grading)
- Pavement Striping and Marking

1.1. Data Sources Used

The major data sources are: 1) the BidTabs database developed and updated by Oman Systems, 2) the Battelle research which developed detailed materials requirements as inputs to FHWA’s HERS and HERS-ST models, and 3) established FHWA and AASHTO roadway construction profiles. For fuel use estimates, the team relied on the estimates developed for recent NCHRP research into updating the fuel use factors associated with roadway construction projects. In addition, the research of Mikhail Chester, which the team used primarily to support its work on estimates regarding alternative modes, also provided minor support in the roadway area. Finally, the GreenDOT model was utilized to estimate the energy and emissions associated with the upstream activities required to extract, refine, transport, and manufacture roadway materials.

The BidTabs and Battelle data sets served to contribute jointly to each estimate. The BidTabs data from construction bids over the past five years provided comprehensive estimates of materials associated with resurfacing projects, which are by far the most common type of roadway construction work. Battelle data was used to develop a larger share of the materials requirements and activity volumes for the more complex project types, but BidTabs data on the resurfacing components remained in use and were integrated with Battelle data on surface-material requirements for all project types. As a result, estimates were developed with the two data sets in

mutual support rather than as alternative sources. These estimates are “pavement material-neutral,” in that they represent a weighted average of the concrete and asphalt requirements from a wide range of projects utilizing both materials. Battelle weighted these values using the observed frequency of each surface type in the project data it collected in developing its own estimates of materials used.

Table A-1 shows which data sources were used to develop materials estimates for each project type and toggle.

Table A-1: Data Sources Supporting Roadway Estimates

Project Type	Data Source
New Construction	Battelle with BidTabs Support
Re-alignment	Battelle with BidTabs Support
Construct Additional Lane	Battelle with BidTabs Support
Lane Widening	Battelle with BidTabs Support
Shoulder Improvement	Battelle with BidTabs Support
Re-construct Pavement	Battelle with BidTabs Support
Resurface Pavement	BidTabs
Rolling/Mountainous/Rocky Soil Toggle	BidTabs

1.2. Materials Estimates

Through the use of the sources described previously, the team developed quantity estimates for each combination. The quantities were developed for four materials: asphalt, concrete, base stone, and steel. Steel estimates represent material required for both guardrail and fencing, which were separately estimated and then merged into a single quantity. Because the emissions and energy factors identified for concrete assumed some reinforcing steel (“rebar”) content already, the steel estimates were not adjusted to include rebar.

As an example, consider the approach to estimating new construction of an interstate through a rural area in Table A-2. The analysis began with extraction of Battelle’s estimates for major materials and activities.

Table A-2: Battelle Estimates for New Rural Highway Construction

ASPH	BASE	CONC	DRNG	EROC	ERTH	GATE	GRDR	PVMK
Asphalt	Base Course	Concrete	Drainage pipes, culverts, conduits	Erosion control activities	Earthwork incl grading & rolling	Gates & fences	Guardrail	Striping & marking
ton/lane mile	cubic yards	cubic yards	lineal feet	square yards	cubic yards	lineal feet	lineal feet	lineal feet
6,787	1,571	389	2,508	4,022	12,042	1,014	873	13,272

The next step involved adjusting these estimates to represent BidTabs data for the requirements of resurfacing projects, as shown in Table A-3. BidTabs data indicated that Battelle’s estimates for the resurfacing components of all project types were higher than the quantities actually used in the past five years. Asphalt quantities, in particular, were smaller per lane mile than Battelle’s report estimated.

Table A-3: BidTabs-Adjusted Battelle Estimates for New Rural Highway Construction

ASPH	BASE	CONC	DRNG	EROC	ERTH	GATE	GRDR	PVMK
Asphalt	Base Course	Concrete	Drainage pipes, culverts, conduits	Erosion control activities	Earthwork incl grading & rolling	Gates & fences	Guardrail	Striping & marking
ton/lane mile	cubic yards	cubic yards	lineal feet	square yards	cubic yards	lineal feet	lineal feet	lineal feet
3,232	1,662	364	2,412	4,247	12,228	1,120	829	13,404

Asphalt and base stone were the largest quantities reported. Concrete was comparatively minor. Steel quantities were also limited to ancillary elements.

Variance of Materials Requirements

Construction projects vary dramatically in their requirements for materials, even when nominally involving similar project types on similar roadway types. In practice, a specific project may require significantly more or significantly less than any single average would indicate.

In the development of the Battelle data, researchers assessed the distribution of data points for several major construction materials and activities, including asphalt, base, drainage, and earthwork. Even after deciding to eliminate outliers and values entirely at odds with typical construction profiles (which they defined as the top and bottom 10% of projects by quantity of each type of material or activity), Battelle researchers found fairly large variances in the quantities of materials required on a per-lane-mile basis. The Battelle team never developed variance estimates of materials by project type; rather, they used mean values after eliminating outliers and adjusting for assumed differences based on standard profiles of materials required by each functional class. As a result, the Battelle data does not provide a clear statement of the variance, or the potential range of likely requirements, for the specific materials estimates provided in this report.

In the development of the BidTabs data collected by Oman Systems, Inc., final estimates were developed by analysis of profiles requirements as well, leaving no clear indication from data of a standard deviation or typical range of materials requirements. Because project data from that database were not amenable to correlation with lane miles of affected roadway, the ICF team could not establish any indications of variance on a per-lane-mile basis for any project type.

The ICF team estimates, based on anecdotal experience, that the quantities of materials and fuels used in resurfacing projects can vary by approximately 15% above or below the estimates developed in this document. More intensive projects, such as reconstruction, lane addition, or new construction, likely have wider ranges of requirements – as much as 40 percent above or below average quantities.

1.3. Fuel Use Estimates

Fuel use by construction equipment corresponds to construction activities. These activities, such as paving, grading, placing drainage pipe, or placing base stone, all have different fuel use intensities. Striping a roadway, for example, requires few vehicles and involves moving no asphalt, stone, or earth. Building a bridge structure or laying large drainpipes, by contrast, require several vehicles and the movement of large quantities of material. These activities are thus much more fuel intensive per unit of work done.

The ICF team started with the quantities of each material required per lane mile of roadway for each combination, and applied appropriate fuel factors from the NCHRP research to develop estimates of the fuel use requirements of placing each material. For activities not estimated by volume or weight of materials (such as striping or guardrail placement), the team applied the appropriate fuel factors based on the volume of activity (such as the lineal feet of striping, or cubic yards of earth moved). All fuel is presumed to be diesel fuel. The research process used to develop the fuel factors was based on the development of lists of equipment required to complete each activity, and the overwhelming majority of fuel used for each activity was required by diesel-powered equipment. Gasoline, when required at all, was primarily used in light-duty support vehicles.

Table A-4 shows a simplified example of estimating fuel use involved in a single activity placing asphalt as part of a resurfacing project on a rural interstate.

Table A-4: Fuel Factor Application Example

Activity:	Asphalt Placement	
Fuel Factors:	Surface Course Placement (5-15 mile haul) and Milling (<2") (5-15 mile haul)	
Asphalt Quantity (Resurface Rural Interstate)	995	tons/lane mile
Fuel Use/Ton (Placement and Milling)	0.848	gallons/ton
Total Fuel Use	843.76	gallons per lane mile

A process similar to that depicted above was carried out for all activity volumes estimated, whether directly or through volumes of materials estimated to be placed. As an example, Table A-5 shows the fuel use estimates for nine major construction activities for the new construction of a rural interstate.

Table A-5: Fuel Use for New Rural Highway Construction

ASPH	BASE	CONC	DRNG	EROC	ERTH	GATE	GRDR	PVMK
Asphalt	Base Course	Concrete	Drainage pipes, culverts, conduits	Erosion control activities	Earthwork incl grading & rolling	Gates & fences	Guardrail	Striping & marking
ton/lane mile	cubic yards	cubic yards	lineal feet	square yards	cubic yards	lineal feet	lineal feet	lineal feet
3,232	1,662	364	2,412	4,247	12,228	1,120	829	13,404
Factor (gallons/unit)	Factor (gallons/unit)	Factor (gallons/unit)	Factor (gallons/unit)	Factor (gallons/unit)	Factor (gallons/unit)	Factor (gallons/unit)	Factor (gallons/unit)	Factor (gallons/unit)
0.847	0.406	1.517	0.645	0.017	0.412	0.043	0.004	0.00085
Fuel Use/ Lane mile	Fuel Use/ Lane mile	Fuel Use/ Lane mile	Fuel Use/ Lane mile	Fuel Use/ Lane mile	Fuel Use/ Lane mile			
2,737	675	553	1,555	72	5,036	48	3	11

Haul Distance

For some materials, the distance hauled to the site can be expected to vary, and the work required to haul is expected to represent significant energy expenditure and emissions generation. The Fuel Factors data contains differing estimates for certain activities based on haul distance to the job site. These activities include paving, milling of pavement, and grading. The haul distance options are:

- Less than five miles
- Five to fifteen miles
- Over fifteen miles

While other materials are heavy and require energy-intensive hauling as well, the Fuel Factors research effort did not develop differing estimates based on haul distance in all cases. The expectation that manufactured steel elements and pre-cast concrete elements would all be hauled great distances, and that quarried base stone haul distances could vary extremely from project to project, led the research team developing the Fuel Factors estimates to develop single estimates of energy use for those materials.

In its research, the team did not find a basis to assume different haul distances based on road type or urban/rural location of projects. With regard to asphalt, the team judged that the practice of establishing a dedicated plant near the construction site (in order to reduce delays and haul distances) is expected to be very rare in the future, and so should not be used to assume shorter haul distances for the most intensive project types. However, the team did elect to use the fuel factors associated with longer hauls for projects in rocky or mountainous terrain. The team expects that greater elevation change between plant and site will increase the fuel intensity of hauling materials, and has no basis to assume any shorter haul distance to offset this upward pressure on fuel use.

Table A-6 lays out estimates of fuel use associated with construction activities for each combination in the roadway area.

Table A-6: Fuel Use Estimates for Roadway Projects

Roadway Facility Types	Re-construct Pavement (per lane mile)	Resurface Pavement (per lane mile)	New Construction/ Re-Alignment (per lane mile)	Construct Additional Lane (per lane mile)	Lane Widening (per lane mile)	Shoulder Improvements (per ROW mile)
Rural Interstate	5,022	1,427	13,728	15,675	3,088	507
Rural Principal Arterials	4,100	1,311	11,853	12,702		
Rural Minor Arterials	3,784	1,011	11,489	12,430		
Rural Collectors	3,806	834	12,081	13,541		
Urban Interstates / Expressways	6,467	1,765	14,714	13,723		
Urban Principal Arterials	6,006	1,577	12,994	12,475		
Urban Minor Arterials / Collectors	5,686	1,213	14,159	12,884		
Rolling/Mountainous/ Rocky Soil Toggle	474					

1.4. Energy and Emissions Estimates

The ICF team estimated energy use and CO₂ emissions from construction projects from two sources: the fuel use required to place materials and carry out activities, and the energy and emissions embedded in the materials themselves. This estimate of “embedded” energy and emissions seeks to capture the processes of extracting raw materials, refining those materials into final products, and transporting those materials through all steps prior to its delivery to the project site and final placement.

Materials quantities were converted to estimates of embodied energy and CO₂ emissions in a two-step process. First, any composite materials were converted to primary materials using default mixing ratios provided in the GreenDOT model. For example, asphalt is generally composed of aggregate and bitumen. Concrete is generally composed of aggregate, cement, water, and sometimes steel. Second, volumes of primary materials were converted to embodied energy and CO₂ emissions using lifecycle values derived from the Pavement Lifecycle Assessment Tool (PaLATE), the source of emission factors in GreenDOT. PaLATE provides energy factors (MJ/ton) and emission factors (CO₂/ton) for primary materials, representing the energy and emissions associated with extraction and production of primary materials.

Table A-7 presents estimates of energy use, in millions of BTUs, associated with materials and fuel use for each project type. Table 8 presents estimates of CO₂ emissions (in metric tons) associated with materials and fuel use.³⁴

Table A-7: Energy Use (in Million BTUs) Associated with Roadway Construction Projects

Roadway Facility Types	Re-construct Pavement (per lane mile)	Resurface Pavement (per lane mile)	New Construction/ Re-Alignment (per lane mile)	Construct Additional Lane (per lane mile)	Lane Widening (per lane mile)	Shoulder Improvements (per ROW mile)
Materials subtotal	945	532	3,463	1,349	274	209
Asphalt	798	475	2,603	825	146	58
Base stone	36	13	319	157	71	83
Concrete	101	34	459	336	47	58
Steel	10	10	82	31	10	10
Construction subtotal	243	61	1,262	648	150	25
Construction fuel (DGEs)	243	61	1,262	648	150	25
Electricity (kWh)	0	0	0	0	0	0

Table A-8: Carbon Dioxide Emissions (in Metric Tons) Associated with Roadway Projects

Roadway Facility Types	Re-construct Pavement (per lane mile)	Resurface Pavement (per lane mile)	New Construction/ Re-Alignment (per lane mile)	Construct Additional Lane (per lane mile)	Lane Widening (per lane mile)	Shoulder Improvements (per ROW mile)
Materials subtotal	58	32	214	89	17	14
Asphalt	46	27	149	47	8	3
Base stone	2	1	19	10	4	5
Concrete	9	3	41	30	4	5
Steel	1	1	5	2	1	1
Construction subtotal	18	4	92	47	11	2
Construction fuel (DGEs)	18	4	92	47	11	2
Electricity (kWh)	0	0	0	0	0	0

³⁴ BTUs and metric tons were chosen as units for these tables because they are consistent with the units typically used in other greenhouse gas inventory and analysis efforts. The fuel use emissions estimates reflect direct emissions only (so-called “tailpipe” emissions of carbon dioxide). These estimates do not capture other greenhouse gases or “upstream” emissions associated with extraction, refinement, and transport of diesel fuel.

1.5. Indirect Impacts

The team also developed estimates for two distinct indirect impacts expected as a result of many construction projects: roadway delay impacts, in which roadway delays reduce vehicle efficiency of vehicles passing construction zones, and post-construction roadway smoothness improvements, in which new roadway surfaces improve the fuel efficiency of vehicles over the existing roadway. Both delay and smoothness effects are considered to apply only to projects over which existing traffic flows already exist; delays apply on projects for which traffic continues to flow, but on fewer than the total number of lanes and smoothness effects apply on roadways for which traffic was present prior to the construction project and for which the surface was improved.

Delay impacts of construction were developed as an estimate of excess emissions per project-day of lane closure per AADT. In practice, delays are highly sensitive to a number of factors. Existing traffic volumes on individual roadway links affect the likelihood of congestion when one or more lanes are taken out of use. The number of lanes of a road, and the number left in use while others are removed from use, also affect the potential for congestion. The team judged that model users were unlikely to know with confidence these details in a long term planning context. Model users would be able to estimate delay based on a single estimate of project-days of lane closure and an estimate of average systemwide traffic volumes. An adjustment factor for percentage of lanes closed was also developed with three options: less than 50 percent, 50 percent, and greater than 50 percent.

The delay impacts were developed using a 2001 study completed by the Texas Transportation Institute (TTI) on emissions of CO, NO_x, and VOC on a one-mile roadway segment during construction delay.³⁵ The report estimated emissions scenarios for lane reductions on roadways from two to five lanes across, and from one lane reduced up to all but one lane reduced, for a one-mile segment. These estimates were developed for three traffic volume levels, and were developed for seven combinations of peak and off-peak traffic across four locations around Texas. For this analysis, the team used data from a single scenario – a four lane road with moderate travel volume experiencing one lane reduced per direction for construction work.

Because the TTI study did not provide emissions estimates for baseline scenarios of traffic without construction, the research team modeled a separate scenario of traffic delay using the Highway Capacity Software. The research team modeled excess emissions on a one-mile segment of arterial/expressway with AADT of 20,000 and a free-flow travel speed of 45 mph. Construction was assumed to close one lane in each direction for eight hours per day during off-peak travel times, with a traffic volume of 800 vehicles per hour. The resulting excess emissions of CO₂ per day were about 40 percent higher than the baseline. This information was used to adjust the TTI estimates to approximate excess emissions due to construction delay.

Table A-9 presents the estimates developed from the TTI research for delay impacts, assuming 50 percent of lanes closed. (Adjustment factors were also developed from the various scenarios to account for closures of different numbers of lanes.) Because projects vary greatly in the length of

³⁵ Benz, Robert and Fenno, David. "Emissions Due to Construction Equipment and Traffic Delays – Task 6: Contribution of Vehicular Emissions Caused by Reduction in Capacity During Roadway Construction." Texas Transportation Institute (TTI), 2001.

time required for completion (and consequently, in the number of days of delay), estimates are provided per day of lane closure per AADT.³⁶

Table A-9: Roadway Delay Energy & Emissions Effect Estimates on 1 mile segment Per Project Day of Lane Closure

Additional Grams CO2 per AADT	Additional Gallons of Gasoline per AADT
99.6	0.01

The number of days of delay varies widely by project and is not necessarily related to the duration of the project itself. Therefore the ICF team does not propose default values for duration of delay in the tool. The user of the tool will be free to enter assumptions about delays expected.

Road Smoothness Impacts were estimated using another source. Using the same travel volume assumptions for roadways as in the delays estimate in order to keep the two indirect impact analyses consistent, the team utilized the Missouri and WesTrack studies to establish estimates for vehicle efficiency improvements resulting from smoother surfaces. These estimates were 1 percent for light-duty vehicles (from the Missouri testing program) and 3.4 percent for heavy-duty vehicles (the average of the Missouri and WesTrack testing results). These efficiency gains were applied to current fleetwide fuel efficiency averages derived from DOE Annual Energy Outlook 2013. Assumptions about the relative mix of light-duty and heavy-duty vehicle traffic on roadways are derived from FHWA Highway Statistics. Using Mikhail Chester’s assumption that asphalt pavements endure ten years on average, this analysis assumed a declining efficiency-gain effect over a ten-year period. The profile of this decline was established to be roughly consistent with FHWA Long-Term Pavement Project understandings that pavements lose optimal surface smoothness quickly, but retain relatively consistent roughness levels (IRI indices) for several years until a rapid increase in roughness occurs.³⁷

Table A-10 depicts the fuel-use, energy-use, and carbon dioxide emission reductions achieved per 1000 VMT per lane mile of resurfaced road estimated under the approach described above.

Table A-10: Roadway Smoothness Impacts per 1000 VMT in the First Ten Years after Repaving

	Fuel Savings (Gallons)	Energy Savings (MMBTU)	CO2 Emissions Reduction (MT CO2)
Per 1000 VMT (weighted average of light-duty and heavy-duty)	22.4	2.8	0.2

By these estimates, for example, a resurfacing project on a one-mile segment of a roadway with two lanes in each direction and average daily traffic volumes of 1000 vehicles per direction, and requiring four days of lane closure with one lane closed at a time, would induce approximately 0.4 metric tons of CO₂ emissions from delayed traffic over the duration of the resurfacing effort (in addition to

³⁶ To validate this method, the research team used an analysis approach specified by the Highway Capacity Manual to analyze the same parameters of the roadways in the TTI study. Similar results were obtained.

³⁷ FHWA TechBrief, “Roughness Trends of Flexible Pavements.” Publication #FHWA-RD-97-147. 1998. Last accessed August 30, 2012 at <http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltp/98132/98132.pdf>.

emissions from construction activities and materials), and would induce a reduction of approximately 0.4 metric tons over the following decade.

2. Rail, Bus, Bicycle, and Pedestrian

The alternative mode facilities for which construction energy and emissions estimates were developed are:

- Light Rail
- Heavy Rail
- Bus Rapid Transit (BRT)
- Bicycle Lanes
- Pedestrian Sidewalks

Estimates for rail and BRT construction are separated into estimates for actual transitway and estimates for transit stations. This allows the end user make separate decisions about the length of a new transit line and the number of stations to be constructed.

2.1. Review of Data Sources

The primary source of data for transit infrastructure projects is Mikhail Chester's research into the lifecycle energy and emissions of transit infrastructure. This work served as the central resource for material requirement estimates associated with rail transit, including new construction on dedicated rights-of-way as well as transit stations at-grade, underground, and elevated above ground. The station estimates for light rail from Chester's work also informed the development of BRT station estimates.

Some alternative mode projects are connected to roadway work, such as the construction of bicycle lanes, light rail on existing roadways, and BRT routes. The ICF team sought in these cases to identify the most appropriate roadway project estimates as the basis for estimates to complete these projects.

For example, the team analyzed the conversion of an existing lane to a BRT lane by starting with estimates for roadway reconstruction projects on urban major collectors, while converting a lane to a bike lane was deemed more consistent with resurfacing – specifically resurfacing a local roadway in an urban area. With these roadway projects as templates, specific activities and materials (e.g., guardrail construction) were adjusted to more accurately reflect the differences between the alternative mode facility and standard roadway construction.

Bicycle lanes were also analyzed within the framework of the roadway analysis, because the materials and activities (the laying of base stone and asphalt, or the conversion of existing roadway space to bike lanes) are the same in nature as the materials and activities associated with roadway projects. However, the quantities required were adjusted to be consistent with the profiles for Class I bicycle paths (dedicated rights-of-way not attached to roadways) and Class II bicycle paths (which are exclusive to bicycles but use space on existing roadways). These paths are between 5 and 9 feet wide – narrower than a roadway lane – and require far less ancillary infrastructure such as guardrails and drainage. The estimates reflect these smaller, simpler profiles, as well as the reduced likelihood that Class II lanes will require any new base stone or pavement.

Finally, ICF team member Hatch Mott MacDonald completed its own dedicated analysis of the materials requirements associated with digging underground transit tunnels and building elevated rail transitways. In particular, this analysis estimated the energy requirements associated with boring tunnels for underground transit.

Table A-11 displays the data sources used for materials estimates of each rail, bus, and bicycle facility type.

Table A-11: Rail, Bus, and Bicycle Facilities Materials Data Sources

Facility Type	Project Type	Data Source
Light Rail Transit	New Dedicated Lane or Right of Way (At Grade)	Chester Analysis
	Converted or Upgraded Existing Facility (At Grade)	Chester & Roadway Analysis
	New Dedicated Lane or Right of Way (Elevated)	HMM Analysis
	New Dedicated Lane or Right of Way (Underground Through Hard Rock)	HMM Analysis
	New Dedicated Lane or Right of Way (Underground Through Soft Soil)	HMM Analysis
Bus Rapid Transit	New Dedicated Lane or Right of Way	Chester & Roadway Analysis
	Converted or Upgraded Existing Facility	Chester & Roadway Analysis
Bicycle	New Dedicated Lane or Right of Way	Roadway Analysis & Profiles
	Converted or Upgraded Existing Facility	Roadway Analysis & Profiles
Heavy Rail Transit	New Dedicated Lane or Right of Way (At Grade)	Chester Analysis
	New Dedicated Lane or Right of Way (Elevated)	HMM Analysis
	New Dedicated Lane or Right of Way (Underground Through Hard Rock)	HMM Analysis
	New Dedicated Lane or Right of Way (Underground Through Soft Soil)	HMM Analysis
At Grade Station	Light Rail Station	Chester Analysis
	Heavy Rail Station	Chester Analysis
Elevated Station	Light Rail Station	Chester Analysis
	Heavy Rail Station	Chester Analysis
Underground Station	Light Rail Station	Chester Analysis
	Heavy Rail Station	Chester Analysis

2.2. Materials Estimates

Through the use of the sources described above, the team developed quantity estimates for each combination. The quantities were developed for four materials: asphalt, concrete, base stone, and

steel. Concrete becomes a very significant material in these estimates, requiring hundreds of thousands of tons per track mile in some cases. Steel estimates represent material required for both train rails and underground support structures, which were separately estimated and then merged into a single quantity. Because the emissions and energy factors identified for concrete assumed some reinforcing steel (“rebar”) content already, the steel estimates were not adjusted to include rebar.

Table A-12 presents the materials requirement estimates, in metric tons, developed for alternative mode infrastructure.

Table A-12: Materials Required for Construction of Rail, Bus, Bicycle, and Pedestrian Facilities

Facility Type	Project Type	Materials Required (MT/lane mile, track mile or station)			
		Asphalt	Concrete	Steel	Base Stone/ Ballast
Light Rail Transit	New Dedicated Lane or Right of Way (At Grade)	0	897.1	79.8	12,410
	Converted or Upgraded Existing Facility (At Grade)	1334.1	0	79.8	12,779
	New Dedicated Lane or Right of Way (Elevated)	0	16,433	1,315	9,571
	New Dedicated Lane or Right of Way (Underground Through Hard Rock)	0	904,493	2,404	0
	New Dedicated Lane or Right of Way (Underground Through Soft Soil)	0	904,493	2,404	0
Bus Rapid Transit	New Dedicated Lane or Right of Way	1,325	746	0	2,590
	Converted or Upgraded Existing Facility	1,139	302	0	1,143
Bicycle	New Dedicated Lane or Right of Way	530	0	1	760
	Converted or Upgraded Existing Facility	190	0	1	40
Heavy Rail Transit	New Dedicated Lane or Right of Way (At Grade)	0	2,691	80	16,567
	New Dedicated Lane or Right of Way (Elevated)	0	18,898	1,315	11,022
	New Dedicated Lane or Right of Way (Underground Through Hard Rock)	0	904,493	2,404	0
	New Dedicated Lane or Right of Way (Underground Through Soft Soil)	0	904,493	2,404	0
At Grade Station	Light Rail Station	0	20,643	6	1315
	Heavy Rail Station	0	672,827	23	4706
Elevated Station	Light Rail Station	0	474,037	6	0
	Heavy Rail Station	0	1,100,989	23	0
Underground Station	Light Rail Station	0	293,597	188	0
	Heavy Rail Station	0	1,177,446	706	0
Pedestrian	New sidewalk	0	82	0	123

2.3. Fuel Use Estimates

The ICF team worked to identify the most appropriate fuel factor for the placement of each type of material. In many cases, appropriate fuel factors already existed. In other cases, the team reviewed the fuel factors work to identify the most appropriate factor based on machinery used and material handled.

Table A-13 shows the fuel use estimates developed using this approach.

Table A-13: Fuel Use Estimates for Rail, Bus, Bicycle, and Pedestrian Construction Projects

Facility Type	Project Type	Fuel Use (gallons of diesel/lane mile, track mile, or station)	Fuel Use (kWh/lane mile or track mile)
Light Rail Transit	New Dedicated Lane or Right of Way (At Grade)	10,729	
	Converted or Upgraded Existing Facility (At Grade)	7,331	
	New Dedicated Lane or Right of Way (Elevated)	61,459	
	New Dedicated Lane or Right of Way (Underground Through Hard Rock)	314,615	2,177,700
	New Dedicated Lane or Right of Way (Underground Through Soft Soil)	288,115	891,750
Bus Rapid Transit	New Dedicated Lane or Right of Way	19,370	
	Converted or Upgraded Existing Facility	6,905	
Bicycle	New Dedicated Lane or Right of Way	1,200	
	Converted or Upgraded Existing Facility	560	
Heavy Rail Transit	New Dedicated Lane or Right of Way (At Grade)	35,685	
	New Dedicated Lane or Right of Way (Elevated)	70,678	
	New Dedicated Lane or Right of Way (Underground Through Hard Rock)	314,615	2,177,700
	New Dedicated Lane or Right of Way (Underground Through Soft Soil)	288,115	891,750
At Grade Station	Light Rail Station	859	
	Heavy Rail Station	45,041	
Elevated Station	Light Rail Station	29,672	
	Heavy Rail Station	111,811	
Underground Station	Light Rail Station	60,625	
	Heavy Rail Station	161,558	
Pedestrian	New sidewalk	174	

2.4. Energy and Emissions Estimates

The team estimated energy use and CO₂ emissions from construction projects using two sources: the fuel required to place materials and carry out activities, and the energy and emissions embedded in the materials themselves. The team utilized GreenDOT to estimate the embedded energy and emissions associated with materials.

Materials quantities were converted to estimates of embodied energy and CO₂ emissions in a two-step process. First, any composite materials were converted to primary materials using default

mixing ratios provided in the GreenDOT model. For example, asphalt is generally composed of aggregate and bitumen. Concrete is generally composed of aggregate, cement, water, and sometimes steel. Second, volumes of primary materials were converted to embodied energy and CO₂ emissions using lifecycle values derived from the Pavement Lifecycle Assessment Tool (PaLATE), the source of emission factors in GreenDOT. PaLATE provides energy factors (MJ/ton) and emission factors (CO₂/ton) for primary materials, representing the energy and emissions associated with extraction and production of primary materials.

3. Bridges

The analysis of the energy requirements and CO₂ emissions associated with bridge construction projects took into account the following parameters:

- **Length of a Bridge.** Most bridges are less than 150 feet in length. Major crossings of significantly greater length require much more extensive engineering and construction, and require significantly more materials to support the additional load.
- **Water or Land Crossing.** Bridges crossing land require less intensive construction and maintenance than those crossing water, which must either span larger lengths between supports or utilize supports built into the floor of the body of water itself. In either case, the structure is significantly more materials-intensive and labor-intensive than an equivalent crossing over land, for which supports may generally be placed more freely.
- **Width.** The width, either in number of lanes and shoulders or in actual feet, affects the load and the design of a bridge significantly. These changes in turn require significant changes in material and energy requirements.

Based on the combinations of these characteristics and the data typically available for user to input, four bridge types were selected to estimate materials and energy use: single span; two-span; multi-span over land; and multi-span over water.

3.1. Materials Estimates

To develop materials estimates for bridges, the following parameters were selected for consideration:

- Structure length
- Shoulder width
- Slab thickness

Based on these parameters, estimates were created for the concrete required to build the components of the bridge structure shown in Table A-14. The total concrete requirement was normalized by average lane span.

Table A-14: Sub-component Estimates of Bridge Substructure and Superstructure

Superstructure	Substructure
Deck	Footings
Beams	Piers
Barrier Rail	Caps
	Incidental Concrete

Adjustments for steel structures were made by removing the concrete beam calculations and substituting steel weight based on a steel beam weight of 375 pounds per linear foot of beam as well as increasing the average span of steel beams over concrete beams by 20 percent.

Calculating the requirements for structures over water, adjustments were made to the substructure requirements based on using concrete piling instead of concrete footings. The quantity calculation for piling uses less concrete but requires additional equipment time to place; therefore, the quantities will be lower but the overall fuel consumed will be higher for structures over water.

These calculations assume “typical” structure construction design. There are numerous examples across the country of structures that are unique and do not conform to this typical design. Although many of the same assumptions apply to these special structures (i.e., the bridge deck assumptions are still valid), the substructures and steel support structures will vary widely.

Table A-15: Estimates of Concrete, Steel, and Fuel Required for Bridge by Type

Material or Fuel	Bridge Type	Construct New Bridge	Reconstruct Bridge	Add Lane to Bridge
Concrete (metric tons per lane-span)	Single-Span	199	199	199
	Two-Span (over land or water)	268	268	268
	Multi-Span (over land)	291	291	291
	Multi-Span (over water)	260	260	260
Steel (metric tons per lane-span)	Single-Span	0	0	0
	Two-Span (over land or water)	3	3	3
	Multi-Span (over land)	9	9	9
	Multi-Span (over water)	9	9	9
Fuel (DGEs per lane-span)	Single-Span	525	700	800
	Two-Span (over land or water)	740	1,020	1,090
	Multi-Span (over land)	1,190	1,540	2,140
	Multi-Span (over water)	1,040	1,360	1,890

3.2. Fuel Use Estimates

Fuel use by construction equipment corresponds to the volume and fuel intensity of different construction activities required to complete the project in question. The analysis relied on fuel use factors developed as part of the NCHRP Fuel Factors research effort. The key factors which informed fuel use estimates for bridges were as follows:

- Substructure Concrete Placement
- Superstructure Concrete Placement
- Steel Beam Placement
- Concrete Barrier Placement
- Concrete Pavement Placement
- Pavement Removal (for Reconstruction projects)
- Structure Demolition (for Reconstruction projects)

In addition, the team utilized Oman Systems' expertise to modify the fuel factors where appropriate to represent more accurately the way in which different project types or terrains require different levels of work to achieve the same quantity of bridge construction. This was done for both over-water bridges and for lane-addition projects. Bridges over water were assumed to have a slightly smaller quantity of total deck square footage per 100 feet of lane than were bridges built over land. Using fixed fuel factors for both risked misrepresenting the increased amount of work and machinery use required to place support footings over (or in) bodies of water. As such, fuel factors for substructure placement were modified upward by 30 percent to represent the extra effort and time required. In lane-addition projects, which are also routinely more labor-intensive and time-consuming per unit of construction, the team adjusted fuel factors for both superstructure and substructure activities upward by 22.5 percent. These adjustments are important because the materials requirements per lane-span for all of the project types can be quite similar, but the work involved with completing each is distinct in its activities and fuel use requirements. Because the Fuel Factors analysis itself did not develop different estimates for bridge structure construction based on the type of project or the terrain crossed, the team took these steps to ensure the estimates above represented these different work requirements.

3.3. Energy and Emissions Estimates

The team used the GreenDOT model to develop estimates of energy and emissions embedded in materials and EPA estimates for the direct CO₂ emissions associated with construction equipment operation.

4. Routine Maintenance Fuel Usage

4.1. Roadways

Average annual maintenance fuel use per mile or per lane mile was calculated primarily from maintenance fuel records obtained from state DOTs. Utah and Washington DOTs provided a list of maintenance activities performed and the corresponding fuel use for each activity. These activities were then categorized into three categories of interest: snow removal, vegetation management, and preventive maintenance, plus an additional category for all other maintenance activities. (Preventive maintenance techniques include crack sealing, patching, chip seals, and micro-surfacing.) The data provided by these two DOTs lacked sufficient information to separate out fuel usage associated with bridge maintenance and to differentiate between fuel used for asphalt and concrete preservation, so fuel used for bridge maintenance is included in the other maintenance category, and the preventive maintenance category includes both asphalt and concrete preservation. Fuel use from all maintenance activities was summed to find total maintenance fuel use per year. Additionally, New York DOT provided totals for snow removal and vegetation management fuel use, and Pennsylvania DOT provided the total annual maintenance fuel use. Maintenance fuel use per year by category for all four states is shown in Table A-16.

Table A-16: Total Fuel Use per Year, in Diesel Gallon Equivalents (DGEs)

Category	UT	WA	NY	PA
Snow Removal	713,921	900,831	3,192,508	—
Vegetation Management	27,340	224,188	67,426	—
Preventive Maintenance	51,721	347,724	—	—
Other Maintenance	771,593	1,352,950	—	—
Total Maintenance	1,564,576	2,825,692	—	9,872,509

The state DOT maintenance fuel records only take into account maintenance activities performed by the state and do not factor in fuel use from maintenance activities performed by contractors. The ICF team obtained estimates from Utah and Washington DOT on the percentage of work in each category completed by contractors in terms of costs and assumed that the amount of fuel used by contractors was proportional to the amount spent on their work in order to estimate fuel used by contractors. The contractor fuel use was added to the state total to calculate the total fuel use for the state. The percentage estimates of road maintenance completed by contractors are shown in Table A-17, and the total maintenance fuel use including contractor fuel use factored in is shown in Table A-18.

Table A-17: Estimated Percentages of Road Maintenance Completed by the State and by Contractors by Activity Category

State	Category	State %	Contractor %
Utah	Snow Removal	99.0%	1.0%
	Vegetation Management	80.0%	20.0%
	Preventive Maintenance	90.0%	10.0%
	Other	90.0%	10.0%
Washington	Snow Removal	97.5%	2.5%
	Vegetation Management	95.3%	4.8%
	Preventive Maintenance	97.5%	2.5%
	Other	97.5%	2.5%

Table A-18: Total Annual Fuel Use Including Contractor Fuel Use, in Diesel Gallon Equivalents (DGEs)

Category	UT	WA	NY	PA
Snow Removal	721,133	923,929	3,192,508	—
Vegetation Management	34,175	235,368	67,426	—
Preventive Maintenance	57,468	356,640	—	—
Other Maintenance	925,641	1,382,209	—	—
Total Maintenance	1,738,418	2,898,146	—	9,872,509

Next, the ICF team calculated the total maintenance fuel use per mile or per lane mile of state-owned roadways. Because vegetation management occurs on the roadside or in the median, the associated fuel use was calculated on a per mile basis, while all other activities are calculated on a per lane mile basis. Total state-owned miles and lane miles were obtained from FHWA Highway Statistics and are shown in Table A-19. The calculated gallons per lane mile or per mile, including contractor fuel use, are shown in Table A-20. The team estimated the total fuel usage for other maintenance activities for Utah and Washington by subtracting the fuel used for snow removal, vegetation management, and preventive maintenance from total fuel usage and dividing the result by the total number of lane miles in each state.

Table A-19: Total State-Owned Centerline Miles and Lane Miles³⁸

	UT	WA	NY	PA
Total State-owned Centerline Miles	5,841	7,042	14,969	39,862
Total State-owned Lane miles	15,699	18,443	38,142	88,475

³⁸ 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>

Table A-20: Estimated Annual Fuel Usage by Category³⁹

Category	Units	UT	WA	NY	PA
Snow Removal	DGEs/Lane mile	45.9	50.1	83.7	—
Vegetation Management	DGEs/Mile	5.9	33.4	4.5	—
Preventive Maintenance	DGEs/Lane mile	3.7	19.3	—	—
Other Maintenance	DGEs/Lane mile	59.0	74.9	—	—
Total Maintenance	DGEs/Lane mile	110.7	157.1	—	124.0

The fuel usage associated with maintenance activities varies heavily according to climate. Because there was significant climatic variety among the states that supplied data, the team estimated the range of fuel usage associated with different maintenance activities using the following assumptions:

- New York, which typically experiences relatively heavy snowfall statewide, represents the upper end of fuel usage associated with snow removal.
- Utah and Washington, which typically experience heavy snowfall in some areas and lighter snowfall in others, represent the middle range of fuel usage associated with snow removal. The mean of the values was calculated from these two states.
- States that experience little to no snowfall do not use any fuel for snow removal.
- Washington, which is a temperate state with a variety of vegetation zones, represents the upper end of fuel usage associated with vegetation management.
- Utah, which is primarily desert, represents the lower end of fuel usage associated with vegetation management.
- Fuel usage for preventive maintenance varies primarily in proportion with level of effort. Preventive maintenance data was only received from two states, Washington and Utah; based on an analysis of this data, Washington was assumed to represent the upper end and Utah the lower end of fuel usage for preventive maintenance.

In order to estimate the total maintenance emissions within a given state, the team also added in fuel used for other maintenance activities. Only two states, Washington and Utah, submitted data on both total fuel usage and fuel usage associated with all three categories of maintenance activities in this study. ICF estimated the total fuel usage for other maintenance activities for these two states, which is shown in Table 20, by subtracting the fuel used for snow removal, vegetation management, and preventive maintenance from total fuel usage and dividing the result by the total number of lane miles in each state. The average of the values for Utah and Washington was used as the average fuel usage associated with other maintenance activities. Table 21 summarizes the assumptions discussed above and the associated fuel usage values.

³⁹ Note that columns do not sum to the total because of the different units used for each category.

Table A-21: Estimated Range of Annual Fuel Usage by Category

Category	Units	Low Value	Middle Value	High Value
Snow Removal	DGEs/Lane mile	0.0	47.2	83.7
Vegetation Management	DGEs/Mile	5.9	—	33.4
Preventive Maintenance	DGEs/Lane mile	3.7	—	19.3
Other Maintenance	DGEs/Lane mile	67.0		

In order to estimate total fuel used for roadway maintenance for a given project, the spreadsheet tool sums four elements:

- Gallons used per lane mile for snow removal from Table A-21, based on whether the area of analysis receives little to no snow, moderate snow, or heavy snow, multiplied by the total number of lane miles.
- Gallons used per roadway mile for vegetation management from Table A-21, based on whether the area has high or low levels of vegetation, multiplied by the total number of roadway miles.
- Gallons used per lane mile for preventive maintenance from Table A-21, based on the DOT's relative level of effort, multiplied by the total number of lane miles.
- Gallons used per lane mile for other maintenance activities from Table A-21, multiplied by the total number of lane miles.

The resulting sum is then divided by the number of lane miles in order to arrive at a figure for maintenance fuel usage per lane mile for roadway maintenance.

4.2. Bus Rapid Transit and On-street Bike Lanes

The ICF team drew on the analysis of roadway maintenance costs to estimate the energy use associated with bus rapid transit (BRT) and bike lanes, which share the same basic characteristics as vehicular travel lanes and are maintained using similar equipment and approaches. It was 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 bike lanes varies, the team 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. This means that the total fuel used for maintenance per lane mile for dedicated BRT lanes would be equal to the total fuel used per lane mile for roadway maintenance, while for bike lanes it would be half of the total fuel used per lane mile for roadway maintenance.

4.3. Off-street Bike Paths and Trails

We assumed that off-road bike paths and trails have the roughly the same dimensions as on-street bike lanes, and that these facilities are maintained half as frequently as roadway facilities.⁴⁰ Therefore, we estimated that the total amount of fuel used per lane mile for maintenance of these facilities is equal to one-quarter the fuel used per lane mile for roadway facilities.

4.4. Rail

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, annual maintenance fuel use for all modes was 832,974 DGEs in 2010. We estimated the amount of fuel used for rail maintenance based on the percentage of the agency's vehicle revenue miles travelled by rail (13 percent), which amounts to 104,973 DGEs for annual rail maintenance fuel use. We then divided this total by LA Metro's 153 directional miles of rail to obtain a value of 686 DGEs per directional mile per year for rail maintenance fuel use.

4.5. Parking

We drew on the analysis of roadway maintenance costs to estimate the energy use associated with parking lots, which share the same basic pavement characteristics as vehicular travel lanes and are maintained using similar equipment and approaches. However, parking is not measured in terms of lane miles, but in terms of surface area. The recommended width for a freeway lane is 12 feet, which means that there are 63,360 square feet per lane mile.⁴¹ We divided total maintenance costs per lane mile by this factor in order to estimate the gallons of fuel used per square foot for maintenance activities.

⁴⁰ A survey of rails-to-trails projects found that asphalt trails were typically sealed after 9 years. (Rails-to-Trails Conservancy Northeast Regional Office, *Rail-Trail Maintenance & Operation: Ensuring the Future of Your Trails – A Survey of 100 Rail-Trails* July 2005, available at: http://www.railstotrails.org/resources/documents/resource_docs/maintenance_operations_report.pdf. Meanwhile, Pennsylvania DOT seals roadway cracks every 3 to 5 years and seal coats rural bituminous roadways every 4 to 7 years. "Pavement Preservation at PennDOT," presentation at NEPPP, December 12, 2007. Available at: <http://www.pavementpreservation.org/wp-content/uploads/presentations/Pavement%20Preservation%20at%20PennDOT.pdf>.)

⁴¹ American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets*, 6th ed. Washington, DC: AASHTO. 2011.

5. Alternative Construction and Maintenance Techniques

The ICF team quantified the GHG emissions and energy usage associated with the 19 alternative construction and maintenance strategies listed below in terms of the percentage reduction below typical construction practices.

- Alternative fuels and vehicle hybridization
 - Hybrid vehicles / equipment in maintenance vehicles
 - Switch from diesel to B20 in maintenance vehicles
 - Switch from diesel to B100 in maintenance vehicles
 - Combined hybridization/B20 in maintenance vehicles
 - Hybrid vehicles / equipment in construction vehicles
 - Switch from diesel to B20 in construction vehicles
 - Switch from diesel to B100 in construction vehicles
 - Combined hybridization/B20 in construction vehicles
- Vegetation management
- Snow fencing and removal strategies
- In-place roadway recycling
 - Cold in-place recycling
 - Full depth reclamation
- Warm mix asphalt
- Recycled and reclaimed materials
 - Use recycled asphalt pavement as a substitute for virgin asphalt aggregate
 - Use recycled asphalt pavement as a substitute for virgin asphalt binder
 - Use industrial byproducts as substitutes for portland cement
 - Use recycled concrete aggregate as a substitute for base stone
- Preventive maintenance

Developing reduction percentages involved either comparing the GHG emissions and energy use associated with alternative techniques to emissions and energy use associated with a baseline scenario or reviewing available research on the reduction potential of alternative techniques. In both cases, we drew first on the research summarized in the literature review, and turned to other sources only if this research did not contain sufficient information to quantify the impacts of alternative techniques. Table A-22 summarizes the reduction in energy use and GHG emissions from

each of the alternative construction and maintenance techniques quantified, as well as to what these reductions apply.

Table A-22: Reductions in GHG Emissions and Energy Use Due to Mitigation Strategies and Applicability of Strategies

Strategy	Maximum Recommended Deployment	GHG Reduction Factor	Energy Use Reduction Factor	Applied to
Alternative fuels and vehicle hybridization				
Hybrid vehicles / equipment in maintenance vehicles	44%	11%	11%	Fuel use by maintenance equipment
Switch from diesel to B20 in maintenance vehicles*	100%	14%	-9%	Fuel use by maintenance equipment
Switch from diesel to B100 in maintenance vehicles*	100%	76%	-50%	Fuel use by maintenance equipment
Combined hybridization/B20 in maintenance vehicles*	44%	27%	1%	Fuel use by maintenance equipment
Hybrid vehicles / equipment in construction vehicles	44%	11%	11%	Fuel use by construction equipment
Switch from diesel to B20 in construction vehicles*	100%	14%	-9%	Fuel use by construction equipment
Switch from diesel to B100 in construction vehicles*	100%	76%	-50%	Fuel use by construction equipment
Combined hybridization/B20 in construction vehicles*	44%	27%	1%	Fuel use by construction equipment
Vegetation management				
Temperate states	N/A**	25%	25%	Fuel use by vegetation management equipment
Desert states	N/A**	1%	1%	Fuel use by vegetation management equipment
Snow fencing and removal strategies				
States with high level of snow removal effort	N/A**	50%	50%	Fuel use by snow removal equipment
States with moderate level of snow removal effort	N/A**	1%	1%	Fuel use by snow removal equipment
States with no snow	N/A**	0%	0%	Fuel use by snow removal equipment
In-place roadway recycling				
Cold in-place recycling	99%	37%	33%	Asphalt and fuel use by construction equipment in roadway resurfacing and BRT conversions

Table A-22: Reductions in GHG Emissions and Energy Use Due to Mitigation Strategies and Applicability of Strategies

Strategy	Maximum Recommended Deployment	GHG Reduction Factor	Energy Use Reduction Factor	Applied to
Full depth reclamation	99%	68%	68%	Base stone and fuel use by construction equipment in roadway reconstruction and BRT conversions
Warm mix asphalt				
Warm mix asphalt	100%	37%	37%	Asphalt use in all projects
Recycled and reclaimed materials (not recycled in place)				
Use recycled asphalt pavement as a substitute for virgin asphalt aggregate	25%	12%	12%	Asphalt use in all projects
Use recycled asphalt pavement as a substitute for virgin asphalt binder	40%	84%	84%	Asphalt use in all projects
Use industrial byproducts as substitutes for portland cement	33%	59%	59%	Concrete use in all projects
Use recycled concrete aggregate as a substitute for base stone	100%	58%	58%	Base stone use in all projects
Preventive maintenance				
Preventive maintenance	100%	29%	33%	Materials and construction fuel use in roadway resurfacing and reconstruction projects

* These reductions are applied to the entire “well to wheels” fuel cycle, which means that they account for the energy and emissions impacts of extracting and producing fuel as well as the impacts of using fuel in vehicles.

** Users will only enter whether strategies are in use (yes/no), not the percentage deployment of strategies.

The following sections describe the data sources, assumptions, and methods used to quantify the impacts and maximum potential deployment of each technique.

5.1. Alternative Fuels and Vehicle Hybridization

Feedback from pilot testers suggest that it is much easier for MPOs and DOTs to use alternative fuels and hybrid vehicles for maintenance rather than construction, since transportation vehicles typically use their own fleets for maintenance, whereas they hire contractors for construction projects. The tool therefore includes separate inputs on the implementation of strategies in this category for maintenance and construction projects.

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therefore includes separate inputs on the implementation of strategies in this category for maintenance and construction projects.

Data Sources

- We used data from Jack Faucett Associates (JFA) on the types of equipment associated with different construction processes.
- We used GreenDOT to estimate the potential for GHG and energy reductions from hybridization for each equipment type and as a source of emissions factors for different fuel types.⁴²
- We derived reduction factors for GHG emissions and energy use from biodiesel using the U.S. Department of Energy's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.⁴³

Assumptions

Since hybridization reduces the fuel consumed by maintenance vehicles, we assumed that reductions in energy are proportional to reductions in GHG emissions.

Methodology

In order to calculate the GHG emissions for hybridization of a given piece of equipment, we subtracted the reduction in fuel usage due to hybridization from the baseline fuel usage.

In order to calculate the GHG emissions due to different diesel fuels, we multiplied the fuel usage for a given piece of diesel equipment by the GreenDOT emissions factors for conventional diesel and applied GREET GHG reduction factors for B20 and B100 biodiesel blends.

In order to calculate the energy impacts due to biodiesel, we applied energy factors for B20 and B100 derived from GREET to the fuel use for a given piece of diesel equipment.

In order to calculate the GHG emissions for a given piece of equipment under a scenario where the equipment uses both hybrid engine and B20, we converted the hybrid and B20 emissions to percentages of baseline emissions and multiplied these two percentages.

We summed GHG emissions under all scenarios (baseline, hybrid, B20, B100, and hybrid-B20) for all of the vehicles involved in a given construction process and calculated the reduction in GHG emissions compared to the baseline for each alternative technique and each scenario.

We took the mean GHG reduction for each alternative technique across all construction activities for each scenario.

⁴² National Cooperative Highway Research Program (NCHRP), Greenhouse Gas Calculator for State Departments of Transportation (GreenDOT) v 1.5b, NCHRP 25-25, Task 58, Methods to Address Greenhouse Gas Emissions from Transportation Construction/Maintenance/Operations Activities, August 2010.

⁴³ Argonne National Laboratory, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model 1, 2012, rev 1, U.S. Department of Energy, 2012.

HYBRID VEHICLES AND EQUIPMENT

To estimate the breadth of application of vehicle hybridization, the team identified, from prior industry research completed by ICF, the type of construction vehicles and equipment for which hybrid alternatives are currently available or likely to become available in the near-term future. This includes excavators, scrapers and graders for earth-moving, material-handling equipment, crushing equipment and loaders for moving and placing asphalt, base course and concrete, and cranes and drill rigs for the placement and construction of bridges and supports. Using data on fuel use by project type compiled by JFA, the ICF team estimated that, on average, the vehicles and equipment for which hybrid alternatives will likely be available account for roughly 44 percent of total fuel use for the project types included in the tool. We therefore limited the deployment of this strategy to 44 percent or less.

There are minor differences in the GHG and energy reductions for different equipment types, and for the mix of equipment used in different project types, but the variation was not significant given the margin of error in our forecasts of hybrid efficiency availability. We therefore applied average reduction factors for hybridization across all project types to all energy and GHG emissions due to fuel use in construction and/or maintenance vehicles.

SWITCH FROM DIESEL TO B20/B100

The ICF team's research shows that B20 (a blend of 20 percent biodiesel and 80 percent petroleum diesel) is generally compatible with construction equipment, without any notable limitations on which equipment may use it and which may not. There is a change in energy content, and so slightly more B20 must be burned per hour than petroleum diesel to carry out the same activity – the cost of which is estimated below. Therefore, we applied the reduction factors for B20 usage to all energy and GHG emissions due to fuel use in construction and/or maintenance vehicles.

The use of B100 in construction and maintenance equipment is currently limited by manufacturers' warranties. While B100 can theoretically be used as a diesel replacement in all equipment types, few if any equipment manufacturers would honor the equipment warranty if B100 is used. (Biodiesel is sometimes blamed for clogging fuel filters or causing other system failures and, depending on the quality of the biodiesel, may require changes in equipment maintenance practices). However, the tool treats B100 as applicable to all construction and maintenance activities in recognition of the fact that manufacturers' warranty policies may change as B100 use becomes more widespread. We therefore applied the reduction factor for B100 usage to all energy and GHG emissions due to fuel use in construction and/or maintenance vehicles.

COMBINED HYBRIDIZATION/B20

Because B20 may be used without restriction in construction equipment, the availability of hybridized equipment, as discussed above, constitutes the only limiting factor to consider in this case. We therefore applied the reduction factors for combined use of B20 and hybrid vehicles and equipment to all energy and GHG emissions due to fuel use in construction and/or maintenance vehicles and limiting this strategy to a maximum deployment of 44 percent, based on the likely availability of hybrid technology discussed above.

5.2. Alternative Vegetation Management and Snow Management Strategies

Data Sources

- We used fuel usage data on maintenance activities from Washington and Utah state DOTs.
- We collected e-mail survey responses from Washington and Utah DOTs on current deployment of alternative vegetation management strategies and alternative snow fencing and removal strategies, estimated fuel savings from the use of alternative strategies, and maximum potential deployment of alternative strategies.

Assumptions

- 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.
- We assumed that Utah, which is primarily desert, 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.
- 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.
- 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.
- 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.
- Since energy conserved by alternative snow management strategies is in the form of fuel consumed by maintenance vehicles, we assumed that GHG reductions are proportional to reductions in energy usage.

Methodology

- 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.

- 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.
- We used state DOT estimates of the maximum possible percentage reductions in energy use due to alternative snow management strategies 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.

The applicability of these techniques varies widely according to climatic conditions. In order to account for variation in vegetation, we asked DOT staff from a state with large regions of low vegetation (Utah) and a state with highly-vegetated regions (Washington) to provide information on the current total fuel used for vegetation and snow management, current reductions in fuel use due to alternative vegetation management strategies, and the maximum potential applicability of these strategies, and used this data to calculate the maximum potential GHG and energy reductions due to these strategies. The applicability of these strategies depends upon the level of vegetation in a state, which in turn depends on the level of rainfall. We assumed a low level of effort for vegetation management if the land area of the state is predominantly covered by areas that receive less than 25 inches of rain per year

For snow removal strategies, we applied a similar analysis to data from a state with high amounts of snowfall (New York) and two states with moderate snowfall (Utah and Washington). The applicability of alternative snow management strategies depends upon the level of snowfall in a state; we assumed that the level of effort required for snow maintenance is low if the state average annual snowfall is less than 13 inches and medium if the average is less than 24 inches. These are relatively low thresholds due to the fact that state DOTs are likely to be responsible for maintaining roads in mountainous areas that receive higher snowfall and are less developed.

All data supplied by DOTs dealt with management of the road system, and no reliable data was available on the potential of these strategies to reduce energy use or GHG emissions for other transportation facilities. We therefore applied the reduction factors for these strategies to all energy and GHG emissions due to fuel used for snow removal and vegetation management in the maintenance of roadway facilities. Due to the variety of snow and vegetation management strategies considered and the role of climate in shaping the reductions from these strategies, the tool allows users to input whether they use alternative vegetation and snow management strategies via a yes/no dropdown menu rather than entering a percentage deployment for each strategy.

5.3. Soil Stabilization and Balanced Earthwork

According to the literature review, these practices do not consistently reduce fuel consumption. Further research did not yield any reliable sources that can be used to quantify the impacts of these strategies on GHG emissions and energy use. We therefore removed the toggle for this practice from the model.

5.4. In Place Recycling and Full Depth Reclamation

Data Source

- We used data on the energy and GHG reductions associated with different cold in place recycling methods and with baseline mill-and-fill repaving from The New York State DOT (NYSDOT) report on cold in-place recycling.⁴⁴
- We used data 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.⁴⁵

Assumptions

- NCHRP did not quantify the reductions in energy use associated with in-place recycling. Based on the results of the NYSDOT report, which did quantify both energy use and GHG reductions, we assumed that the reductions in energy use from in-place recycling were equivalent to the reductions in GHG emissions.

Methodology

- 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.
- We took the midpoint of the range of GHG reductions identified for various in place recycling techniques surveyed in NCHRP 421.
- We took the average of the average reduction values from the NYSDOT report and from NCHRP 21.

According to the National Asphalt Paving Association (NAPA), these activities are generally applicable with no notable restrictions to all but very rare cases of asphalt roadways.⁴⁶

COLD IN-PLACE RECYCLING

CIR is applicable to asphalt use in roadway resurfacing projects, where there is an existing roadway in place that can serve as a source of recycled materials for the new roadway surface. It is also applicable to conversions of vehicle lanes to bus rapid transit lanes, which typically involve some replacement of base course, which then requires resurfacing. The other project types included in the tool that involve conversion or upgrades are not candidates for this strategy because they do not

⁴⁴ Chesner Engineering (2010). Cold-In-Place Recycling in New York State.

⁴⁵ 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.

⁴⁶ Hansen, Kent and David Newcomb. "Asphalt Pavement Mix Production Survey on Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, and Warm-mix Asphalt Usage: 2009-2010." National Asphalt Pavement Association. November 2011. http://www.asphaltpavement.org/images/stories/is-138_rap_ras_wma_survey_2009_2010.pdf

involve asphalt resurfacing; bridges, rail projects, and sidewalks do not typically have asphalt wearing surfaces, while conversion of existing facilities to bicycle lanes typically does not involve resurfacing.

FULL DEPTH RECLAMATION

FDR is applicable to base stone use in roadway reconstruction projects, where there is an existing roadway in place that can serve as a source of recycled materials for the new roadway base course. It is also applicable to conversions of vehicle lanes to bus rapid transit lanes, which typically involve some replacement of base course that makes these projects candidates for FDR. The other project types included in the tool that involve conversion or upgrades are not candidates for this strategy because they either do not involve reconstructing a base course or because existing facilities are unlikely to have asphalt in place that can be recycled to create a new base course.

5.5. Warm Mix Asphalt

Data Sources

- We used data from Kristjansdottir et al on the impacts that different WMA technologies have on mixing temperatures and energy consumption.⁴⁷

Assumptions

- Since WMA reduces fuel consumption for the equipment used to heat asphalt, we assumed that GHG reductions from WMA were equivalent to reductions in energy consumption.

Methodology

- Kristjansdottir et al reported percentage reductions in energy consumption for four different WMA processes. For those processes for which they reported a range of reductions, we took the midpoint value. We then took the average energy reduction across all four processes.

The ICF team has found that warm mix asphalt can be used as a substitute for conventional asphalt in all project types and modes included in the tool. We therefore applied reduction factors for WMA to the materials embodied GHG emissions and energy use due to construction fuel used in asphalt batch plants for all projects included in the tool.⁴⁸

⁴⁷ Kristjansdottir, O., Muench, S., Michael, L., & Burke, G. (2007). "Assessing Potential for Warm Mix Asphalt Technology Adoption." *Transportation Research Record* 2040, 91-99.

⁴⁸ The ICF Team has identified asphalt batch plant fuel use factors that will be integrated into the spreadsheet tool.

5.6. Recycled and Reclaimed Materials

Data Sources

- We used GreenDOT to quantify the GHG emissions associated with different construction materials and to identify the average proportion of binders and aggregates in asphalt pavement and concrete.
- We used statewide concrete usage data from Caltrans to identify the average concrete mix associated with standards encouraging the usage of recycled materials and industrial byproducts in lieu of portland cement.
- We used Caltrans' Standard Specifications to identify the average mixture of fine and coarse aggregates in concrete mixes.⁴⁹
- We used data from Federal Highway Administration and the Portland Cement Association on the maximum amount of recycled concrete that can be used as a substitute for fine and coarse aggregates in concrete mixes.^{50, 51}

Assumptions

- We assumed that reclaimed concrete material and reclaimed asphalt pavement are the most widely available and feasible source for recycled aggregates. The team did not find any research that evaluates how recycled aggregates can be combined with other aggregate substitutes, so we did not attempt to quantify reductions from different blends of recycled and reclaimed aggregates.
- We assumed that energy reduction associated with recycled and reclaimed materials was equivalent to GHG reductions, except in the case of cement. According to GreenDOT, half of the embodied GHG reductions from portland cement come from a chemical reaction, so we assumed energy reductions from using recycled and reclaimed cement substitutes were equal to 50 percent of the associated GHG reductions.

Methodology

- We used GreenDOT to quantify the embodied GHG emissions associated with baseline mixes for concrete and asphalt and with mixes that used the maximum feasible proportions of recycled and reclaimed materials asphalt and cement. We then compared the values to calculate percentage GHG reductions associated with recycled and reclaimed materials.

⁴⁹ California Department of Transportation (Caltrans) (2012). Standard Specifications, section 90-1.02C(4)(d).

⁵⁰ Federal Highway Administration (1997). *FHWA-RD-97-148: User Guidelines for Waste and Byproduct Materials in Pavement Construction*. <http://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/rcc2.cfm>.

⁵¹ Portland Cement Association (2012). Frequently Asked Questions: Recycled Aggregate. http://www.cement.org/tech/faq_recycled.asp.

- We repeated the process for energy use by assuming that energy use was proportional to GHG emissions, except for cement, as discussed above.

RECYCLED ASPHALT PAVEMENT

Recycled (or reclaimed) asphalt pavement (RAP) can substitute for either virgin aggregate or binder in asphalt mixes. The GHG/energy reductions and deployment vary widely depending on which of these two materials RAP replaces, so we broke RAP use out into two separate strategies. Bitumen is more energy-intensive to produce than aggregate, so using RAP as a substitute for bitumen yields greater GHG and energy reductions. 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.

INDUSTRIAL BYPRODUCTS

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. The limitations on the use of these byproducts, which are not always widely available, are due more to cost constraints than engineering constraints, making it unlikely that a DOT or MPO would mandate their use in construction projects. Caltrans, which has been a leader in amending specifications to allow for greater use of industrial byproducts in concrete mixes, reports that these byproducts account for 33 percent of cement in the average statewide mix, so we limited deployment of this strategy to 33 percent.

RECYCLED CONCRETE AGGREGATE

Recycled concrete aggregate (RCA) replaces virgin aggregate in intermediate courses or aggregate base courses. We therefore applied GHG and energy reductions due to the use of RCA to base stone in all projects.

5.7. Preventive Maintenance

The research that is the source of GHG and energy reduction factors for preventive maintenance focuses on analyzing materials and fuel used for resurfacing roadways assuming normal level of wear from light- and heavy-duty vehicles.⁵² Therefore, we applied reductions for preventive maintenance to construction equipment and materials in the resurfacing and reconstruction of roadway facilities. All impacts from preventive maintenance are bundled under the construction module in the tool.

⁵² Chehovits, Jim, and Larry Galehouse, "Energy Use and Greenhouse Gas Emissions of Pavement Preservation Processes," http://techtransfer.berkeley.edu/icpp/papers/65_2010.pdf.

Data sources

- Typical cycles for roadway maintenance and rehabilitation were developed for two treatment regimes using expert input:
 - Pavement lifecycle without preservation
 - Pavement lifecycle with preservation
- Energy usage associated with each activity in the pavement lifecycle was drawn from Chehovits and Galehouse⁵³

Methodology

- We calculated average annual energy use associated with roadway maintenance and rehabilitation (following new roadway construction) for both cycles, in order to estimate the relative energy and emissions savings from a preventive maintenance cycle.

Table A-23 shows the comparison of energy use throughout the lifecycle of pavement with and without preservation. These typical cycles were developed using expert input. They are not recommended cycles, since the resurfacing and rehabilitation needs of roadways vary widely based on climate, design, and use levels. Rather they are a starting point for estimating resurfacing and reconstruction activities when no other information is available.

⁵³ Chehovits, J. and L. Galehouse, 2010, "Energy Usage and Greenhouse Gas Emissions of Pavement Preservation Processes," Compendium of Papers from the First International Conference on Pavement Preservation, http://techtransfer.berkeley.edu/icpp/papers/65_2010.pdf.

Table A-23: Pavement Preservation Energy Benefits

Year	Pavement Lifecycle without Preservation		Pavement Lifecycle with Preservation	
	Process	BTUs/sy	Process	BTUs/sy
0	New Construction	156,820	New Construction	156,820
5	-	-	Seal Coat	3,800
10	-	-	-	-
12	-	-	Thin Surface Treatment/Micro Surfacing	3,800
15	Mill and Overlay (2") (Mill/Replace 2")	56,400	-	-
20	-	-	Mill and Overlay (2") (Mill/Replace 2")	56,400
24	-	-	-	-
25	-	-	Thin Surface Treatment/Micro Surfacing	3,800
30	Hot Mix Rehab (Mill 2"/Replace 4")	112,800	-	-
35	-	-	Hot Mix Rehab (Mill 2"/Replace 4")	112,800
36	-	-	-	-
40	-	-	Thin Surface Treatment/Micro Surfacing	3,800
45	Mill and Overlay (2") (Mill/Replace 2")	56,400	-	-
48	-	-	-	-
50	-	-	-	-
55	-	-	Mill and Overlay (2") (Mill/Replace 2")	56,400
60	Hot Mix Rehab (Mill 2"/Replace 4")	112,800	-	-

Notes:

- All cycles represent a suggested practice, not an idealized or standard practice. Maintenance and preservation strategies will differ based on agency practice.
- All cycles represent practices averaged for low volume and high volume roads
- All cycles include crack sealing conducted approximately every 3 years. This is not shown in the table in order to simplify the comparison of differences in cycles.

ⁱ Figure ES1 on page 6 lifecycle images, from left to right, top to bottom:

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